AECU-3377

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Laboratory for Nuclear Science

ANNUAL PROGRESS REPORT

June 1, 1955 to May 31, 1956

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

I

AECU-3377

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Laboratory for Nuclear Science

ANNUAL PROGRESS REPORT

Researches During the Period June 1, 1955 to May 31, 1956

Reproduction in whole or in part is permitted for any purpose by the U. S. Government. The data and the results which are presented in this report should not otherwise be published without prior consultation with the Laboratory for Nuclear Science.

Researches herein reported by the Chemistry Groups have been supported by the Atomic Energy Commission under Contract No. AT(30-1)-905; the work of the remaining groups has been supported by the joint program of the Office of Naval Research and the Atomic Energy Commission under Task Contract N5ori-07806.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

III

This is the forty-first progress report of the Laboratory for Nuclear Science at the Massachusetts Institute of Technology. Progress during the period June 1, 1955 to May 31, 1956 is reported under the following group headings:

1. Chemistry of the Fission Elements Group
2. Nuclear Chemistry (Inorganic) Group
3. Nuclear Chemistry (Organic) Group
4. Cosmic Ray Group
5. Elementary Particle Scattering Group
6. Neutron Physics Group
7. ONR Generator Group
8. Radioactivity Group
9. Cyclotron Group
10. Synchrotron Group
11. Theoretical Group
12. Cambridge Accelerator Project Group

Reprints of published papers listed herein are available in limited numbers upon request from the Laboratory for Nuclear Science.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

	Page
Introduction	
Chemistry of the Fission Elements Group	1
I. Introduction	1
II. Complex Chemistry of the Fission Elements	1
III. Interfacial Tension in Complex Formation	4
IV. Thermometric Titrations	4
V. Flame Photometry	6
VI. Photometric Titrations	6
VII. Ion-Exchange Studies	7
VIII. Precipitation of Metal Sulfides with Thioacetamide	8
IX. Analysis of Spectrophotometric Curves	8
X. Coulometry	9
XI. The Electrodeposition Behavior of Trace Amounts of Elements	9
XII. Rates of Electrochemical Reactions	11
XIII. Fluorescence of Metal Chelates	11
XIV. Turbidimetry in the Ultraviolet	12
Nuclear Chemistry (Inorganic) Group	13
I. Introduction	13
II. Instrumentation	14
III. Physico-Chemical Studies	15
IV. Solvent-Extraction Studies	16
V. Ion-Exchange Studies	23
VI. Nuclear Chemistry	29
VII. Fission Radiochemistry	35
VIII. Discussion of Research Plans	36
Nuclear Chemistry (Organic) Group	39
I. Introduction	39
II. The Enolization of Ketones	39
III. Comparison of Deuterium and Tritium Isotope Effects	41
IV. Proton Exchange Between Alcohols	41
V. The Thermal Decomposition of Benzoyl Peroxide	44
VI. Comparison of Hydroxide and Deuterioxide Ion Isotope Effects	46
VII. Isotope Effects in Decarboxylation	46
VIII. Isotope Effects in Hydrolysis	46
IX. Isotope and Substituent Effects in Oxidation of Alcohols	46
X. Isotope Effects in Reactions of Hydroxylic Compounds	47
XI. Intramolecular Hydrogen Transfer	47
XII. Study of Ion Pair Formation in the Decomposition of Alkyl Chlorosulfites	47
XIII. Methyl Activation in Coenzyme A-Type Compounds	48
Cosmic Ray Group	49
I. Introduction	49
II. Operation of the Multiplate Chamber at Echo Lake	49
III. Photometric Ionization Measurements	50
IV. Operation of the Multiplate Cloud Chamber at Brookhaven National Laboratory	51

Table of Contents

	Page
V. Southern Hemisphere Air Shower Monitor	56
VI. A Large Meson Telescope	57
VII. High-Energy Cross Sections	58
VIII. Air Shower Experiment	59
IX. Arrival Directions of Air Showers	66
X. Calculations on High-Energy Cosmic-Ray Cascades	66
XI. Heavy Mesons and the Electromagnetic Properties of Nucleons	69
XII. Preparation of Large Plastic Scintillators	71
XIII. A Structured Picture of the New Unstable Particles	71
XIV. High Pressure Rectangular Ionization Chamber	72
XV. Search for Long-Lived K-Mesons Using the Cosmotron	73
Elementary Particle Scattering Group	75
I. Photo Emulsion Research	75
II. Atomic Model of the Nucleon and Pion-Nucleon Interactions	88
III. Interpretation of the Second Pion-Nucleon Scattering Resonance in Terms of the "Low-Energy" Isobar	88
IV. A Remark on the Application of Causality Relationships to the Interpretation of Pion-Nucleon Scattering	88
V. Bubble Chamber Program	89
VI. Linear Accelerator	89
Neutron Physics Group	95
I. Introduction	95
II. Crystal Efficiency Calibration and As^{71} Half Life	102
ONR Generator Group	104
I. Introduction	104
II. Energy Levels of S^{32} and S^{34}	104
III. Energy Levels of P^{31} and Si^{28}	105
IV. Energy Levels of Cl^{35} and Cl^{37}	106
V. Energy Levels of Ni^{58} , Ni^{60} , and Ni^{62}	106
VI. Energy Levels in Ne^{20} and Na^{23}	107
VII. Energy Levels in A^{36} and K^{39}	109
VIII. (d, p) Reactions of the Iron Isotopes	111
IX. Inelastic Scattering from Iron	113
X. Excited States of Mn^{55} and Co^{59}	113
XI. Excited States of Mn^{56}	114
XII. Inelastic Proton Scattering from Gold	116
XIII. Angular Distribution of Protons from Deuteron Bombardment of Calcium Isotopes	116
XIV. Inelastic Scattering from Silver	117
XV. $Al^{27}(d, p)Al^{28}$ Stripping Analysis	118
XVI. The Energy Levels of Be^9	123
XVII. Inelastic Scattering from In, Cd, Sm, and Tb	130
XVIII. Excited States of F^{19} and O^{16}	135
XIX. The $C^{12}(p, p')C^{12}$ Reaction	136
XX. The $O^{16}(d, \alpha)N^{14}$ Reaction	138
XXI. The $O^{16}(d, d)O^{16}$ Reaction	143
XXII. The $Si^{28}(d, \alpha)Al^{26}$ Reaction	146
XXIII. Apparatus Development	148

	Page
Radioactivity Group	152
I. Introduction	152
II. Positronium	152
III. $0^+ - 0^+$ Transitions in Medium-Weight Nuclei	160
IV. Resonance Absorption of γ Rays	161
V. Co^{57} Decay Scheme	163
VI. Al^{26} Decay Scheme	164
VII. Measurement of g-Factor of Low-Lying Excited States of Nuclei	165
Cyclotron Group	166
I. Introduction	166
II. Maintenance and Improvement	166
III. Elastic Deuteron Scattering	167
IV. Elastic Proton Scattering	167
V. Fast Coincidences from Cyclotron Reactions	168
VI. Instrumentation	173
Synchrotron Group	174
I. Synchrotron Operation	174
II. Photoproduction of π^+ Meson from Hydrogen at 265-Mev Gamma-Ray Energy	175
III. π^0 Photoproduction from Various Elements	176
IV. The Momentum of Nucleons in Various Nuclei from the High-Energy Photoeffect	178
V. Study of Photomeson Production from Complex Nuclei	179
VI. Photomeson Production from Deuterium	179
VII. The Electric-Dipole "Giant Resonance" in Photonuclear Reactions from a Microscopic Point of View	180
VIII. γ -Ray Scattering	183
IX. Pulse-Height Telescope	187
X. High-Energy γ -Ray Detector	187
Theoretical Group	189
I. Introduction	189
II. The Cloudy Crystal Ball Model	189
III. Investigations Regarding the Optical Model Potential	189
IV. Investigations Regarding the Bohr-Mottelson Model	190
V. Investigations Regarding the Nature of the Spin-Orbit Coupling	190
VI. Direct Interaction in Inelastic Neutron Scattering	191
VII. Nucleon-Nucleon Scattering	191
VIII. Photodisintegration of the Deuteron	191
IX. The Bohr-Mottelson Model	192
X. Nuclear Saturation	192
XI. Relativistic Wave Mechanics	192
XII. Strange Particles	193
XIII. Theory of S-Wave Meson Scattering and Photoproduction	193
XIV. Two S-Wave Meson Phenomena	194
XV. Proton Polarizability	194
XVI. Nuclear Saturation	194
XVII. A High-Energy Approximation for Relativistic Scattering Cross Sections	195
XVIII. The Inelastic Scattering of 30-Mev Protons by Heavy Nuclei	195
XIX. Pion Production in Pion-Nucleon Collisions	195

Table of Contents

	Page
Cambridge Accelerator Project Group	197
I. Introduction	197
II. General Description	197
III. Phase-Modulated Injection	199
IV. Magnet Alignment	200
V. Radiation-Induced Oscillations	201
VI. Magnet Model Studies	201
VII. Building Plans and Shielding Arrangements	203
VIII. Research Program.	203
Appendix A --- Personnel Listing by Projects	205
Appendix B --- Publications	210
Appendix C --- Addresses	215
Appendix D --- Theses	221
Appendix E --- Technical Reports	223

LIST OF FIGURES

			Page
Figure	2.1	Cosmic abundances of the element, A	31
Figure	4.1	Calibration record for ten air shower detectors, February 17 - May 18, 1956	60
Figure	4.2	Measured lateral distribution of electrons in six large showers that arrived near the zenith. The solid line is the theoretical distribution for pure electron cascades with $S = 1.4$	63
Figure	4.3	Measured lateral distribution of electrons in six large showers that arrived at large zenith angles. The distributions are in a plane perpendicular to the shower axis, and the solid lines are for $S = 1.4$ as in Figure 4.2	
Figure	4.4	Zenith angle distribution of a group of showers having 2.10^6 or more particles	74
Figure	4.5	Photograph of the new apparatus for the determination of shower arrival directions by part timing. This apparatus is currently being installed at Ahmedabad, India	67
Figure	4.6	Block diagram of the electronic arrangement of the apparatus described in Figure 4.5.	66
Figure	5.1	Experimental arrangement of the strong-focussing channel used in the exposure	76
Figure	5.2	Ranges of secondaries of K_L -mesons	78
Figure	5.3	Ranges of gray secondaries of K-mesons	77
Figure	5.4	Cross section for K^+ scattering	84
Figure	5.5	Experimental layout of linear accelerator x-ray beam	90
Figure	5.6	Energy distribution of photoprotons from ^{14}N	91
Figure	5.7	Yield of photoprotons from 10.43 Mev $^{14}\text{N}^*$ versus E_{max}	92
Figure	5.8	Measured bremsstrahlung spectra	92
Figure	6.1	Level scheme for a typical odd-A rotational nucleus, showing electric quadrupole excitation of the first two energy levels and the subsequent decay. The crossover from the second level to the ground state is pure E2 while the cascade transitions are mixed M1 and E2	96
Figure	6.2	Counting assembly cutaway diagram showing solid angle and lead shielding. The lower inset shows the complete assembly	98
Figure	7.1	Proton spectrum observed at 130° from bombardment of a thin target with 7.04-Mev incident protons	108
Figure	7.2	Spectrum of elastically scattered protons with energies between 2.2 and 5.0 Mev observed at 60° from bombardment of the NaI target. The incident proton energy was 7.45 Mev	108
Figure	7.3	Proton spectrum observed at 130° from bombardment of a thin KI target. The incident proton energy was 7.45 Mev	110
Figure	7.4	Spectrum of inelastically scattered protons with energies between about 2.2 and 5.0 Mev observed at 60° from bombard- ment of a KI target. The incident proton energy was 7.45 Mev	110

List of Figures

			Page
Figure	7.5	Proton spectrum observed at 30° from MN^{55} targets. Incident deuteron energy was 7.006 Mev	115
Figure	7.6	Example of theoretical stripping curve with $\ell_n = 0$ fitted to experimental points	119
Figure	7.7	Example of theoretical stripping curve with $\ell_n = 1$ fitted to experimental points	119
Figure	7.8	Example of theoretical stripping curve with $\ell_n = 2$ fitted to experimental points	119
Figure	7.9	Energy spectrum of Al^{28} from two different reactions	121
Figure	7.10	Levels expected to be formed in Al^{28} by adding neutron to a core of Al^{27} in a pure $d_{5/2}$ state.	122
Figure	7.11	Spectrum of protons inelastically scattered from a beryllium target.	124
Figure	7.12	Spectrum of alpha particles plus tritons emitted from a boron target under deuteron bombardment	126
Figure	7.13	Expected distributions from three-particle reactions. The dashed curves are the distributions expected for no interaction between the neutron and Be^8 . The solid curves graph the distributions in the case of an s-wave potential scattering of the neutron by Be^8 of strength measured by a scattering length of 2×10^{-12} cm	129
Figure	7.14	Data for angular distribution $\ln(p, p) - 7.04$ Mev	131
Figure	7.15	Experimental angular distributions inelastic proton scattering $E_{in} = 7.0$ Mev. Natural indium targets	131
Figure	7.16	Spectra of protons scattered from terbium, samarium, and cadmium targets	133
Figure	7.17	Yield of inelastic protons from first excited state of C^{12}	137
Figure	7.18	Angular distributions of inelastic protons from first excited state of C^{12}	137
Figure	7.19	Five plots of alpha particles from SiO_2 targets at various bombarding energies	139
Figure	7.20	Yield of alpha groups leading to the ground state and first two excited states of N^{14}	140
Figure	7.21	Yield of first excited-state group	141
Figure	7.22	Preliminary data for angular distribution of ground state and first excited state of N^{14}	141
Figure	7.23	Energy-level diagram of the compound nucleus F^{18}	142
Figure	7.24	Yield of elastically scattered deuterons from O^{16}	144
Figure	7.25	Relative response of CsI (Tl) crystal to protons, deuterons, and alpha particles	145
Figure	7.26	Yield curve from $Si^{28}(d, \alpha)Al^{26}$	147
Figure	8.1	Energy levels of argon and krypton atoms	155
Figure	8.2	Formation of positronium in mixtures of argon and krypton.	155
Figure	8.3	Formation of positronium in mixtures of argon and freon	155

			Page
Figure	8.4	Observed three-photon annihilation rate in mixtures of argon and nitric oxide	156
Figure	8.5	Ratio of three-quantum annihilation with quenching gas added to that in pure argon, as a function of magnetic field	159
Figure	8.6	Ratio of the number of delayed coincidences in magnetic field to that without field in teflon, strong field.	159
Figure	8.7	Effect of magnetic field in teflon, medium field.	158
Figure	8.8	Experimental arrangement for measuring lifetime of 0^+ state in Zr^{90}	161
Figure	9.1	Top view of Thomas type wedge shim	166
Figure	9.2	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 13$	169
Figure	9.3	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 28$	169
Figure	9.4	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 29$	169
Figure	9.5	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 33$	170
Figure	9.6	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 48$	170
Figure	9.7	Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 49$	170
Figure	9.8	Schematic drawing of coincidence circuit	171
Figure	9.9	Time resolution curve of the cyclotron beam as compared to prompt resolution curve of the electronic equipment	172
Figure	10.1	π^+ photoproduction from hydrogen at 265-Mev gamma-ray energy	175
Figure	10.2	π^0 photoproduction from hydrogen and deuterium	177
Figure	10.3	π^0 differential cross section near 0^0 divided by $A^{4/3}$	177
Figure	10.4	Variation of potential well calculation with absorption	177
Figure	10.5	Gamma-ray scattering data on hydrogen and deuterium	184
Figure	10.6	Gamma-ray scattering data in complex nuclei	185

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

LABORATORY FOR NUCLEAR SCIENCE

INTRODUCTION

The program of the Laboratory for Nuclear Science centers currently about the following general activities: nuclear inorganic chemistry (Professors C. D. Coryell, J. W. Irvine, Jr., and G. Scatchard); nuclear organic chemistry (Professors F. D. Greene, II, J. C. Sheehan, and C. G. Swain); chemistry of the fission elements (Professors D. N. Hume and L. B. Rogers); cosmic ray research (Professors Bruno B. Rossi, R. W. Williams, G. W. Clark, W. L. Kraushaar, J. B. Linsley, and Drs. H. H. Bridge, S. Olbert, and D. O. Caldwell); photo-meson and photo-nuclear research using MIT's synchrotron and linear accelerator (Professors B. T. Feld, D. H. Frisch, R. Weinstein, Drs. L. S. Osborne, D. M. Ritson, A. Wattenberg, P. T. Demos, C. P. Sargent); theoretical nuclear physics (Professors V. F. Weisskopf, H. Feshbach, F. Villars, F. L. Friedman, S. Drell, and Drs. M. H. Friedman and F. Zachariasen); nuclear energy level studies using the MIT-ONR Van de Graaff generator (Professors W. W. Buechner, H. A. Enge, and Drs. C. P. Browne, F. J. Eppling, and Mr. A. Sperduto); coulomb excitation and gamma ray angular correlation studies using the Rockefeller Van de Graaff generator (Professor M. Deutsch, Dr. G. Goldring and R. P. Scharenberg); elastic scattering of alpha particles, protons and deuterons from nuclei using MIT's Markle cyclotron (Professors M. Deutsch, M. S. Livingston and Dr. N. S. Wall); radioactivity research and positronium studies (Professors R. D. Evans and M. Deutsch, C. J. Maletskos, H. W. Kendall); high-energy nuclear emulsion studies (Drs. D. M. Ritson, A. Pevsner, L. S. Osborne, R. A. Schluter); bubble chamber studies (Dr. I. Pless).

Persons active in the work of the Laboratory over the past year, not including visitors, totalled 285. These included 52 academic staff members of the Departments of Chemistry and Physics, 26 DIC staff members, 38 graduate students from the Department of Chemistry, 64 graduate students from the Department of Physics, 68 full-time non-staff employees, and 37 part-time non-staff employees. Theses carried by students working in the Laboratory involved 4 B.S. degrees, 6 M.S. degrees, and 13 Ph.D. degrees. Publications submitted to scientific journals numbered 72, and 93 addresses were delivered to various scientific conferences and meetings. Foreign scientists from 20 universities were active in the researches of the Laboratory.

Studies in Nuclear Chemistry have continued under the three general categories: "Chemistry of the Fission Elements", "Nuclear Organic Chemistry", and "Nuclear Inorganic Chemistry". The researches of the first group have included chemical studies of several elements via complex and separation chemistry and the development of techniques applicable to analytical and physico-chemical work. Researches of the Nuclear Inorganic Chemistry group have currently involved a concentrated study of the physical chemistry of complexes and their hydrogen acids to further the quantitative understanding of solvent extraction and ion-exchange processes. In addition, the work

of this group has included the development of new separation techniques useful for the characterization of short-lived radioactive species and the proposal and investigation of some ideas concerning the creation of the elements. The work of the nuclear organic chemistry group has centered about the use of tritium and deuterium isotope effects to study ketone enolization, the mechanism of fast exchange of protons between the hydroxyl groups of triphenyl-carbon and t-butanol, and a number of other important problems in organic chemistry.

The activities of the Cosmic Ray Group have been concerned with high energy nuclear interactions and with high energy air showers. Both cosmic rays and artificially accelerated particles (Brookhaven Cosmotron) have been used for the first of these, supplemented by theoretical work in the interpretation of the "strange" particles. Extensive experimental work has been done on the energy distribution of air showers, supplemented also by theoretical computations relating the observable properties of the showers to the primary particle energies and the character of their nuclear interactions. A significant advance in the air shower experiment was achieved during the year through the development of extremely large, but relatively inexpensive, plastic scintillators up to 50" in diameter. The program of the group currently includes: operation of multiplate cloud chambers in Colorado and at the Brookhaven National Laboratory; photometric ionization measurements; operation of an air shower monitor in India; the construction of a large meson telescope; operation of the large air shower experiment at the Harvard Agassiz Observatory; calculations of high energy cosmic ray cascades; development of a structured picture of the new unstable particles; and a search for long-lived K-mesons using the Brookhaven Cosmotron.

Considerable work was done through the year using nuclear emulsions to study the relatively intense, well-focussed K-meson beams which have become available at Brookhaven and Berkeley. The method is ideal as an exploratory technique and was used to examine the general properties and inter-relationships of the K-mesons. Specifically explored were: masses of the K-mesons based on range-momentum measurements; secondary mass values and relative frequencies of occurrence of the various modes of decay using the ranges and identities of the secondaries; lifetimes from decays occurring in flight; the absence of high mass secondaries from the K-meson beam; spin-parity properties of the tau meson; the interaction properties with nucleons of K-mesons in flight and relative scattering cross sections for tau and theta particles.

Nuclear Emulsion experiments have been initiated to extend the measurement of K-interaction cross sections to higher energies and to look for the long-lived neutral "strange" particles required by current theory. Absence of the latter particles would lead to a radical revision of current basic concepts. A pulsed magnet of about 300,000 gauss field strength is being developed in the hope of focussing very short-lived particles in distances of a few centimeters. The use of emulsions immersed in liquid hydrogen (or deuterium or helium) is also being investigated as a means of stopping K-particles or antiprotons by simple nuclei.

Work throughout the year with the synchrotron has continued at a very active pace. The proposed new Van de Graaff injector has been tested and is in the process of being installed. A hundred-fold increase in beam intensity is expected which should allow the performance of

secondary scattering experiments; for example, polarization measurements of secondary nucleons and the use of secondary mesons for scattering and absorption experiments. Research throughout the past year included: the photoproduction of π^+ mesons from hydrogen at 265 Mev; π^0 production from a number of elements; a study of the momentum distribution of nucleons in nuclei; the photoproduction of mesons from complex nuclei; measurement of the energy spectrum of neutrons emitted in coincidence with positive mesons; a study of the photoproduction of mesons from deuterium; investigation of the electric-dipole "giant resonance" in terms of the quasi-deuteron model; completion of the experiments in nuclear γ -ray scattering; the development of a fast coincidence-anticoincidence telescope detector for ionizing particles; and what it is hoped will be a higher resolution γ -ray detector using lead glass chips in conjunction with scintillating liquid.

Research with the linear accelerator has been directed towards scintillation spectrometer measurements of photoproton energy distribution; measurement of cross sections for the Coulomb excitation of nuclei by electrons; and time-of-flight measurement of photo-neutron energy distributions. Quantitative measurements have been made, incidentally, of the bremsstrahlung beam produced by the linear accelerator, including a method for determining the shape of the high energy end of the spectrum.

Theoretical studies have, as usual, covered a broad range of nuclear physics. In the low energy region, the Bohr-Mottelson model has been studied extensively with a view to understanding some of its difficulties. At higher energies, further meson investigations have included the development of a phenomenological s-wave theory; the study of two meson phenomena involving p-wave mesons; and the connection between p-wave meson effects and spin-orbit forces in nuclei. A model has been developed for nucleon-nucleon scattering which gives a qualitative fit to experimental data for 0 to 275 Mev. Additional investigations have involved: further calculations in terms of the "Cloudy Crystal Ball" model of the nucleus; examination of the significance of the real and imaginary parts of the optical potential; the nature of spin-orbit coupling; the direct interaction in inelastic neutron scattering; photo-disintegration of the deuteron; nuclear saturation; relativistic wave mechanics; proton polarizability and the inelastic scattering of 30-Mev protons by nuclei.

The general program of nuclear spectroscopy using the MIT-ONR Van de Graaff generator has continued. The level schemes of a large number of nuclei have been investigated and clarified. Studies have been continued of means of obtaining spin and parity information of individual levels. The mechanisms of certain reactions have been investigated with emphasis on Coulomb excitation and the role of the isotopic quantum number.

Work with the MIT cyclotron has centered about an investigation of the general properties of nuclear reactions, as determined by the measurement of elastic scattering angular distributions, and a study of the mechanisms of nuclear reactions. The elastic scattering of protons, deuterons and alpha particles has been examined in an effort to interpret the data in terms of the "cloudy crystal ball" nuclear model. Effort is being made to increase the intensity of the cyclotron beam with a view to performing magnetic analysis on the emergent beam and the reaction products.

The work of the radioactivity group has continued to be concerned with radioactive decay processes and investigations of the properties of positronium. Additional programs are the investigation of excited 0^+ states in medium weight nuclei and the resonance absorption of γ -rays.

All research with the Rockefeller Generator in the past year was in the electric excitation field, the major project being the measurement of relative transition probabilities for two excited states in odd-A nuclei. Work has been in progress also, in cooperation with the Radioactivity Group, on the measurement of magnetic moments of excited rotational states.

Members of the Laboratory have participated over the past two years in association with scientists from Harvard University in preliminary design studies on a 6-Bev electron accelerator to be located in Cambridge, Mass. on Harvard University grounds. Responsibility for the construction contract with the AEC will be assumed by Harvard University; however, a joint committee of scientists and administrators from Harvard and MIT will supervise the construction and operation of the accelerator as a research facility. Detailed designing of the machine has begun and construction of some of the buildings should be underway by late 1956.

Chemistry of the Fission Elements Group

I. INTRODUCTION

As in previous years the work of this group has proceeded along several distinct lines. The investigations of the chemical behavior of a number of elements have tended to concentrate on complex and separation chemistry. Simple and mixed ligand studies on indium, copper, bismuth, silver and lead have been made. Ion exchange and thioacetamide precipitation methods of separation are under study as are the properties of non-aqueous solvent systems. An intensive study is underway on the fundamental characteristics of electrodeposition of elements from very dilute solutions.

The development of new and improved techniques which may be generally applicable to analytical and physicochemical work occupies a sizable portion of the effort of the group. Particular emphasis has been given to very dilute solutions, and coulometry; potentiometry, fluorimetry and flame photometry are currently under study. Both photometric and thermometric titration methods are being applied not only for analytical purposes but as a means of doing fundamental studies on non-aqueous solutions.

II. COMPLEX CHEMISTRY OF THE FISSION ELEMENTS

A. Silver Bromide Complexes

Recently reported work in the Journal of the Indian Chemical Society¹ cited potentiometric titrations and polarographic studies in support of a claim that the substance HAgBr_2 was a weak acid. The observations of these workers did not seem to be in harmony with prior solubility measurements by German investigators and our own experience with the polarographic behavior of silver ions. Accordingly, potentiometric and polarographic measurements have been made with hydrobromic acid solutions saturated with silver bromide. It has been shown that the polarographic work in the Indian journal contained a number of errors which completely invalidated the interpretation. The appearance of a weak acid in the potentiometric titration curves was shown to be due to the presence of carbonate in the sodium hydroxide. This fact and solubility studies together with pH measurements of sodium bromide solutions saturated with silver bromide has led us to the conclusion that the compound HAgBr_2 , if it exists, must be a strong acid. The results of this investigation have been published in the Journal of Physical Chemistry². (R. C. DeGeiso)

B. Copper Pyridine Complexes

A study has been made of complex formation between cupric ions and pyridine. The method used was distribution of the complexing ligand between toluene and the aqueous solution. Analysis

of the resulting distribution coefficients of pyridine between water and toluene gave results in general agreement with previously reported values for the copper pyridine complexes except in highly alkaline solutions. In highly alkaline solutions the results indicate the presence of mixed pyridine and hydroxide complexes of copper. (W. E. Ohnesorge)

C. Iron Thioglycolate Complexes

A study has been made of the kinetics of the fading of ferric thioglycolate in alkaline air-free solutions. The course of the reaction was followed by measuring the absorbance of the ferric complex at 550 millimicrons as a function of time. Between the pH 8.4 and 10.1, the reaction is second order with regard to the total concentration of ferric iron and can be explained by a reaction involving the formation of a hydroxyl bridge dimer. The electron transfer occurs within the dimer which then breaks up into two molecules of ferrous iron and a molecule of the disulfide. Reaction rate constants and heats of activation have been evaluated. A paper describing these investigations has been published in the Journal of the American Chemical Society. (L. Newman)

D. Lead Acetate Complexes

The nature and stability of the acetate complexes of lead in solution have been studied by polarographic, potentiometric, and solubility methods. The existence of three species, $\text{Pb}(\text{OAc})^+$, $\text{Pb}(\text{OAc})_2$ and $\text{Pb}(\text{OAc})_3^-$ has been shown in perchloric solutions of lead containing excess of sodium acetate and acetic acid. The three methods have given concordant values for three successive overall stability constants of these species at an ionic strength of 1.98. The average values of the formation constants are 145, 810 and 2950, respectively. Direct determination of both lead and iodate in solutions saturated with lead iodate has revealed that this substance does not dissolve to give a stoichiometric lead to iodate ratio of 2:1. This fact probably accounts for the failure of previous workers to observe complexes higher than the 1:1 based on measurement of the solubility of lead iodate in ammonium acetate. The existence of non-ionic species was confirmed in our work by an anion exchange technique. The results of this investigation have been submitted for publication in the Journal of the American Chemical Society. (E. A. Burns)

E. Indium Bromide Complexes

Further studies of the ultraviolet absorption spectra of indium in bromide medium has permitted the determination of the formation constant of InBr_3 from the InBr_2^+ ion at an ionic strength of 4.00. This completes the determination of the series of stepwise formation constants from the mono to the tetrabromide complexes and the values obtained are $K_1 = 120$, $K_2 = 19$, $K_3 = 3.4$ and $K_4 = 6.8$, all at an ionic strength of 4.00. (E. A. Burns)

F. Mixed Ligand Complexes of Bismuth

Ultraviolet spectrophotometric studies of low concentrations of bismuth in perchloric acid solution as a function of added chloride or bromide has shown the existence of series of chloride and of bromide complexes. In the chloride series, it has been possible to show evidence for the existence of the ions BiCl^{++} , BiCl_2^+ , BiCl_3 , BiCl_4^- , and BiCl_5^{--} . Formation constants for these

complexes were determined in 1 M perchloric acid solutions at an ionic strength of 4.0 molar. The successive stepwise formation constants for the bismuth chloride complexes under these conditions were found to be $k_1 = 270$, $k_2 \sim 100$, $k_3 = 20$, $k_4 = 3$, $k_5 = 3$. It was observed that in bismuth solutions containing concentrations of chloride such as to favor the formation of the highest chloride complex, gradual replacement of the chloride in the solution with bromide at constant ionic strength resulted in a striking change in the absorption spectrum. The spectra of chloride-bromide mixtures could not be deduced from the spectra of bismuth-chloride and bismuth-bromide systems alone and it was concluded that mixed ligand complexes were being formed. Methods of the analysis of the absorption curves in the mixed system were developed and applied to the experimental data. As a result it has been possible to show the existence of the ions BiBrCl_4 , $\text{BiBr}_2\text{Cl}_3^{--}$, $\text{BiBr}_3\text{Cl}_2^{--}$, $\text{BiBr}_4\text{Cl}^{--}$, and BiBr_5^{--} . By use of newly developed equations it has been possible to estimate formation constants of a number of these complexes, specifically,

(L. Newman)

G. Mercury Cyanide Complexes

Mixed ligand complexes have been observed by polarographic, spectrophotometric and solubility studies. Polarographic measurements served as the basis for the determination of the formation constants.

$$K = \frac{[\text{Hg}(\text{CN})_3\text{X}^-]}{[\text{Hg}(\text{CN})_3^-][\text{X}^-]}$$

and the values obtained were 0.4, 2.3 and 2.9 for $x = \text{chloride}$, bromide , and thiocyanate respectively at an ionic strength of 2.0 and a temperature of 30°C .

The compound HgOHCN has long been known in the solid state and although it has been assumed to exist as an entity in solution, no estimate of its stability has hitherto been available. Studies on the solubility of HgO in $\text{Hg}(\text{CN})_2$ solutions have given a value of $(2.6 \pm 0.3 \times 10^2)$ for the constant

$$K_m = \frac{[\text{HgOH}\text{CN}]^2}{[\text{Hg}(\text{OH})_2][\text{Hg}(\text{CN})_2]}$$

at an ionic strength of 2.0. Polarographic studies of the reduction of HgOHCN give $(2.8 \pm 0.2) \times 10^2$, in excellent agreement. Anodic oxidation of the dropping mercury electrode in basic solutions containing a large excess of mercuric cyanide gives a value of about 1.4×10^2 , as did studies of the HgOHCN wave in excess $\text{Hg}(\text{CN})_2$. Finally, from spectrophotometric data at ionic strength of 4.0, the formation constant

$$K = \frac{[\text{HgCl}(\text{CN})_2^-]}{[\text{Hg}(\text{CN})_2][\text{Cl}^-]}$$

was found to be 0.6. (L. Newman)

III. INTERFACIAL TENSION IN COMPLEX FORMATION

Recent reports by Kazi and Desai³ of successful determination of the composition of complex ions by measurement of interfacial surface tension between the aqueous phase and polar organic solvents such as *n*-butyl acetate have prompted a careful investigation of the potentialities of this method in this laboratory. Initial efforts to duplicate the results of Kazi and Desai were completely unsuccessful. The reproducibility of the method (drop weight technique) was too poor to show differences of the order of magnitude reported. Subsequently, we have observed that the use of the ring method for both surface tension and interfacial tension gives vastly greater precision and the results suggest the existence of fairly sharp peaks in surface or interfacial tension vs. composition curves corresponding to stoichiometric complex formation. So far the systems known to form clear-cut and stable complexes, e.g., mercuric ion and chloride ion, have been examined. The differences in surface or interfacial tension observed, however, are an order of magnitude smaller than those reported by the Indian workers. The observations are being extended to other systems and other polar and non-polar organic ligands. The feasibility of using tensiometry for the location of titration equivalence points is being examined. (E. A. Heintz)

IV. THERMOMETRIC TITRATIONS

A. Theory

Equations have been derived for the temperature vs. time (or volume) curves obtained when thermometric titrations are performed automatically with the sort of apparatus and technique developed in this laboratory. The effect of nonadiabatic conditions is shown to lead to curvature, which effect is observed experimentally. The change in heat capacity of the system, due to added titrant, leads to a logarithmic relationship between temperature and time. It is shown that it is possible, using the initial slope of the temperature versus time curves, to obtain excellent values for heats of the titration reaction when heats of mixing the two solutions are negligible. Estimates obtained for the heat of neutralization of hydrogen with hydroxyl ion, and for the heat of reaction

between perchloric acid and sodium acetate in glacial acetic acid had been obtained which are in excellent agreement with values reported in the literature. Relationships have been derived for the heats of mixing of pure substances and solutions and it is shown that the differential heat of solution of acetic acid in water, as estimated from "titration" curves, agrees very well with that obtained much more laboriously by conventional thermochemical techniques. A manuscript reporting these results has been submitted for publication in Analytical Chemistry.

B. Acetic Acid as a Solvent

The apparatus previously described has been carefully calibrated with respect both to volume and to temperature. Extensive heat capacity measurements have been made on systems of interest, primarily solutions in glacial acetic acid. Heats of mixing of acetic acid and water, acetic acid solutions and acetic acid, and perchloric solutions with acetic acid containing varying amounts of water have been made. A technique has been developed for preparing anhydrous acetic acid from glacial acetic acid by an acid-catalyzed reaction with acetic anhydride. In thermometric work it is essential that no excess either of acetic anhydride or of water remains in the final product. The Karl Fischer titration of water has been shown to be satisfactory for the determination of traces of water in glacial acetic acid and perchloric acid solutions in glacial acetic acid. Studies have been made of the titration characteristics and heats of reaction of a number of substances with both anhydrous perchloric acid in anhydrous acetic acid and perchloric acid monohydrate in glacial acetic acid. The substances studied have been sodium, lithium, potassium, barium, cadmium, lead and mercuric acetates, sodium benzoate, tartrate, citrate, and phosphates, lithium nitrate, potassium acid phthalate, amines, and sodium chloride in the presence of mercuric acetate. A rather uniform difference of about 2.5 kilocalories per mole has been observed in the heats of reaction with anhydrous perchloric acid compared to those with the monohydrate. Most substances in anhydrous acetic acid give very sharp end points, and it was only with the weakest bases that significant rounding was observed. Urea and acetamide give good end points, and even with acetanilide, a good analytical result is obtained by extrapolating straight portions of the curve. (H. J. Keily)

C. Acetonitrile as a Solvent

The use of the thermometric titration technique is being extended to systems in which acetonitrile is used as a solvent. A method for the removal of oxidizing impurities and water is being developed in order that large quantities of highly pure acetonitrile may be available for these studies. A number of organic bases and soluble organic salts have been titrated automatically with 0.5 molar perchloric acid in acetonitrile as the titrant. The initial slopes dT/dV of the titration curves for bases fall into two distinct groups, indicating widely differing heats of reaction. The heats for aliphatic bases generally appear to be much greater than those for aromatic bases. Pyridine appears to be intermediate between the two groups. Small differences in heats of reaction appear to exist within each group for each individual compound, although experimental conditions were such that the reality of these differences cannot be proven unequivocally at this time. The

roundness of the end point appears to be correlated with the strength of the base titrated. Bases as weak as 0-chloroaniline (pK_b in H_2O 10^{-12}) give curves that appear to be amenable to extrapolation to quantitatively useful end points.

As preliminary to titration studies, the solubilities of a total of 47 salts, mostly the Li, Na, K, and NH_4 salts of common acids, were determined. Many of the salts are virtually insoluble in acetonitrile. The thiocyanates, iodides, and perchlorates were generally quite soluble. Lithium salts seem to be more soluble than those of the other alkali cations. All the titrations with perchloric acid gave endothermic reactions in contrast to the exothermic titrations observed with organic bases. A study is being made to see if the apparent small differences in heats of reaction are real, and if they relate to other properties. (E. J. Forman)

V. FLAME PHOTOMETRY

Although it is well known that specific exaltation and suppression effects of one substance upon another occur in flame excitation, and considerable work has been done in the study of binary systems, essentially nothing is known regarding the mutual effects of more than two components. Because of the wide use of flame photometry in the determination of sodium and potassium, particularly with lithium present as an internal standard, a study is being made of the mutual effects of lithium, sodium and potassium upon each other and under the concentrations normally used in practical flame photometry. Factorial experiments are being performed and variance analysis applied to the results. Preliminary indications are that in the range of concentrations ordinarily used, the interaction effects are small but appreciable. (W. E. Ohnesorge)

VI. PHOTOMETRIC TITRATIONS

A. Non-Aqueous Systems

A study has been initiated of the applicability of photometric titration to non-aqueous solvent systems. Titration of basic substances in various solvents with perchloric acid solutions has been performed, using a Beckman Model B spectrophotometer and conventional photometric titration techniques. Excellent results have been obtained with a variety of systems. The use of 5-nitro, 1-naphthyl amine as an indicator substance in glacial acetic acid and in acetonitrile shows great promise. The effect of the dielectric constant of the solvents, acidity and basicity of solvents, and neutral salt concentration on the shape of titration curves is being examined. (L. E. I. Hummelstedt)

B. Cerium

Further work has been done on the determination of small amounts of trivalent cerium by titration with permanganate in neutral pyrophosphate medium. A statistical study has been made

of the precision and accuracy of the method over an extended period of time using different batches of reagents and four levels of cerium concentration over a 20-fold range. Under these conditions the results are good to within 3 - 5 parts per thousand. The effects of 23 substances which were considered potential sources of interference were studied at concentrations 20 times that of the cerous cerium, and only iodide, fluoride, trivalent arsenic and antimony, mercurous, chromic and thalious ions had any effect. (E. P. Przybylowicz)

VII. ION-EXCHANGE STUDIES

A. Volumetric Determination of Sulfate in Mixtures with Weak Acid Anions

An ion-exchange method for the determination of sulfate in the presence of halides has been developed by Whiteker and Swift⁴. In this method the total equivalents of acid and of halide are determined by titrations and the equivalents of sulfate are calculated from the difference.

During the past year an investigation has been undertaken to extend this method to include a determination of sulfate in the presence of weak acid anions such as arsenate and phosphate. As in the method cited, the mixture is passed through a cation exchanger in the hydrogen form and the total acidity determined. If this titration is made with a pH meter, the total acidity may be broken up into that due to strong acids and that due to weak acids. The pH of the titrated solution is then adjusted to 1.0 and the halides titrated argentometrically. The equivalents of sulfate can readily be determined by subtracting the equivalents of halide and the equivalents of weak acids from the total acidity.

In order to keep this method simple, a Beckman Model G pH meter is used with a glass electrode and a silver electrode serving as the electrode pair for both titrations. In the acidimetric titration the glass electrode is the indicating electrode and the silver electrode is the reference electrode. During the argentometric titration the roles of the electrodes are reversed.

As soon as the details of the experimental method have been worked out, a statistical study will be performed in order to determine the optimum flow rate, column height, and amount of wash solution for maximum precision and accuracy. (R. C. DeGeiso)

B. Ion-Exchange Membrane Electrodes

An investigation of the nature of the potential developed across an ion-exchange membrane placed between solutions of different activity in the same or different components has been initiated. The apparatus necessary for such a study has been constructed and preliminary measurements have been made.

Two problems have been chosen for investigation. The first is a study of the factors affecting the potential at submillimolar concentrations. Published data indicate that at low concentrations the potentials obtained are no longer those of a simple concentration cell but tend to be of somewhat

lesser magnitude. These deviations from ideal behavior have been attributed to hydrolysis by some authors and by others to rate of diffusion processes. It is hoped that this situation may be clarified by a comparison of the membrane potentials obtained with sodium chloride and hydrochloric acid, or with other systems in which a solution containing a "sink" of one of the mobile ions is used.

Also of interest is the use of ion-exchange membrane electrodes in potentiometric titrations. Relatively little work has been done in this field, but it appears that these electrodes might prove to be of value in systems where at present no indicating electrode is available, as, for example, with the alkali and alkaline earth metal ions. (R. B. Hanselman)

VIII. PRECIPITATION OF METAL SULFIDES WITH THIOACETAMIDE

A quantitative investigation of the effect of substituting thioacetamide for hydrogen sulfide in a conventional qualitative system of analysis has been undertaken. A preliminary study was made on the precipitation of the sulfides of the hydrogen-sulfide group elements and the ammonium-sulfide group elements as a function of acidity and temperature. The results of this study indicated that precipitation occurred faster at higher temperatures, that the rate of precipitation as a function of acidity was also a function of the element under consideration, and that uncommon colors were obtained during precipitation.

A study of the completeness of precipitation of the hydrogen-sulfide group elements and coprecipitation of the ammonium-sulfide group elements is being initiated. A factorial investigation of the completeness of precipitation of cadmium as a function of acidity, ratio of thioacetamide concentration to cadmium concentration, and time of heating at 90°C is currently being performed. (E. A. Burns)

IX. ANALYSIS OF SPECTROPHOTOMETRIC CURVES

The application of a method of curve-fitting to absorption peaks of spectrophotometric curves is currently being investigated. The method involves the fitting of a linear-polynomial to a plot of absorbance versus wavelength. It is believed that the higher-order coefficients of this polynomial should be independent of the impurities in solution even if the impurities contribute a high, unknown, and inconsistent absorbance. These higher-order coefficients will thus have the property of being proportional only to the concentration of the substance being investigated.

(L. Newman)

X. COULOMETRY

A. Coulometric Titrations with Electrically Generated Mercury (I and II)

During the past year, it has been shown that the substitution of mercury for silver in the titration of halides was advantageous because the smaller solubility products permitted correspondingly smaller amounts of the halides to be determined. Using either an amalgamated gold or silver electrode, the lower limits of an individual halide which were determined with an accuracy of better than 1% in a volume of about 55 ml. were 0.24 mg. of chloride (1×10^{-4} M), 0.067 mg. of bromide (2×10^{-5} M) and 0.038 mg. of iodide (6×10^{-6} M). Smaller amounts of halide down to 0.013 mg. of chloride, 0.0067 mg. of bromide and 0.0012 mg. of iodide were determined with better than 5% accuracy. The coprecipitation errors encountered in argentometric titrations of halide mixtures are also present in this method whereas the usual adsorption errors in the titration of iodide alone were not observed.

During the past quarter, the study has been extended to cyanide with the result that 5 μ g. of cyanide in a 50 ml. sample can be determined with an accuracy and precision of better than 1%. At the present time, optimum conditions are being sought for the determination of sulfide.

(E. P. Przybylowicz)

B. Coulometric Generation of Reagents for Studies of Indicator "Blanks" in Titrations

In titrations of submicrogram amounts of substances in 10-100 ml. of solution, the amount of reagent that must be added to affect a change in the indicator becomes a significant, or even predominant, factor in the titration. In attempting to study potentiometric indication in the bromine-bromide system, polarization of the electrodes appeared to be the limiting factor when commercially available vacuum-tube voltmeters and potentiometers were employed. In order to minimize polarization effects, a vibrating-reed electrometer was obtained. Mechanical and electrical difficulties were encountered when the unit was put into service, and these have just been eliminated. As a result, experiments are now being started in which polarization should play an insignificant role. (J. K. Lee)

XI. THE ELECTRODEPOSITION BEHAVIOR OF
TRACE AMOUNTS OF ELEMENTSA. Nickel

The behavior of an element such as nickel represents the case of an element whose deposition involves considerable overvoltage and hence "irreversibility". An earlier study in our laboratory dealt with millimolar solutions and showed that an appreciable induction period could often exist before deposition started at a measurable rate. During the past year, effort has been directed toward extending the study to lower concentrations of nickel, for which radioactive tracers become a virtual necessity. As a result, most of the time has been devoted to the design and building of

counting rate meters and associated apparatus. In addition, most of the potentiostats were found to be erratic in performance, thereby necessitating a complete overhaul. Finally, equipment for gamma-ray spectroscopy has been received and is in the process of being tested and calibrated.

In preparation for the electrolyses, several glass cups of different sizes have been prepared for use as mercury reservoirs (and electrodes). These will be used for both polarographic determinations and electrolytic separations. It is expected that preliminary runs using millimolar solutions of nickel will be made following which more dilute solutions will be explored using radioactivity. (C. F. Morrison)

B. Copper

The deposition of fractional monolayers of silver upon gold, palladium and platinum electrodes takes place much more readily than one would predict from standard potentials for silver. In order to obtain more data which will permit one to decide between alternative rationalizations for the phenomenon, comparable deposition studies are being made using copper.

Deposition curves showing the percentage deposited as a function of the potential on the platinum gauze electrode have been obtained in a number of media using millimolar copper (II) in 0.1 M supporting electrolyte. In general, the curves agreed with the comparable polarographic ones within 10 mv. A single run using 10^{-4} M copper in perchlorate medium has indicated through the presence of a small plateau at potentials more noble than the regular wave, the definite possibility of "pre-deposition" of the first layer of copper atoms as hoped for on the basis of analogy with silver.

In anticipation of following the behavior in very dilute solutions, two preparations of radioactive Cu^{64} by deuteron bombardment of zinc have been made in order to compare various methods for the separation of the resulting mixture of zinc, gallium and copper. Ion exchange, solvent extraction, precipitation and electrolysis have each been explored briefly. Interestingly enough, it appears at this time that electrodeposition may be the most suitable method for isolating carrier-free copper. (R. C. DeGeiso)

C. Manganese

A study of the anodic co-deposition of Mn^{52} with lead dioxide is being revived after a lapse of several years. In concentrations below 10^{-6} M, manganese has been found not to deposit as the oxide unless substantial amounts of another oxide, such as lead dioxide, were deposited. Thus, an opportunity is available for studying the important factors in electrolytic coprecipitation and to compare them with those encountered in the classical studies. On the basis of the earlier study, it is expected that electrolytic coprecipitation, like homogeneous precipitation, will lead to better reproducibility. In addition, it appears that control of the electrode potential will result in increased selectivity. (E. A. Heintz)

XII. RATES OF ELECTROCHEMICAL REACTIONS

A. Mercury Electrodes

The present study is designed to explore quantitatively the effect of supposedly inert electrolytes on the electron-transfer process and hence upon the polarographic behavior of substances. From a study of the published polarographic literature, as well as from a survey of several other systems that has just been completed, it appears that a surprising number of inorganic reactions will be suitable for such a study. Anomalous shifts of polarographic waves for arsenic (III), heretofore unreported, are now under investigation. (W. H. Reinmuth)

B. Solid Electrodes

Up to the present time, nearly all of polarographic studies of electrochemical reaction rates have been made with mercury electrodes because a new reproducible surface can easily be obtained. The purpose of the present study is to extend the work to solid electrodes realizing that the reproducibility may be limited to determining the order of magnitude of the rate constant rather than a figure with a precision of about 5%.

During the past semester, the following pieces of electronic equipment have been constructed: an electronically regulated constant voltage power supply, a negative pulse amplifier and associated mechanical counter driving circuit, an audio amplifier for amplifying the output from an audio oscillator, and several small electrical junction boxes to be used for connections between various portions of the circuitry to be used in the reaction rate studies. It was decided that the first chemical system to be studied would be the ferrous-ferric oxalate system, the rate constants for which depend upon the oxalate concentration and have been determined by other workers under a variety of conditions. The rate of this reaction changes from very slow to moderately fast as the oxalate concentration is increased.

The work at the present time involves the determination of conventional current-voltage polarograms using both a plain solid platinum microelectrode and a mercury-coated platinum microelectrode. If suitable reduction waves and half-wave potentials are observed, the Heyrovsky circuit for potential-time and potential derivative-time curves will be used to obtain the corresponding curves for the above system. If these curves, as observed oscillographically, show suitable breaks, quantitative measurements using an alternating-current bridge will be made to obtain approximate rate constants for the electrode reactions under study. (Robert F. Breese)

XIII. FLUORESCENCE OF METAL CHELATES

An investigation has been begun to determine the effect of the structure of organo-metallic compounds on their fluorescence spectra and on the extent of the conversion of exciting radiation into fluorescent radiation. A number of qualitative studies have been reported in the literature

but the only exhaustive quantitative study appears to have dealt only with the chlorophylls. However, no systematic study of the effect of changing the metal ion has been discovered. Studies have been initiated at room temperature while awaiting the delivery of apparatus that will permit measurements of absorption, excitation and fluorescence spectra at temperatures down to 77°K. It is expected that phosphorescence will appear at low temperatures.

8-Quinolinol (Oxine)

Reported differences in the absorption spectra for the oxinates of aluminum, gallium and indium have been confirmed. Corresponding differences have been found in the fluorescence spectra of chloroform solutions. At the same time, oxinates of a series of divalent metals are being prepared and analyzed so that they can be examined in the same way. (W. E. Ohnesorge)

Other Systems

At the present time, derivatives of 8-quinolinol as well as those of 1- and 2-naphthol are being purified by fractional recrystallization and by chromatography. Spectra of some of the pure organic compounds have already been recorded. As soon as the selected group of compounds has been surveyed, one of the systems will be selected for study in a way comparable to that described above for 8-quinolinol. (D. M. Hercules)

XIV. TURBIDIMETRY IN THE ULTRAVIOLET

By measuring the apparent absorbance of barium sulfate solutions in 10 cm. cells, sulfate can be determined in the range of 2.5 - 10.0 μg per ml. This is a range which, in the past, has had to be handled by nephelometry. Absorbance measurements in the ultraviolet have also been shown to be useful for following changes, with time, in the average particle size of the solutions. The results of this study have already been accepted for publication so further details will not be presented here. (H. J. Keily)

REFERENCES

1. Mitra, Gupta, and Jain, J. Indian Chem. Soc., 31, 346 (1954).
2. R. C. DeGeiso, and D. N. Hume, J. Phys. Chem., 60, 255 (1956).
3. H. J. Kazi, and C. M. Desai, J. Indian Chem. Soc., 30, 287 (1953).
4. R. A. Whiteker, and E. H. Swift, Anal. Chem., 26, 1602 (1954).

D. N. Hume
L. B. Rogers

Nuclear Chemistry (Inorganic) Group

I. INTRODUCTION

The present high-spot annual report of the work of the Nuclear Inorganic Chemistry Group reports the first results of the major attack on the basic physical chemistry of complexes and their hydrogen acids, which is designed to correlate and explain diverse results in solvent extraction and ion-exchange processes, especially anion-exchange separations. This concerted attack seems to be paying satisfying scientific dividends in increased understanding of the behavior of inorganic metal complexes in concentrated aqueous media (salts and acids), in organic solvents of low dielectric constant, and in anion exchangers of low invasion. The specific results are reported in the following Sections III, IV, and V. To check for specific resin effects, totally aliphatic quarternary anion-exchange resins (Ulex-1 and -2) have been synthesized and examined. A rigorous study is being instituted on the behavior of HCl and H₂O in β, β' -dichlorodiethyl ether (Sections I and III). Some crystal field studies by x-ray absorption (Part II) promise to help clarify problems of bonding in complexes.

Concomitantly, new separations techniques are made available, leading to new possibilities of characterizing short-lived radioactive species, especially among the neutron-rich earlier fission products. Data on short-lived selenium species Se⁸⁴ and hopefully Se⁸⁵ and Se⁸⁶ are given in Section VI, together with new data on short-lived neutron-rich palladium isotopes (Pd¹¹¹ on) and their silver daughters (1.3m, ~22m Ag¹¹⁵ and 5.3h Ag¹¹³). Work is in progress (Parts VI and VII) directed towards increased understanding of valley fission yields.

The availability of new data for the abundances of all the elements in meteorites by H. E. Suess and H. C. Urey¹ has led to some new ideas on the creation of elements above mass-number 70.

Two extensive reviews of experimental work have been published. One is the 40-page paper "Organic Scintillators" by R. C. Sangster and J. W. Irvine, Jr. (J. Chem. Phys., April 1956). The other is Technical Report No. 68 of the Laboratory for Nuclear Science, "Review of Recent Applications of Ion Exchangers in Analytical Chemistry" by U. Schindewolf, December 15, 1955. Dr. R. A. Horne has accumulated an extensive index of constants for inorganic complex formation in aqueous systems, and C. D. Coryell, L. S. Goldring, and R. A. Horne have nearly completed a manuscript, "Generalized Acidity in Radiochemical Separations" for Annual Reviews of Nuclear Science, Vol. 6 (December 1956).

II. INSTRUMENTATION

A. Organic Scintillators

The extensive experimental work on organic scintillators carried out between 1948-1952 has been calculated and interpreted at long last. This included a study on the exhaustive purification, the relative scintillation efficiency as a function of temperature, and the fluorescent spectra of about sixty compounds. The interpretation included a correlation with many structural aspects of the compounds such as steric hindrance, hyperconjugation, heavy atoms and triplet states, ring size and type, bond densities, and magnetic properties. The results of these studies will appear as a forty-odd-page paper in the April 1956 issue of the Journal of Chemical Physics. (R. C. Sangster and J. W. Irvine, Jr.)

B. Precision Conductimetry

As part of the extraction studies of metal-halides from aqueous solutions of hydrogen-halide acids into β, β' -dichlorodiethyl ether, the investigation of the behavior of components in the ether phase has been undertaken. It was decided to concentrate on conductivity measurements, since the experimental data interpreted in terms of ion interaction theories could, under favorable conditions, give information on the dissociation, association, and solvation behavior of the components as functions of their relative and absolute concentrations. Measurements of dielectric constant, viscosity, density, and vapor pressure have been carried out as necessary associate determinations. From preliminary conductivity and analytical data on HCl extracted from aqueous solution into β, β' -dichlorodiethyl ether, Poskanzer has calculated the ionization constant of HCl by using Walden's Rule as $(1.7 \pm 0.5) \times 10^{-7}$. Detailed error analysis has shown that in order to obtain dissociation constants of this magnitude from conductance measurements by using an extrapolation method, the errors in resistance and concentration determinations must be less than one part per thousand. The experimental work has consisted of equipment design -- A. C. Wheatstone Bridge for high impedance measurements, conductivity cells with cell constants ranging from 10 to 5×10^{-3} -- and determining and improving the precision and accuracy of the electrical and chemical measurements, giving particular attention to the low concentration-high impedance range. The progress has been satisfactory and the preparatory stage of the project can be considered as finished. The next step will consist of the redetermination of the equivalent conductance of HCl, HBr and HClO_4 in β, β' -dichlorodiethyl ether extracted from aqueous acid solutions. (E. Rudzitis and J. W. Irvine, Jr.)

C. Radiochemical Instrumentation

Five end-window proportional counters are in operation. Their resolving time has been measured by the paired-source method as $\sim 30 \mu\text{sec}$, using Model EIT-3 decade scalers. Work is underway to reduce the dead time, which appears to arise in the discriminator circuit in the scalers. A Tracerlab Superscaler-Tracegraph combination has been modified to count automatically the inputs from three different counters.

The automatically recording γ -scintillation spectrometer has been improved by the exchange of amplifiers and power supply for more stable units. (R. C. Fix and J. M. Alexander)

III. PHYSICO-CHEMICAL STUDIES

A. Ionization of HAuCl_4

A recent² theory of the solvent extraction of metal halides into organic solvents of moderate dielectric constant postulates that an important reaction is the ionization in the organic phase of the metal halide-hydrohalic acid. A particularly simple system to explore the theory is the $\text{Au(III)}-\text{HCl}-\beta, \beta'$ -dichloroethyl ether system. Activity coefficients in the water-saturated dichloroether phase were calculated by Debye-Huckel theory. On this basis the data of Golden³ indicate an acid ionization constant in water-saturated dichloroether for HAuCl_4 of $(3.8 \pm 0.5) \times 10^{-3}$ over a wide range of HCl and Au(III) concentrations. Further investigation of the system is in progress as a more quantitative test of the theory.

The ionization of HAuCl_4 in the aqueous phase is also under investigation. The method being employed here is the variation in the solubility of $[(\text{CH}_3)_4\text{N}]^+ [\text{AuCl}_4]^-$ in $\text{HCl}-\text{LiCl}$ solutions of constant ionic strength. Preliminary data indicate an ionization constant in 10M LiCl of 1.1 moles/l. (A. M. Poskanzer)

B. Thermodynamic Properties of HCl in the $\text{H}_2\text{O}-\beta, \beta'$ -dichlorodiethyl Ether System

Work is underway on the determination of the activity of HCl in β, β' -dichlorodiethyl ether. The studies will include the effects of H_2O on this activity. Precision conductimetric measurements coupled with vapor-pressure measurements of HCl in the ether will provide the desired information. It will be necessary also to determine the density and viscosity of the solutions used. Preliminary measurements indicate that the desired precision and accuracy can be obtained.

All measurements are being made on solutions held at a temperature constant to $\pm 0.002^\circ\text{C}$. The effects of oxygen and carbon dioxide are eliminated by keeping the solutions under an atmosphere of prepurified nitrogen. (E. Rudzitis and J. W. Irvine, Jr.)

C. The Fast Chloride Exchange between HCl and HAuCl_4 in β, β' -dichlorodiethyl Ether

A solution of HCl in β, β' -dichlorodiethyl ether was prepared with 37.5m Cl^{37} as tracer. An aliquot of this was mixed with one of HAuCl_4 in the dichloroether, and the mixture immediately filtered by suction through a short column of ether-soaked Dowex-1 nitrate (10% crosslinked) and immediately washed with 4M aqueous HNO_3 to remove Cl^- but not AuCl_4^- from the column. The activity in the HAuCl_4 firmly held on the resin was determined by scintillation counting of the resin phase. The experiments were carried out at room temperature. It is estimated that the ethereal solutions of HCl and HAuCl_4 had a minimum of 30 sec. to exchange.

For all concentrations of HCl and HAuCl_4 investigated, the exchange was found to be complete within the time required for the separation procedure. The lowest formal concentrations used were

<u>Run</u>	<u>HCl</u>	<u>HAuCl_4</u>	<u>HClO_4</u>
1.3	0.004	0.010	0.052
1.4	0.046	0.006	0.052
1.8	0.016	0.002	0.032

This exchange is faster than that observed by Rich and Taube⁴ for Cl^- and AuCl_4^- in aqueous medium. This fact has some interesting structural interpretations.

This work has now been published⁵ and is discussed in greater detail in the journal article. (D. G. Tuck, C. D. Coryell, and J. W. Irvine, Jr.)

D. Stereochemistry of Complexes from X-ray Absorption Edges

Experimental and theoretical studies have been made to determine whether there exists a useful correlation between the stereochemistry (i. e., the crystal field symmetry) of complexes of metal ions of the first transition group and the fine structure of their K-absorption edges. Studies which were previously made⁶ on complexes of copper(II) have been extended to Zn(II), Ni(II), Co(II), and Co(III) in collaboration with H. P. Hanson of the Department of Physics, University of Texas. While the results presently at hand do not justify any dogmatic statements, it appears that certain conclusions of chemical significance can be accorded reasonable credibility. For example, the edge structure of Zn(II) in the tetramminozinc ion, $\text{Zn}(\text{NH}_3)_4^{++}$, seems explicable only by rejecting the previously held belief that this ion has a tetrahedral structure, and assuming instead that it has a square planar configuration. (F. A. Cotton)

E. Thermodynamic Properties of Silver-Ammine Complexes

Measurements of equilibrium constants over a range of temperature in the $\text{Ag(I)}-\text{NH}_3$ system, with provision for extrapolation of the results to infinite dilution, are being made in order to obtain a complete specification of the thermodynamics of complex formation in this system. (F. A. Cotton, H. Frumkin, and E. W. Stone)

IV. SOLVENT-EXTRACTION STUDIES

A. Extraction of HAuCl_4 by Various Solvents

Preliminary measurements indicated a rough correlation of the magnitude of extraction of HAuCl_4 with the basicity of the solvent. The ratio of extraction at low metal to extraction at high metal concentrations shows a rough correlation to the dielectric constant of the solvent, as might be expected from the hypothesis of ionization of HMX_4 in the organic phase. The picture is complicated by the lack of quantitative data on the behavior of the supporting HX acids and on the

TABLE 2.I

Extraction Coefficient of Au^{+3} from HCl Solution

Extractant	Dielectric Constant	Basicity pK_a	Extraction Coefficients				Extraction Ratios	
			Carrier-free $[\text{Au}^{+3}] \sim 10^{-12}$		Carrier Added $[\text{Au}^{+2}] \approx 10^{-3}$		A/C	B/D
			A: 8M HCl	B: 2N HCl	C: 8M HCl	D: 2M HCl		
I. Benzene	2.3	< -12	0.0028	0.0043	0.0006	0.00017	4.8	28
Carbon tetrachloride	2.23	< -12	0.001	0.0015	0.0004	0.0002	2.5	7.5
Chloroform	4.8	< -12	0.0055	0.0046	0.0036	0.0042	1.5	1
II. Monochlorobenzene	5.7	-12	0.033	0.2	0.002	0.01	16.5	20
o-dichlorobenzene	9.93	---	0.034	0.365	0.0011	0.00054	31	675
1-2 dichloroethane	10.6	-12	0.065	0.75	0.0025	0.0014	26	535
Nitrobenzene	35	-10.2	59	23	2.7	0.5	22	46
III. Acetophenone	17.4	- 5.4	2,950	505	2,950	67.5	1	7.5
Dibutylphthalate	6.4	- 6.8	14.7	3.83	17.5	0.85	0.84	4.5
β, β' -dichlorodiethyl ether	21.2	- 4.8	200	14	22	2.4	9	6
Benzaldehyde	18	- 4.7	468	117	187	34.4	2.5	3.4
Diphenyl ether	3.65	---	0.0014	0.023	0.00063	0.0016	2.2	14
Amylacetate	4.75	- 4.2	96	11	429	29	0.22	0.38
Dibenzyl ether	---	- 1.5	2.7	4.5	0.77	0.08	3.5	56
Diisopropyl ether	3.88	- 0.9	9	1.37	16	1.26	0.56	1.1
Tributylphosphate	8	- 1.5	1,400	1,100	4,000	4,500	0.35	0.25

apparent polymerization of HMX_4 at high metal concentrations in some relatively basic solvents.

The data obtained in these preliminary studies are summarized in Table 2.I. Basicities have been calculated from the data of Gordy and Stanford⁷ and are expressed as pK_a , the negative logarithm of the acid ionization constant of the solvent-proton addendum. The scale runs from <-12 for inert solvents to -0.9 for the fairly basic isopropyl ether. (P. Schonken and J. W. Irvine, Jr.)

B. Extraction of Mineral Acids from Aqueous Solution by β, β' -dichlorodiethyl Ether

Work during the past few years on solvent extraction has emphasized the behavior of the halo-metallate complexes, HMX_4 . In order to give a quantitative explanation of this behavior under a variety of conditions, it has become necessary to obtain data on the extraction of the supporting HX electrolyte and of the added acids; HNO_3 and HClO_4 . Phase-volume changes and ionization in the ether phase must be determined also. Using acid-base titrimetric methods, preliminary data have been obtained on the extraction of HCl , HNO_3 , and HClO_4 from relatively concentrated aqueous solutions. These are given in the following Tables 2.II, 2.III, and 2.IV. The superscripts o and w refer to the organic and water phases. The extraction coefficient E is the ratio $(\text{HX})^o/(\text{HX})^w$.

TABLE 2.II

$\text{HCl} - \text{H}_2\text{O} - \beta, \beta'$ -Dichloroethyl Ether

$(\text{HCl})^w$	$(\text{HCl})^o$	$E \times 10^3$
4.075	0.18×10^{-3}	0.04 ₅
6.063	0.82×10^{-3}	0.14
8.103	7.2×10^{-3}	0.89
9.108	2.2×10^{-2}	2.4
9.978	4.6×10^{-2}	4.6
10.895	1.08×10^{-1}	9.9
11.852	2.63×10^{-1}	22.2

TABLE 2.III

$\text{HClO}_4 - \text{H}_2\text{O} - \beta, \beta'$ -Dichloroethyl Ether

$(\text{HClO}_4)^w$	$(\text{HClO}_4)^o$	$E \times 10^3$
0.0983	3.6×10^{-5}	0.41
0.492	3.7×10^{-4}	0.73
0.982	5.4×10^{-4}	0.57
1.964	2.22×10^{-3}	1.14
1.944	4.92×10^{-3}	1.67
4.884	3.06×10^{-2}	6.26
5.452	4.66×10^{-2}	8.56

TABLE 2.IV

HNO₃ - H₂O - β, β' -Dichloroethyl Ether

$(\text{HNO}_3)^w$	$(\text{HNO}_3)^o$	$E \times 10^3$
0.1091	1.56×10^{-4}	1.41
0.544	1.28×10^{-3}	2.42
1.088	4.44×10^{-3}	4.08
2.162	2.18×10^{-2}	10.06
3.216	6.01×10^{-2}	18.69
4.219	1.49×10^{-1}	35.21
5.153	2.87×10^{-1}	55.59

Using radioactive Cl³⁸ in the form of HCl, the extraction of this acid has been measured at lower aqueous concentration.

TABLE 2.V

HCl - H₂O - β, β' -Dichloroethyl Ether

$(\text{HCl})^w$	$(\text{HCl})^o \times 10^4$	$E \times 10^4$	$\gamma^2 M^2 (a)$
3.79	2.3	.61	53
5.18	9.3	1.8	290
5.71	10.3	1.8	520
5.82	15	2.6	(620)
6.17	12	1.9	(850)
6.25	19	3.0	970
6.49	25	3.8	(1250)
6.78	27	4.0	1680
7.02	34	4.9	2200
7.17	48	5.0	(2500)
7.96	69	8.6	6200
8.86	72	8.2	8200

(a) $\gamma^2 \pm M^2$ gives the activity of unionized HCl.

A plot of these data shows that these solutions obey Henry's Law below about 6M HCl for unionized HCl in the water layer, but that marked deviations occur above this concentration. These deviations caused a substantial error in the extrapolation selected by Plank⁸.

Preliminary experiments have indicated the feasibility of synthesizing HCl³⁸O₄ by deuteron bombardment of RbClO₄. When LiClO₄ is used as the target, the yield of HCl³⁸O₄ is extremely low, the activity all appearing as chloride ion.

A procedure has been developed for measuring phase-volume changes when HCl solutions are equilibrated with β, β' -dichlorodiethyl ether. It is found that the total volume is constant, and the volume increase of the aqueous phase approximates a linear function for initial HCl concentrations of 7 to 11.5M. The values of $\frac{\Delta V}{V(aq)}$ range from 0.001 at 7M HCl to 0.05 at 11.5M HCl. Between 11.5M and 12.0M HCl $\frac{\Delta V}{V(aq)}$ rises steeply to 0.07.

Preliminary measurements on HBr indicate values of $\frac{\Delta V}{V(aq)}$ approximately twice as large as for HCl of the same initial concentration. (E. Rudzitis, C. E. Gleit, R. J. Dietz, Jr., and J. W. Irvine, Jr.)

C. The Solvent Extraction of Inorganic Compounds

Recently, H. Irving, F. J. C. Rossotti, and R. J. P. Williams published a paper on "A General Treatment of the Solvent Extraction of Inorganic Compounds".⁹ Their treatment is a combination of Bjerrum's concept of step equilibria with Nernst's concept of partition equilibria. The value of their treatment is that if one knows the metal complexes present in one phase then, from a simple inspection of the solvent extraction behavior, one can determine the average complex in the other phase. For example, for the variation of the distribution ratio, q , with free metal ion activity, $[M]$, at constant ligand acid activity $[HL]$, the above authors derive the equation

$$\left(\frac{\delta \log q}{\delta \log [M]} \right) [HL] = (\bar{m} - \bar{m})$$

where $\bar{m}$ is the average degree of polymerization of the metal in the organic phase and $\bar{m}$ the corresponding quantity for the aqueous phase. According to this, q would have to be independent of $[M]$ for the metal to be monomeric in both phases. However, a more careful treatment reveals that the above equation is only true at low metal concentration and the correct equation at higher metal concentration is

$$\left(\frac{\delta \log q}{\delta \log C} \right) [HL] = \frac{\bar{m}}{\bar{m}(\bar{n}+1)} - 1$$

where $\bar{n}$ is the absolute value of the charge of the average complex in the organic phase, and C is the stoichiometric metal concentration. Thus the metal might be monomeric in both phases and q would depend on $[M]$ because of ionization in the organic phase. (A. M. Poskanzer)

D. Studies of the $TeCl_4$ - H_2TeCl_6 System in Aqueous HCl and β, β' -Dichlorodiethyl Ether

The following is the abstract of the paper presented April 13, 1956 at the Dallas Meeting of the American Chemical Society. It is partly based on older work of Plank^{8, 10} and of Brubaker and Coryell¹¹ and more detail has been given recently.¹²

The distribution of tellurium(IV) between aqueous hydrochloric acid and isopropyl ether has been examined as a function of initial aqueous hydrochloric acid concentration. The distribution coefficient increases with acidity up to about 8.5M hydrochloric acid and falls again.

The distribution of tellurium(IV) between aqueous hydrochloric acid and β, β' -dichloroethyl ether has been studied both as a function of initial aqueous hydrochloric acid concentration and as a function of equilibrium aqueous tellurium(IV) concentration at constant aqueous acidity. The distribution ratio increases with increasing concentration of aqueous hydrochloric acid, and, at constant acidity, decreases with increasing concentration of tellurium(IV). Analytical studies indicate that the species extracted are, at low aqueous acidity, tellurium tetrachloride (TeCl_4) and at high aqueous acidity, hexachlorotellurous(IV) acid (H_2TeCl_6).

Spectrophotometric methods have been employed to study the equilibrium between tellurium tetrachloride and hexachlorotellurous(IV) acid in the β, β' -dichloroethyl ether phase and indicate that the reaction,

takes place in the ether. The constant K is found to have the value 1.0×10^4 .

Variation of distribution ratio with acidity is explained on the basis of increasing aqueous concentration of the extractable species. The variation of the distribution ratio with tellurium(IV) concentration, so-called retrograde extraction, is treated quantitatively on the basis of the dissociation of hexachlorotellurous(IV) and hydrochloric acids in the ether phase. The data indicate that hexachlorotellurous(IV) acid is relatively strong in the ether phase (the first acid dissociation constant is about 10^{-1}) while hydrochloric acid appears to be weak (the dissociation constant is about 10^{-7}). (C. H. Brubaker, Jr., H. F. Plank, and C. D. Coryell)

E. Solvent Extraction of Rb and Cs Tetraphenyl Borides and Hexafluorophosphates

An effort has been made to develop a rapid separation method for rubidium and cesium based on solvent extraction techniques. By the use of a high dielectric solvent and a bulky anion, extraction from aqueous solution can be effected. Solvents such as nitrobenzene, nitromethane, 2-nitropropane, and β, β' -dichlorodiethyl ether and the anions $(\text{PF}_6)^-$ and $\text{B}(\text{C}_6\text{H}_5)_4^-$ have been tested.

Best results were obtained with nitrobenzene and the tetraphenyl boride ion. Extraction coefficients $>10^3$ for Cs and $>10^2$ for Rb are observed. The principal difficulty with this system is due to emulsion formation and the consequent problem of phase separation. Conditions for optimum separation are being worked out. (R. C. Fix and J. W. Irvine, Jr.)

F. Extraction of HAuCl_4 by Tris(2-Chloroethyl) Phosphate

Tris(2-chloroethyl) phosphate has been tested as an extractant for HAuCl_4 from HCl solutions. It was thought that the introduction of chlorine atoms into the organic radicals would decrease the solubility of the phosphate ester to the point where it would be a useful extractant. Preliminary experiments indicated a high solubility of the ester in the aqueous phases with fairly good extraction of HAuCl_4 ($E \approx 10^3$). This solvent does not look particularly attractive and no further work on it is planned. (J. D. Murphy and J. W. Irvine, Jr.)

G. Isolation of Vanadium-48 from a Titanium Target

In order to utilize a direct extraction method for isolating carrier-free vanadium from titanium targets, it was necessary to know the extraction behavior of small amounts of vanadium under conditions where the titanium does not extract. Data in the literature¹³ are only given for the extraction of macro-amounts of vanadium. Good results are obtained by using isoamylalcohol, amylacetate, acetophenone, methylbutylketone, and amylformate.

1. Extraction of small amounts of vanadium.

A tracer solution of V(IV) in conc. HCl shows low extraction; values of the extraction coefficient greater than 0.1 are obtained only with butylphosphate and isoamylalcohol.

If the vanadium solution is oxidized by adding H_2O_2 to the HCl solution, a net increase of the distribution coefficient is noted, especially in the presence of H_2SO_4 . The values of E obtained by the extraction of HCl, HCl and H_2SO_4 , HCl and H_2O_2 , and for HCl, H_2SO_4 , and H_2O_2 solutions of vanadium for the best organic solvents are given in the following Table 2.VI.

TABLE 2.VI

Values of E for Several Mediums and Solvents

	8.5M HCl	7.5M HCl + 4.0M H_2SO_4	8.5M HCl + 0.4M H_2O_2	7.5M HCl + 4.0M H_2SO_4 + 0.4M H_2O_2
acetophenone	0.02	0.07	0.87	1.16
amylacetate	0.06	0.13	0.25	0.52
ethylacetate	0.006	0.01	0.14	0.21
isoamylalcohol	0.66	4.04	0.49	3.26
methylisobutyl- ketone	0.009	0.02	0.91	1.65
nitromethane	0.003	0.001	0.19	0.39
tributylphosphate	0.16	0.22	1.79	3.22

Isoamylalcohol and tributylphosphate cannot be used since they also extract the titanium; thus methylisobutylketone extraction was investigated. Changing the concentration of the components, optimal conditions were found by using 5 ml of a solution containing 3 ml of vanadium solution in conc. HCl, 1.3 ml H_2SO_4 18N and 0.7 ml H_2O . To this solution, which is 7.2M HCl and 4.7M H_2SO_4 , 0.5 ml 30% H_2O_2 is added, followed by 10 ml of methylisobutylketone and the mixture shaken. The extraction is made immediately after the addition of the H_2O_2 , since otherwise the distribution coefficient decreases. Under these conditions the value of the extraction coefficient $E \left(\frac{\text{conc. V}^{48} \text{ org.}}{\text{conc. V}^{48} \text{ aq.}} \right)$ is 6.18, corresponding to 86% vanadium extraction.

2. Isolation of carrier-free vanadium from a titanium target.

The bombarded titanium target was dissolved in conc. HCl, oxidized with a few drops of conc. HNO_3 , and extracted as indicated above. The vanadium is back-extracted into an aqueous phase which is evaporated to dryness. The residue, containing traces of iron, is dissolved in 6N HCl and passed through a Dowex-1 ion-exchange column. (A. E. Claeys and J. W. Irvine, Jr.)

V. ION-EXCHANGE STUDIES

A. Thermodynamics of Anion-Exchange Systems

Studies of Gregor, Belle, and Marcus¹⁴ on anion equilibria with Dowex-2 provide a basis for detailed thermodynamic analysis of various types of resin solid solutions. Gregor and coworkers showed that anions may be characterized as members of Group A (halide, acetate, iodate, or nitrate) or of Group B (thiocyanate, trichloroacetate, or toluene-sulfonate). Resin solid solutions showing replacement of a Group-B anion by a Group-A anion (e.g., $\text{RSCN} \rightarrow \text{RCl}$) form very imperfect solid solutions. Indeed, nearly pure RSCN discriminates against Cl^- exchange for SCN^- by the factor 20, whereas RCl favors Cl^- over SCN^- by the factor 5. Resin imperfection thus leads to a specificity effect of 100 fold as a result of change in loading. This type of effect deserves further study, for it could be very effectively exploited in separations work, and it suggests several new lines of attack on the molecular nature of ion-exchange resins.

Since water uptake data¹⁴ show that the water content (aq.) of such a solid solution is essentially linear in the mole-fraction X_1 of Group-A anion, the Duhem-Margules equation can be applied directly to the resin system as if it contained only two components, $\text{RSCN} \cdot \text{aq}_2$ and $\text{RCl} \cdot \text{aq}_1$. The experimental data¹⁴ for the equilibrium:

can be expressed as

$$K_d = \frac{X_1^r}{X_2^r} \frac{(\text{SCN}^-)_w}{(\text{Cl}^-)_w} = K_{th} \frac{\gamma_1^w}{\gamma_2^w} \frac{\gamma_2^r}{\gamma_1^r} \quad (2)$$

where K_d is Gregor's selectivity coefficient (concentration equilibrium constant, a variable with X_1), X^r represents equivalent fraction in the resin phase, γ represents an activity coefficient, r and w refer to resin and water phases; and subscript 1 refers to Cl^- and subscript 2 to SCN^- . The symbol K_{th} represents the thermodynamic constant in the reference state, taken for convenience as pure $\text{RCl} \cdot \text{aq}_1$. In this treatment, values of both γ_1^r and γ_2^r were taken as 1.00 for $X_1 = 1.00$. In studies at low aqueous ionic strengths, the γ^w values cancel.

The Gregor-Belle-Marcus data show a trend of $\log K_d$ from -1.30 at $X_1 = 0$ to $+0.65$ at $X_1 = 1$. From this trend, the following functions are established for γ_1^r and γ_2^r :

$$\begin{aligned}\log \gamma_1^r &= \beta X_2^2 + \gamma X_2^3 \\ \log \gamma_2^r &= (\beta + 3/2\gamma) X_1^2 - \gamma X_1^3 - (\beta + 1/2\gamma)\end{aligned}\quad (3)$$

with $\beta = 1.81$ and $\gamma = -1.15$, with $\log K_{th} = +0.65$.

Reflection on the implications of solid-solution imperfection represented by the data (or by the parametric equations) leads to the conclusion that phase separation must occur in the resin system. Indeed, the data show* that the SCN^- -rich phase is about 60% RSCN and the Cl^- -rich phase is about 90% RCl. Actually, this will modify the treatment represented in equation (3). We are at present accumulating more equilibrium data and looking for evidence of this type of resin-phase separation, which might lead, at equilibrium, to separate resin beads being all of one phase or the other if the chemical homogeneity of the commercial resins is high enough. (C. D. Coryell and D. H. Freeman)

B. Search for Phase Separation in the Anion-Exchange System R(Cl, SCN)

Experimental studies in the system R(Cl, SCN) where R is Dowex-1 or Dowex-2 are being extended along the lines presented above in Section VB. The first requirement has been precision analyses for SCN^- in the presence of Cl^- , which has presented difficulties. More detailed data are being accumulated on the anion exchange of SCN^- by Cl^- .

Several experiments have been made on separate batches of pure RCl and RSCN brought to equilibrium via interaction with a dilute solution of KCl + KSCN. If the resin beads are microscopically homogeneous, it is expected that the RCl will be transformed to R(Cl, SCN) of the Cl^- -rich phase region, and RSCN will be transformed to the conjugate R(SCN, Cl) of the SCN^- -rich phase region. Results to date do not justify the postulate that individual beads will be all of one or the other phase type. (D. H. Freeman and C. D. Coryell)

C. Anion-Exchange Studies of the System HCl-TlCl₃

The absorption of Tl(I) and Tl(III) from aqueous HCl and HBr solutions on the anion exchange resin Dowex-1 has been studied using tracer amounts of carrier-free Tl^{202} in order to test empirically a theory of anion-exchange resin-absorption developed by Marcus and Coryell¹⁵. The absorption curve ($\log D$ vs. (X^-)) for the Tl(III)-HCl system represents an extension of work by

* This can be seen from a Roozeboom plot, i.e., plot of X_1^w vs. X_1^r , or from a consideration of the total free energy F^r for the resin phase:

$$\frac{F^r}{2.3 RT} = X_1^r \log X_1^r \gamma_1^r + X_2^r \log X_2^r \gamma_2^r \quad (4)$$

Kraus, Nelson, and Smith¹⁶ and its general features are similar to the analogous cation-exchange resin curves¹⁷. Interpreted in terms of the Marcus-Coryell theory¹⁵, the curve yields the following values:

$$(1) k_3 \equiv (\text{TlCl}_3)/(\text{TlCl}_2^+)(\text{Cl}^-) = 143 \text{ M}^{-1} \quad (25^\circ\text{C}, \mu = \text{ca. } 10^{-2})$$

$$(2) k_4 \equiv (\text{TlCl}_4^-)/(\text{TlCl}_3)(\text{Cl}^-) = \text{ca. } 2 \text{ M}^{-1} \quad (25^\circ\text{C}, \mu = \text{ca. } 1)$$

which are in good agreement with the work of Benoit¹⁸. Interpreting the absorption curve for the Tl(I)-HCl system one obtains

$$\left. \begin{aligned} (3) k_1 &\equiv (\text{TlCl})/(\text{Tl}^+)(\text{Cl}^-) = \text{ca. } 1 \text{ M}^{-1} \\ (4) k_2 &\equiv (\text{TlCl}_2^-)/(\text{TlCl})(\text{Cl}^-) = \text{ca. } 0.2 \text{ M}^{-1} \end{aligned} \right\} \quad (\text{at } 25^\circ\text{C}, \mu = 1 \text{ to } 5)$$

the former being in poor, the latter in fair agreement with the corresponding values of 4 and 0.4 reported by Hu and Scott¹⁹. Tl(III) in HBr absorbs strongly with a distribution coefficient, D , greater than 10^6 in the region 10^{-3} to 1 M HBr, while the experimental adsorption curve for the Tl(I)-HBr system is diffuse and ill-defined, seeming to go through a maximum somewhere between 10^{-2} and 10^{-1} M HBr. The presence of ClO_4^- ion depresses the absorption of the thallium species in all of the systems studied; in the Tl(III)-HCl system, for example, $\log D$ decreases roughly in a linear fashion from 5.2 to 3.0 as the concentration of added HClO_4 increases from 10^{-3} to 1 M . At small HCl concentrations, $\leq 10^{-3}$ for Tl(III) and $\text{ca. } 10^{-4}$ for Tl(I), adsorption of the thallium species on the glass surface of the containing vessel becomes important. Instability of the thallium species with respect to oxidation and reduction has tended to impede measurements. (R. A. Horne)

D. Anion-Exchange Behavior of Te(IV) and Te(VI) in HCl and LiCl Solutions

The distribution of Te tracer between the anion exchanger Dowex-1 and aqueous HCl or LiCl or HCl-LiCl mixtures was studied. Te(IV) and Te(VI) form ionic complexes such as TeCl_n^{4-n} and TeCl_n^{6-n} , which are absorbed on anion exchangers. Corresponding to a theory of Coryell and Marcus¹⁵, the highest absorption occurs when the neutral complex (Te(IV)Cl_4 or Te(VI)Cl_6) is formed in the aqueous solution. The maximum of the absorption curve of Te(IV) in HCl lies between 7 and 8 M HCl (distribution coefficient $D \approx 10^4$). At smaller HCl concentrations, the cationic Te-Cl complexes are stable; at HCl conc. $> 8 \text{ M}$, anionic complexes are formed. Due to hydrolysis no absorbable Te-Cl complexes are formed in pure LiCl solutions of concentration $1\text{--}6 \text{ M}$. Te(IV) is absorbed strongly only in concentrated LiCl solution ($> 10 \text{ M}$). The curve of $\log D$ vs. (Cl^-) is still rising at the highest HCl concentration. In LiCl-HCl mixtures, Te(IV) is absorbed stronger than in HCl alone, a phenomenon which is not theoretically understood yet. Absorption of Te(VI) by anion exchange from HCl and LiCl is small at moderate Cl concentrations. In $10\text{--}12 \text{ M}$ HCl the D value increases to 10^4 .

The curves of $\log D$ versus M suggest simple separations of Te from Se and Sb which may be valuable to radiochemists.

Separation

Te(IV) - Se(IV) in $2M$ HCl

$$D_{\text{Te(IV)}} \sim 10^2, D_{\text{Se}} \sim 1$$

Te(IV) - Sb(III) in $1M$ HCl

$$D_{\text{Te(IV)}} \sim 1; D_{\text{Sb(III)}} \sim 10^3$$

Te(IV) - Te(VI) in $2-6M$ HCl

$$D_{\text{Te(IV)}} = 10^2 - 10^4, D_{\text{Te(VI)}} < 10$$

(U. Schindewolf)

1. The anion exchange resin absorption behavior of zinc(II).

Values of the absorption coefficient, D , of tracer amounts of $\text{Zn}^{65}(\text{II})$ on Dowex-1 from aqueous solution over the chloride concentration range 0.5 to $7.0M$ maintained by the addition of LiCl, HCl, NH_4Cl , CsCl, CaCl_2 , MgCl_2 , and AlCl_3 have been measured. Table 2.VII abstracts the values of $\log D$ at total chloride concentrations of 2.0 and $6.0M$ at $24.7 \pm 0.2^\circ\text{C}$ in the presence of these various salts.

TABLE 2.VII

The Dependence of the Anion Exchange Resin Absorption of Zinc(II) on a Second Added Cation. ($1.75 \times 10^{-2}M$ HNO_3 was Present in Each Case.)

Total Chloride, M	Concentrations of Added Salt, M	$\log D$
2	$2.0M$ HCl	3.2
2	$0.5M$ HCl, $1.5M$ LiCl	3.2
2	$2.0M$ LiCl	3.2
2	$2.0M$ NaCl	3.2
2	$1.0M$ CaCl_2	3.2
2	$1.0M$ MgCl_2	3.2
2	$0.67M$ AlCl_3	3.2
2	$0.5M$ HCl, $1.5M$ NH_4Cl	3.0
2	$2.0M$ NH_4Cl	2.9
2	$2.0M$ CsCl	2.4
6	$6.0M$ LiCl	3.7
6	$3.0M$ CaCl_2	3.6
6	$3.0M$ MgCl_2	3.6
6	$2.0M$ AlCl_3	3.6
6	$6.0M$ NaCl (extrapolated)	3.4
6	$0.5M$ HCl, $5.5M$ LiCl	3.2
6	$6.0M$ HCl	2.5
6	$5.5M$ HCl, $0.5M$ LiCl	2.5
6	$6.0M$ CsCl	1.6

In the case of LiCl as the added salt, the acid dependence of D has been studied at a large (6M) constant concentration of LiCl with a small variable concentration of HCl and hence a negligibly small variation in the total concentration of chloride ion. In the hydrogen ion concentration range 0.10 to 10M the following empirical relation holds:

$$\log D = 3.0 - 0.77 \log (H^+)$$

Preliminary semi-quantitative measurements have been made at room temperature of the rate of absorption of tracer $Zn^{65}(II)$ from 2M HCl onto Dowex-1 (50-100 mesh, 8% cross-linked) and the rate of desorption of this metal from Dowex-1 into pure water. Both processes seem to be first order and to have a half-life of 4 ± 2 minutes.

The above studies are being continued and expanded. (R. A. Horne)

2. The relation between anion exchange absorability and complex constants in the resin phase.

Fronaeus²⁰ has shown that

$$D = K \frac{\beta_{\nu}^w (A)_w^{\nu}}{\bar{X}^w} \frac{\bar{X}^R}{\beta_{\nu}^R (A)_R^{\nu}} \quad (4a)$$

where D is the stoichiometric distribution constant of the metal between the two phases; K is the Nernst distribution constant for the neutral complex, MA_{ν} ; β_{ν} is the overall formation constant for the species MA_{ν} ; and $\bar{X}$ is the formation function, $\sum_i \beta_i (A)^i$. The indices R and w refer to the resin and aqueous phases respectively. It was also shown that when D is at a maximum, the concentration of MA_{ν} is at a maximum in the aqueous phase. Assuming that the complexes form successively, then at maximum adsorption the mole fraction of MA_{ν} , $\beta_{\nu}^w (A)_w^{\nu} / \bar{X}^w$, is almost unity. Also, K is of the order of magnitude of unity. Therefore from Equation 4a

$$D_{\max} \approx \frac{\bar{X}^R}{\beta_{\nu}^R (A)_R^{\nu}} \quad (4b)$$

Since cationic complexes are excluded from the resin this becomes

$$D_{\max} \approx 1 + K_{\nu+1}^R (A)_R + K_{\nu+1}^R K_{\nu+2}^R (A)_R^2 + \dots \quad (4c)$$

where the K's are the successive formation constants. Assuming that the capacity of the resin $(A)_R$ is of the order of unity and neglecting the first term on the right, we obtain

$$D_{\max} \approx K_{\nu+1}^R + K_{\nu+1}^R K_{\nu+2}^R + \dots \quad (4d)$$

(C. D. Coryell and A. M. Poskanzer)

3. The anion exchange resin absorption of metal complexes as a Lewis acid-base interaction.

Simple cations and anions absorb on cation and anion exchange resins respectively to approximately the same extent, and the chemical processes involved can be visualized in part as a simple ion exchange or metathesis. The absorption of metal complexes on anion exchange resins, however, is much stronger and exhibits a different coulombic dependence, suggesting that a different type of chemical interaction is operative, possibly a Lewis acid-base type addition.

Many neutral metal halide complexes, such as FeCl_3 , are well known Lewis acids, while the functional groups of an anion exchange resin with absorbed halide ions or possibly the aromatic ring of the resin matrix, the latter by virtue of their unsaturated π -electrons, may behave as Lewis bases. Neither, say, FeCl_4^- nor FeCl_2^+ is as strong a Lewis acid as FeCl_3 ; the latter because the hydration sphere of cationic species, while enhancing electrostatic interactions by increasing the microscopic dielectric constant, should be an effective insulator with respect to Lewis acid-base interactions, water itself being a Lewis base and the attractive forces decreasing with a greater than r^2 dependence. Fronaeus²⁰ and Coryell and Marcus¹⁵ have theorized that the neutral metal complex, MA_ν , is most strongly absorbed.

The strength of absorption of the metal species, as measured by the maximum value of the absorption coefficient, D_{max} , is related to the Lewis acidity of the neutral complex, the equilibrium constant for the reaction:

in aqueous solution being taken as a measure of the latter. Using values of $(K_{\text{MA}_{\nu+1}^-})_{\text{soln.}}$ measured by methods other than anion exchange resin absorption, for PbCl_2 , SnCl_2 , TlCl , CdCl_2 , BiCl_3 , TeCl_3 , TeCl_4 , CdBr_2 , HgCl_2 , and possibly TlBr_3 , AuCl_3 , and InCl_3

$$(K_{\text{MA}_{\nu+1}^-})_{\text{soln.}} = 10^{-3.1} (D_{\text{max}})^{0.8} \quad (4f)$$

while for FeCl_3 , TlCl_3 , and possibly GaCl_3

$$(K_{\text{MA}_{\nu+1}^-})_{\text{soln.}} = 10^{-7.3} (D_{\text{max}})^{1.2} \quad (4g)$$

In the case $\nu = 3$ (Equation 4g) resin addition absorption might result in octet completion. Comparing Equation (4f) with the expression derived in the previous section

$$D_{\text{max}} \approx (K_{\text{MA}_{\nu+1}^-})_{\text{resin}} + (K_{\text{MA}_{\nu+1}^-})_{\text{resin}} (K_{\text{MA}_{\nu+2}^=})_{\text{resin}} \quad (4h)$$

We see that $(K_{\text{MA}_{\nu+1}^-})_{\text{resin}}$, when $\nu \neq 3$, is much greater than $(K_{\text{MA}_{\nu+2}^=})_{\text{resin}}$, the corresponding K's for simple anions, or $(K_{\text{MA}_{\nu+1}^-})_{\text{soln.}}$. These effects are even more pronounced

when $\nu = 3$. (R. A. Horne)

E. Studies of Some Aliphatic Quarternary Anion-Exchange Resins

All commercially available anion exchangers (Dowex, Nalcite, Amberlite, Permutite, etc.) are polymerization products which contain aromatic groups. The anion exchangers play an important role in the absorption of the chloro-complexes of metals from HCl or LiCl solutions. An anion exchanger without any aromatic groups was prepared by polymerization of tetraethylenepentamine and epichlorohydrin. This exchanger contains quarternary ammonium groups and is therefore a strong anion exchanger.

Experiments have been made on the distribution of Ag(I), Zn(II) and Au(III) between HCl and the aliphatic anion exchanger (Ulex-2) (distribution coefficient versus HCl concentration). The distribution curves are similar to those obtained with Dowex-1, but absorption is not as strong, probably due to a smaller degree of cross linking. In LiCl the absorption of Zn and Au by the new anion exchanger is slightly higher than from HCl (factor ~ 4), whereas Dowex-1 absorbs Zn and Au in conc. LiCl solution 10^2 to 10^3 times stronger than in HCl. Experiments are in progress with a higher cross-linked resin. (U. Schindewolf)

F. Separation of Short-Lived Pd and Ag Isotopes in Fission

Fast separation methods with high decontamination factors are needed for the study of short-lived nuclides produced in fission. Pd can be separated from other fission products by extraction of the Pd-dimethylglyoxime (DMG) complex with chloroform. The separation is made by shaking a solution of the fission products in 0.5-3M HCl with chloroform in which DMG is dissolved. Re-extraction of the chloroform phase with dilute HCl increases the decontamination factor. The silver which is formed by β decay of Pd may be extracted with dilute HCl and then be precipitated with silver carrier.

Another way to separate silver from Pd is to absorb the Pd on an anion-exchange column (Dowex-1) from 12M HCl after its oxidation to Pd(IV) with chlorine. Silver can be eluted very rapidly from the column with 8-12M HCl saturated with chlorine gas. (U. Schindewolf)

VI. NUCLEAR CHEMISTRY

A. Neutron Shell-Numbers and the Aggregate Total β Decay in the Creation of the Elements of Mass Number Above 70

Several conclusions are fairly well established about the abundances in nature of nuclear species above 70 in mass number A. Isotopic abundances indicate that β decay was the principal last mode of formation of the stable and long-lived nuclides. Nuclides of even A not shielded from formation by β decay are roughly twice as abundant as their odd-A neighbors. Some authors have noted an inverse dependence²¹ of cosmic abundance in fast neutron (~ 1 Mev) cross sections suggesting multiple neutron condensation in competition with β decay.

Relative nuclear cosmic abundances H depend on a reasonable chemical analysis of the cosmos. The most reliable detailed data available are based on the chemical analysis of meteorites, all of which presumably belong to our solar system. Brown²² reviewed the existing data in 1949. Another review has just appeared by Suess and Urey²³ which has considerably greater detail apparent, as the result of newer data and several new standards of criticism. These authors stress the principle of continuity of the H vs. A curve. According to this, the slope of the curve is determinable wherever an element is encountered with two stable odd- A isotopes.

The Suess and Urey data for odd- A nuclides above $A = 68$ are plotted in Figure 2.1, where H represents the abundance of nuclides compared to $\text{Si}^{28} = 10^6$. The data for the elements with two stable odd- A isotopes are emphasized in the figure. Limits of the data are also given for Th^{232} , U^{235} , and U^{238} , based partly on lunar thermogeology²⁴. Abundances are computed for the individual isobars using terrestrial isotope abundance data. The curve for H of even- A isobars vs. A gives²³ a curve of essentially the same shape, so the interpretations given here will be based on the odd- A nuclides.

It is well known^{21, 25} that the fast neutron capture cross sections of nuclides increase with A up to $A = 100$, and then remain fairly independent of A at 0.1 barn, except that nuclides with closed shells of protons or neutrons have cross sections lower by 10-100 fold, presumably as a result of the fall in level density. It is reasonable to suppose that such a fall in cross section associated with the neutron closed shells of 50, 82, and 126 neutrons will reflect itself in peaks in the abundance curve, according to the neutron numbers present during the last important period of nucleogenesis (the primordial neutron numbers N^*). The difference between N^* and N the neutron numbers of the abundant stable species can be defined as Δ , the average β -decay chain length of the primordial species. From the spread in Δ , estimates may be made of the average Z width of the band of nucleogenesis by neutron capture.

It is postulated that the broad abundance peaks in Figure 2.1 at $A = 79$ and 81 ($_{35}\text{Br}$) corresponds to the now stable β decay products of the primordial species with $N^* = 50$. Thus Δ values of 6 and 4 are prominent, and two prominent primordial species are $_{29}^{50}\text{Cu}^{79}$ and $_{31}^{50}\text{Ga}^{81}$. The height of this peak is about five times the roughly estimated base abundance curve (broken line in Figure 2.1), and it is fairly broad, suggesting a wide Z band for the nucleogenesis reaction paths.

Correspondingly, it is postulated that the moderately sharp peak near $_{54}\text{Xe}^{129}$ corresponds to β decay of $_{47}^{82}\text{Ag}^{129}$, corresponding to a Δ value of 7. The peak stands out quite strong (about 12X) above the nominal base line.

The next peak of similar shape is that for $_{77}^{116}\text{Ir}^{193}$ and $_{78}^{117}\text{Pt}^{195}$ which also stands out very strongly, about 15X the nominal base line. The N^* value 126 postulated leads to identification of the primordial species as $_{67}^{193}\text{Ho}$ and $_{69}^{195}\text{Tm}$. The Δ values of 10 and 9 respectively seem surprisingly high, but the valley of stability is known to be much wider for high masses²⁶, corresponding to lower fall of neutron affinity with N and to less time sensitivity (higher half-life for given Δ).

Figure 2.1

Cosmic abundances of the element, A.

Neutron-shell numbers should be more decisive than proton-shell numbers, because a neutron-shell number is regained by a β -decay step followed by condensation of another neutron, whereas proton-shell numbers occur once, and are irrevocably lost by a β -decay step. Any consequence of primordial $Z^* = 50$ would be lost in the 129 peak if Δ is about 4. Any consequence of the primordial $Z^* = 82$ would have decayed into the Z region of great α instability, and then have decayed back to Pb^{206} , Pb^{207} , Pb^{208} , or Bi^{209} . This, plus the normal α decay of species created in this mass region (up to 232, 235, and 238 for the $A = 4n$, $4n+3$, or $4n+2$, and any A above 209 for the $A = 4n+1$ series) explains the hump around Pd^{207} and Bi^{209} .

An explanation is required for the narrow spikes for Y^{89} and La^{139} , stable species with 50 and 82 neutrons respectively. These abundance spikes might result from the effect of residual neutrons later giving mass-shift by secondary condensation, or they might result from an undue weighting of the data for rare earths in meteorites. It is barely possible that they might bespeak the occurrence of a small amount of fission of the first important species subject to fast-neutron fission in the synthesis process. Such a species might be something like ${}_{87}\text{Fr}^{238}$, so neutron-rich as to give about 10 neutrons per fission and an unexpectedly narrow yield-mass curve.

We have no good explanation for the small broad hump with peak at ${}_{66}\text{Dy}^{163}$, except perhaps the imperfectly understood possible subshell effects noted²⁶ for $Z = 64$ and $N = \sim 106$.

The shoulder at ${}_{72}\text{Hf}^{177}$ may also be related to subshell effects^{26, 27}, or to post-synthesis mass readjustments.

There is a small spike at ${}_{44}\text{Ru}^{101}$ which may reflect the effect of the possible obscure subshells^{26, 27} at $Z = 40$, $N = 58$ or $N = 64$. The reality of this spike depends on the relative odd-isotope abundances of molybdenum and ruthenium. It is probably real unless substantial changes in mass number occurred after the major nucleogenesis.

Most of the primordial species discussed in this note are richer in neutrons even than the shortest lived fission products observed²⁸. Their β -decay energies may, however, be predicted with reasonable accuracy^{26, 27, 29} and since their decay energies are very great, permitted transitions will generally occur which use most of the nuclear potential energy. Their decay properties are thus subject to statistical treatment of the type that Way and Wigner introduced for fission products³⁰.

In this section, attempts have been made to explain every abundance spike observable in Figure 2.1 in terms of neutron shell and subshell numbers. Later changes in the estimates of cosmic abundances of the mass numbers will of course lead to some changes in conclusions. Lower rare-earth abundances would cut the Y^{89} and La^{139} spikes, but also lead to trouble in the trough near $A = 171$.

Alpher and Herman developed a fairly satisfactory explanation²¹ for the trend in estimated cosmic abundances given by Brown²² (which did not have definite fine structure) by ignoring shell effects and postulating competition between fast neutron capture and β decay. The rough "normal"

abundance curve of Figure 2.1 lies about one power of 10 below the Alpher-Herman prediction near $A = 150$. If this base line can be taken roughly as quantitatively significant, it must be considered that about two-thirds of the yields of nuclides above mass 68 come from yield peaks associated with neutron-shell numbers. This line suggests that Alpher and Herman have overestimated their parameter for neutron density at their reference time in the original cosmic explosion. If, on the other hand, simple theory^{26, 30} is used to estimate β half-lives of the primordial nuclides (0.1 - 1 sec.), and reasonable estimates²⁵ are made of their cross sections (~ 0.001 barns for predominantly closed neutron shells) the neutron flux may have to be much higher than Alpher and Herman estimated. Indeed, it is not easy to see how the heavy element pattern of the meteorites was attained, and the answer may only apply to the solar system.

No attention has been given to the distribution pattern below $A = 69$, where β decay does not appear to be the last step. It should also be noted that the elements above $A = 69$ correspond²³ to about 10^{-8} of all of the nuclides or about 10^{-4} of all those except ${}^1_1\text{H}$ and ${}^4_2\text{He}$.

The author is very grateful to Professor H. C. Urey of the University of Chicago and Professor H. E. Suess of the University of California at La Jolla for advance copies of their data and for very helpful advice and criticism. (C. D. Coryell)

B. The Decay Properties of $\text{Ag}^{111\text{m}}$

A short-lived $\text{Ag}^{111\text{m}}$ was known to be formed by β decay of 22m Pd^{111} . It was reported³¹ to decay with a half-life of less than 5 min. by observation³² of conversion electrons in the isomeric transition to 7.5d Ag^{111} . The β decay to $49\text{m Cd}^{111\text{m}2}$ was also reported³¹.

With the ion-exchange technique described in Section VF, $\text{Ag}^{111\text{m}}$ was separated from deuteron-bombarded enriched Pd^{110} and its decay properties were determined. It decays with a half-life of 72 ± 3 sec. to the ground state 7.5d Ag^{111} . More than 99% of its conversional electrons are cut off by a 20 mg Al-absorber, indicating that it decays by less than 1% by β decay to Cd^{111} . Other experiments (milking $49\text{m Cd}^{111\text{m}2}$ from 22m Pd^{111} in equilibrium with $72\text{s Ag}^{111\text{m}}$) showed that the β -decay to $\text{Cd}^{111\text{m}2}$ occurs to less than $10^{-2}\%$. (U. Schindewolf, J. W. Winchester, and C. D. Coryell)

C. The Decay of Cs^{139}

Aluminum absorption measurements show the β ray energy of 9.7m Cs^{139} to be 4.3 ± 0.2 Mev. About 0.2 Mev of γ radiation per β decay is also present by this analysis, made in the presence of β and γ rays from 33m Cs^{138} . By scintillation γ counting, ratios of $\text{Cs}^{139}/\text{Cs}^{138}$ divided by the corresponding proportional-counter β -counting ratios, it appears that Cs^{139} emits γ rays in $\sim 15\%$ of its decays. The Cs^{139} γ ray appears to have an energy greater than 0.2 Mev from γ -counting experiments using the γ -ray scintillation spectrometer. No evidence for a Cs^{139} γ ray was found by displaying the linear amplifier pulses on an oscilloscope and taking photographs of the screen. The presence³¹ of the Cs^{138} γ rays of 0.46 Mev (26% abundance), 1.010 Mev (25% abundance) and 1.426 (73% abundance) in these experiments, limits the Cs^{139} γ ray to $\lesssim 20\%$ abundance unless its

energy is approximately the same as that of one of these Cs^{138} γ rays. Thus the experimental β -decay energy Q^β of 4.3 ± 0.2 Mev (obtained by extrapolation methods) is not seriously affected by γ complexity. It is interesting to compare this with the value for Q^β of 4.3 from the Coryell-Brightsen-Pappas parameters²⁶. (R. C. Fix)

D. The Identification and Decay Properties of 31.6m Br^{84}

The mass assignment of Br^{84} has been confirmed by measuring the β -ray absorption curves of the 32m bromine activity produced by fission and that produced by the reaction $\text{Rb}^{87} (n, \alpha) \text{Br}^{84}$. The isochronous absorption curves of the 32m Br were identical in both cases, and the half-lives agreed within experimental error. The half-life for Br^{84} as measured on bromine from fission, bromine from fission selenium, and bromine from $\text{Rb}(n, \alpha)$ is 31.6 ± 0.2 min, and was the same in all cases.

This mass identification gives assurance that Se^{84} is short-lived (~ 2 min), contrary to the predictions of Professors T. P. Kohman and C. D. Coryell (private communication) that it may be very long-lived.

An investigation of the Br^{84} γ spectrum by pulse height analysis has been initiated in conjunction with Mr. James Simanton and Professor T. P. Kohman of the Carnegie Institute of Technology. (R. C. Fix and U. Schindewolf)

E. The Decay Properties of 2.5m Se^{84} and Search for Se^{85} and Se^{86}

The analyses of two β decay curves on samples of selenium from fission show a component of ~ 2.5 min with a fission yield within 10% of that expected for Se^{84} . Milking of 31.6m Br^{84} from fission selenium suggests that the half-life of Se^{84} is between two and four minutes. Two γ -decay curves suggest the presence of a component of about the same half-life.

No evidence was obtained for the presence of Se^{85} or Se^{86} . Since counting was started within 3 min. after the end of bombardment, and since a component of ~ 60 sec half-life and about the expected fission yield for 69s Se^{83m} was observed, the half-lives of Se^{85} and Se^{86} must be shorter than ~ 50 sec. (R. C. Fix, U. Schindewolf, and C. D. Coryell)

F. The Cyclotron Production of Slow Neutrons

Measurements of fission yields in the valley (in the mass region 105 - 121) and shielded nuclides formed in low yield are very sensitive to the energy of the bombarding particle. The most intense source of neutrons available at M.I.T. until the reactor is completed is obtained by bombarding Be with deuterons (60 μ amps) at the cyclotron. These neutrons, after being slowed down by 10 cm. of paraffin, give a flux of 5×10^8 neutrons/sq. cm./sec. Measurements and calculations have been made to determine what fraction of these neutrons fail to be thermalized. Indium has been bombarded with and without a cadmium shield and phosphorus has been separated from irradiated sulfur. The measurements indicate that about 10% of the neutrons are above thermal energies and most of them are probably above 1.5 Mev. Further studies are in progress to

establish the conditions for good study of thermal fission yields in the valley region. (C. E. Gleit and J. M. Alexander)

VII. FISSION RADIOCHEMISTRY

A. Delayed Neutrons in Fission

G. R. Keepin³³ has summarized all existing work on the experimental yields of delayed-neutron emitters in fission. Reasonably well based theoretical predictions³⁴ indicate that many nuclides with $S+2$, $S+4$, $S+6$, or $S+8$ neutrons, where S is the shell number 50 or 82, should emit neutrons following β decay. Indeed, the requirements are that the β -decay energy Q^β exceed the neutron binding energy B^n of the daughter, and that the independent or cumulative fission yield not be too small.

Present curve analyses³³ show only six species of half-life 54.3, 21.7, 5.87, 2.18, 0.46, and 0.13 sec. with the first identified as Br^{87} , the second as I^{137} , the third as $\text{Br}^{89?}$, and the fourth as Sb or Te . Calculations are being made of the expected nuclear properties of probable delayed neutron emitters. Experimental work will be undertaken when the possibilities are evaluated.

(C. D. Coryell and J. M. Alexander)

B. Deuteron Fission Yields

A study of the fission of U^{238} with deuterons of 8 - 15 Mev is presently in progress. The fission yields are being studied from mass numbers 83 to 140 here at M.I.T. and will be supplemented above mass 140 by work under Professor T. T. Sugihara at Clark University. The charge distribution will also be studied at various energies. The yields measured to date are Ag^{111} , Pd^{112} , Ag^{113} , Ag^{115} , I^{131} , Te^{132} , I^{133} , Sr^{89} , Ba^{139} , and Ba^{140} ; those in progress are Rb^{86} , Br^{82} , Br^{83} , Br^{84} , and Cs^{136} . These measurements together with previous work by D. R. Wiles in this laboratory³⁵ will give a rather complete picture of U^{238} fission with low-energy deuterons.

(J. M. Alexander)

C. The Yields of Silver Activities (1.3m, ~22m, and 5.3h) Found in the Decay of Short-Lived Pd Fission Products

The methods described in Section VF were applied to separate short lived Pd isotopes from fission products. From the mixture of neutron-rich Pd isotopes, fast silver extractions gave evidence for three components, ~1.5m, ~22m, and 5.3h. The 5.3h species is Ag^{113} ; the ~22m component should be principally 21m Ag^{115} ; the 1.5m component could be partly or all the poorly characterized ~2m Ag^{114} . All three of these silver components seem to show half-lives close to 1.5 min. for the Pd precursors. Assuming the 1.3m Ag and the 5.3h Ag^{113} are formed from different Pd isotopes, then the fission yield of Pd^{113} would be about 10 times higher than the fission yield of the Pd which decays to the 1.5m Ag. This is not in agreement with the smooth deuteron fission yield curve, and we assume that the 1.5m Ag is a metastable isotope of 5.3h Ag^{113} and that Pd^{113}

decays by β -decay to 5.3m Ag^{113g} (90%) and to 1.5m Ag^{113m} (10%).

The apparent fission yield of the Pd parent of the ~22m Ag component is also low, about 0.1 of that for Pd¹¹³ $\rightarrow$ 5.3h Ag¹¹³. There are some difficulties with half-life of the ~23m component. (U. Schindewolf and C. D. Coryell)

VIII. DISCUSSION OF RESEARCH PLANS

The current two years provide heartening evidence for the increase in interest of new graduate students in nuclear science, and increased interaction with the vigorous M.I.T. Laboratory for Nuclear Engineering. It has been the constant interest of the leaders of this group to encourage such trends. Thus our research program has been designed with a broad base extending from physical-inorganic chemistry through to nearly pure nuclear physics.

In the spring of 1955 a special task force was organized with the goal of completing a comprehensive treatment of the physico-chemical parameters governing the formation and distribution of anion complexes between aqueous media and organic solvents or anion-exchange resins. Considerable progress has been achieved in carrying out the work in this special program, as shown in Sections III, IV, and V of this report. The special work outlined has, however, been only about one-third accomplished, largely due to the time required to recruit postdoctoral personnel and to orient graduate students. It is hoped that the coming academic year (1956-57) will see the fruition of the program. The early results from it seem to justify its promise.

The new elaborations of the principles of radiochemical separation will be used to explore nuclear properties of short-lived species and of complex mixtures of radionuclides, especially among the fission products. Several research areas that have shown great promise are those of ruthenium, rhodium, palladium, silver, cadmium, indium, tin, and antimony. For all of these elements isomerism is common, and difficult chemical separations further complicate the experimental attack. These elements comprise also the valley region of the fission spectrum, and elucidation of fission yields as a function of energy ought to contribute substantially to fission radiochemistry.

In the area of nuclear theory, it is hoped to obtain more information on energy systematics and on activation functions, which relate to nuclear level density. These problems lead reasonably to further study of delayed-neutron emitters. The group is planning experiments to be carried out in the M.I.T. pile as soon as it is in operation. Special interest has also been developing in the interrelations of nuclear shell effects and the meteoritic and cosmic abundances of the nuclides. (Charles D. Coryell and John W. Irvine, Jr.)

REFERENCES

1. H. E. Suess and H. C. Urey, *Revs. Modern Phys.* 28, 53 (1956).
2. J. Saldick, *J. Phys. Chem.*, 60, 500 (1956).
3. G. S. Golden, S. B. Thesis, Department of Chemistry, Massachusetts Institute of Technology, June 1954; Laboratory for Nuclear Science Annual Report, May 31, 1954, p. 18.
4. R. L. Rich and H. Taube, *J. Phys. Chem.*, 58, 1 (1954).
5. D. G. Tuck, C. D. Coryell and J. W. Irvine, *J. Phys. Chem.*, 60, p. 378 (1956).
6. F. A. Cotton and C. J. Ballhausen, *J. Chem. Phys.*, in press; F. A. Cotton and H. P. Hanson, *ibid.*, in press.
7. W. Gordy and S. C. Stanford, *J. Chem. Phys.*, 9, 204 (1941).
8. H. F. Plank, Ph.D. Thesis in Chemistry, Massachusetts Institute of Technology, June 1950.
9. H. Irving, F. J. C. Rossotti, and R. J. P. Williams, *J. Chem. Soc. (London)*, 1955, 1906.
10. H. F. Plank and C. D. Coryell, Laboratory for Nuclear Science and Engineering Annual Report, July 1, 1950, pp. 64-66.
11. C. H. Brubaker, Jr. and C. D. Coryell, Laboratory for Nuclear Science Annual Report, May 31, 1953, p. 89.
12. C. H. Brubaker, Jr., Laboratory for Nuclear Science Quarterly Report, August 31, 1955, pp. 7-10; *ibid.*, November 30, 1955.
13. V. Kusnetsov, *J. Gen. Chem. U.S.S.R.*, 22, 2083 (1952).
14. H. P. Gregor, J. Belle, and R. A. Marcus, *J. Am. Chem. Soc.*, 76, 1984 (1954) and 77, 2713 (1955).
15. C. D. Coryell and Y. Marcus, *Bull. Res. Council of Israel*, 4, 7 (1954).
16. K. A. Kraus, F. Nelson, and G. W. Smith, *J. Phys. Chem.* 58, 11 (1954).
17. R. A. Horne, unpublished work, Brookhaven National Laboratory, 1955.
18. R. Benoit, *Bull. Soc. Chim. France*, 16, 518 (1949).
19. K. H. Hu and A. B. Scott, *J. Am. Chem. Soc.* 77, 1380 (1955).
20. S. Fronaeus, *Svensk Kem. Tidskr.*, 69, 1 (1953).
21. R. A. Alpher and R. C. Herman, *Revs. Modern Phys.* 22, 153 (1950).
22. H. S. Brown, *Revs. Modern Phys.* 21, 624 (1949).
23. H. E. Suess and H. C. Urey, *Revs. Modern Phys.* 28, 53 (1956).
24. H. C. Urey, *Geochim. et Cosmochim. Acta* 1, 209 (1951); *idem* "The Planets. Their Origin and Development", Yale University Press, New Haven, 1952.

Nuclear Chemistry (Inorganic) Group

25. D. J. Hughes, "Pile Neutron Research", Chapter 4, Addison-Wesley Press, Inc., Cambridge, 1953.
26. C. D. Coryell, Ann. Rev. Nucl. Sci. 2, 305 (1953).
27. H. E. Suess and J. H. D. Jensen, Arkiv. f. Fysik 3, 577 (1951).
28. C. D. Coryell and N. Sugarman, "Radiochemical Studies: The Fission Products", Vol. 9, Div. IV, Nat. Nucl. En. Series, McGraw-Hill Book Co., New York, 1951.
29. K. Way and M. Wood, Phys. Rev. 94, 119 (1954).
30. K. Way and E. P. Wigner, Phys. Rev. 73, 1318 (1948); see also Paper 43 in Ref. 28.
31. P. C. Stevenson and H. G. Hicks; see J. M. Hollander, I. Perlman, and G. T. Seaborg, Table of Isotopes, Rev. Mod. Phys. 25, 531 (1953).
32. C. L. McGinnis, Phys. Rev., 87, 202 (1952).
33. G. R. Keepin, Progress in Nuclear Energy, London: Pergamon Press, (1956).
34. A. C. Pappas, Laboratory for Nuclear Science Technical Report No. 63, December 1953, and earlier work in this Laboratory.
35. D. R. Wiles, Ph.D. Thesis in Chemistry, Massachusetts Institute of Technology, November 1953, with appendix on the work of F. van Goetsenhoven, M.I.T., 1953.

C. D. Coryell
J. W. Irvine, Jr.

Nuclear Chemistry (Organic) Group

I. INTRODUCTION

The researches of this group involve the application of isotopes to problems in organic chemistry. Tritium (H^3) isotope effects have been used to demonstrate that "acetic acid catalysis" of ketone enolization involves attack by acetate ion and hydrogen ion rather than by acetic acid. Tritium has also been used as a tracer to study the mechanism of the fast exchange of protons between the hydroxyl groups of two alcohols, triphenylcarbinol and t-butanol, in toluene solution, to study the "cage effect" in the thermal decomposition of benzoyl peroxide by isotope dilution methods, and the acidity of methyl hydrogens in structural analogs of coenzyme A. Work has begun on comparison of deuterium and tritium isotope effects, on comparison of the reactivity of hydroxide and deuterioxide ions in a common solvent, and on a study of ion pair formation in the decomposition of alkyl chlorosulfites labeled with Cl^{36} .

II. THE ENOLIZATION OF KETONES

Work was continued on the determination of the tritium isotope effect in the enolization of α -phenylisocaprophenone. We define the isotope effect for a particular catalyst as the ratio of the catalytic coefficient for racemization of D(+) α -phenylisocaprophenone to that for tritium exchange with dl- α -phenylisocaprophenone - α -t. The studies were made at 97.8° with 0.1 M. ketone, 0.1 M. ionic strength, 34.6 mole per cent dioxane, and 65.4 per cent water. The reactions were carried out in sealed Pyrex bulbs except for hydroxide ion studies, which were done in Teflon tubes.

Table 3.1 below gives the ratio of catalytic coefficients for the racemization studies to that of tritium exchange as well as the catalytic coefficients for the racemization work.

TABLE 3.1

Terms in Rate Expression

Catalyst	Isotope Effect	Racemization $M.^{-1} sec.^{-1}$	Base	Acid
HO^-	12.9	9.92×10^{-2}	HO^-	H_2O
H_3O^+	9.7	2.64×10^{-4}	H_2O	H_3O^+
AcO^-	10.2	1.07×10^{-5}	AcO^-	H_2O
HOAc	11.4	8.74×10^{-8}	AcO^-	H_3O^+
$HOAc - AcO^-$ ^a	—	6.91×10^{-6} ^b	AcO^-	HOAc

(See footnotes next page.)

^aDue to the smallness of this third-order term, the isotope effect cannot be estimated accurately.

^bIn $M^{-2} \text{ sec.}^{-1} \times 10^2$.

There was some question as to whether water and acetic acid or acetate ion and hydronium ion were the catalysts in studies using acetic acid. The dissociation constant for acetic acid under these special reaction conditions was not known. If the reaction were partially due to the dissociation of acetic acid, the acetate and hydronium ions would be in equal concentrations and, since hydronium ion is about twenty-five times more effective as a catalyst than acetate ion, adding small amounts of acetate ion to an acetic acid reaction mixture should slow down the reaction.

In table 3.II below is tabulated the effect of adding small amounts of acetate ion to reaction mixtures containing 0.1 M. ketone, 0.1 M. sodium chloride, and 1.0 M. acetic acid.

TABLE 3.II

Effect of Acetate Ion on Acetic Acid Catalysis

Amt. of Added Acetate M. $\times 10^4$	k_1 obs. ($\times 10^8 \text{ sec.}^{-1}$)	Calc. % Reaction Due to Undissoc. Acetic Acid
None	8.90	—
14.6	10.0	94.6
6.45	9.31	96.6
4.73	9.33	99.3

Average = 96.8%
 $K_A \text{ calc.} = 1.2 \times 10^{-10}$

The identification of the base and acid involved in the hydroxide and hydronium terms is unequivocal. The other possibilities for acetate (OH^- and HOAc) and acetic acid (H_2O and HOAc) are eliminated by the following considerations. The magnitude of the isotope effect is a function of the strength of bonding of the exchangeable proton in the transition state. This should be most dependent on the basicity of the attacking base, but also somewhat dependent on the acid, which acts on the carbonyl oxygen several atoms away. Since the effect of a stronger acid on the oxygen must be to weaken bonding of the proton, the isotope effect with water acting as both base and acid must be below 9.7. If acetate ion had involved hydroxide ion and acetic acid, its isotope effect would have been greater than 12.9; if acetic acid had involved water and acetic acid, its isotope effect would have been less than 9.7.

The isotope effect for water alone was not measured because the uncatalyzed rates were too slow. However, approximately the same ratio should exist between water and hydronium ion isotope effects as between acetate ion and acetic acid, in view of the above assignment. Table 3.III shows the isotope effects arranged as a function of the base and acid involved.

TABLE 3.III

Isotopic Effects

BASE	ACID	
	H ₂ O	H ₃ O [⊕]
H ₂ O	8.7 ^a	9.7
AcO [⊖]	10.2	11.4
HO [⊖]	12.9	14.4 ^a

^a Estimated.

It was of interest to determine whether the isotope effect for the reverse reaction (enol and proton to ketone) was the same as that for the forward reaction (enolization). From a run containing 0.04 M. hydrochloric acid and 0.06 M. sodium chloride which had been left at 97.8° C. for eight months (half time of tritium exchange 200 hours) both the spent ketone and the enriched water were isolated in pure form. The ratio of the specific activities of the water and ketone was 1.99. Since water has two exchangeable protons while the ketone has but one, the value of 1.99 indicates practically no isotope fractionation in this reaction. (E. C. Stivers)

III. COMPARISON OF DEUTERIUM AND TRITIUM ISOTOPE EFFECTS

A comparison of deuterium and tritium isotope effects is being made by studying the rate of enolization of α -phenylisocaprophenone. The rate of racemization of the D(+)-ketone and the rate of enolization of α -tritiated dl-material have been measured already in this laboratory. The rate of enolization of the α -deuterated ketone is now being measured by following the increase of deuterium in the solvent. A falling-drop apparatus is being used for the determination of the deuterium. (J. F. Reuwer, Jr.)

IV. PROTON EXCHANGE BETWEEN ALCOHOLS

Further work was done indicating that the exchange between triphenylcarbinol and t-butanol in toluene solution at 25° is first order in triphenylcarbinol and zero order in t-butanol, with a half-life of about 0.5 sec., and is strongly catalyzed by acids or bases. These results suggest that only solvent and one molecule of either triphenylcarbinol or an impurity in the triphenylcarbinol are involved in the rate-determining step. In view of the much slower ionization of triphenylmethyl chloride in benzene, it seems likely that only oxygen-hydrogen bonds are breaking. Let HA represent triphenylcarbinol or an acidic impurity in the triphenylcarbinol (e.g., benzoic acid).

The kinetics indicate that the first ion pair ($\text{H}^{\oplus} \text{A}^{\ominus}$) has no covalent bond to the proton, and exchanges (k_2) faster than it collapses (k_{-1}) under our experimental conditions. (M. M. Halmann)

The applicability of nuclear magnetic resonance (NMR) methods to the study of proton exchange between hydroxyl groups of alcohols was investigated briefly. NMR can distinguish between differently bonded protons and, in favorable cases, even between similarly bonded protons in different molecular environments. A number of practical difficulties, however, may seriously limit the usefulness of NMR. Chief among these is the lower concentration limit. NMR phenomena involve transitions between very closely spaced energy levels which are almost equally populated. The net absorption or emission of energy in an NMR experiment, thus, is exceedingly small, and a large number of nuclei must be observed at one time in order to offset this. Under the conditions of high resolution which must be employed to observe small differences in proton bonding and environment, the physical dimensions of the sample must unfortunately be quite small. High sensitivity and high resolution are, therefore, incompatible.

Proton NMR spectra of various alcoholic solutions were measured in the MIT instrument (Varian Associate Model V-4300b) to determine what the lower concentration limit actually is. It was found that benzene a very desirable solvent from the kinetic point of view, could not be used because even in the most concentrated solution tried, 1.0 M. ethanol, benzene absorption was so strong as to completely mask the hydroxyl region. Carbon tetrachloride fulfilled the requirement of transparency in the desired region, but when the spectrum of 0.10 M. ethanol in this solvent was measured, the signal could not be distinguished from electronic noise. The signal from 0.20 M. ethanol in carbon tetrachloride was roughly twice the amplitude of noise. A two- or three-fold improvement might be gained by the fortuitous use of a particularly homogeneous magnetic field, but it does seem that 0.10 M. is roughly the lower concentration limit for hydroxylic proton resonance. Thus, use of an NMR spectrometer as an analytical tool to follow proton concentrations would involve use of solutions in the concentration range where kinetic significance of the data obtained is questionable.

Two somewhat less obvious applications of NMR remain and are currently being investigated. Both involve mathematical relationships between exchange half-lives and the fine structure of NMR spectra, and, as such, present opportunity for the direct calculation of exchange rates from spectra. Both, however, are subject to the limitations outlined above, though perhaps not to the same degree.

A re-evaluation of the flow method used previously in this investigation has revealed that one of the assumptions on which the method is based is invalid. Flash distillation in the original apparatus does not quench proton transfer: separation of reactants is not quantitative because it is not sufficiently rapid.

Table 3.IV describes the results of five such flash distillations in terms of percent t-butanol separated. t-Butanol was determined volumetrically both in distillate and in residue by using a standard solution of lithium aluminum hydride with N-phenyl-p-aminoazobenzene indicator. It was found that use of a dry nitrogen atmosphere throughout the determination permitted direct titration of the alcohol and that back titration of an excess of hydride with standard butanol solution was not necessary.

TABLE 3.IV

Separation of t-Butanol from Solvent in Flash Distillation

Expt. No.	Solvent	t-BuOH M.	Contact Time (sec.)	Distilln. Time (sec.)	% t-BuOH Separated	Total % Isolated
1	Toluene	0.10	0.49	25	57	97
2	Toluene	.10	.50	55	66	97
3	Toluene	.025	.54	30	42	94
4	Tetralin	.10	—	40	64	98
5	20% by vol. Ethyl Ether in Tetralin	.10	.96	55	59	100

Roughly one-half of the t-butanol used was separated. Experiment No. 2 shows, furthermore, that what is separated is not removed instantaneously upon introduction into the vaporization chamber, but that some distillation of t-butanol from the liquid remaining behind also occurs. This means that contact time as calculated in the usual manner from the dimensions of the flow tube is not a true measure of reaction time. Reaction time here is, in fact, not constant during each experiment but rather varies over the considerable range from "contact time" to total time of the experiment (distillation time). Calculation of reaction time under these circumstances is prohibitively difficult.

The relative insensitivity of percent separation to changes in alcohol concentration and changes in solvent seems to indicate that here the physical dimensions of the vaporization apparatus are the limiting factor. Apparatus dimensions could control the rate of separation in two ways: by limiting the rate of vaporization through control of the amount of distilland surface exposed, or by impeding the flow of vapor to the cold trap. Rates of vaporization under conditions of dynamic equilibrium are difficult to calculate directly, but an estimation of the rate at which molecules leave the surface of the distilland shows that vaporization is probably not rate-controlling in this case. The rate at which vapor must flow to the cold trap, on the other hand, is much greater than

the system under investigation can handle. Work is now underway, therefore, on the construction of a system offering less impedance to vapor flow. (A. J. Kresge)

V. THE THERMAL DECOMPOSITION OF BENZOYL PEROXIDE

The decomposition of 0.003 M. benzoyl peroxide in cyclohexane solution is first order in peroxide and the rate is independent of styrene concentration between 0.01 and 0.15 M. styrene.

Tritium labeled benzoyl peroxide of specific activity $18.2 \mu\text{C}/\text{m. mole}$ was prepared by the method reported earlier. The products were determined by the method of isotope dilution. Phenyl benzoate and diphenyl were separated from the reaction mixture by chromatography as described in an earlier report. Benzoic acid was extracted with aqueous base.

It proved more difficult to isolate the benzene. Distillation was not effective since benzene and the solvent cyclohexane boil within one degree of each other. Chromatography was tried without success. Nitration of 1 g. of benzene in 1.5 liter of cyclohexane gave about 0.5 g. of impure nitrobenzene, but distillation of this crude product gave no pure nitrobenzene, only a series of fractions of increasing refractive index.

Using stronger conditions (fuming nitric acid, heating at 80° for six hours) 0.25 g. of m-dinitrobenzene was obtained in good purity. The dinitration was repeated with tritium-labeled benzene. The dinitrobenzene obtained had two-thirds the specific activity of the benzene, showing that there was neither isotope effect in the reaction nor isotope exchange with the nitrating mixture. It should, therefore, be possible to determine the amount of benzene formed in benzoyl peroxide decomposition by nitrating and isolating dinitrobenzene.

Two 0.003 M. solutions of benzoyl-(p, p'-t) peroxide in cyclohexane were decomposed at 91° with 0.015 M. and 0.12 M. styrene respectively to trap solvent radicals. To each reaction mixture were added weighed amounts of diphenyl, phenyl benzoate, benzoic acid, and benzene. The benzoic acid was re-extracted with aqueous sodium hydroxide. The organic layer was dried and concentrated to 20 ml. This residue was chromatographed, giving diphenyl and phenyl benzoate. The distillate (presumably containing benzene) was nitrated, but we were not successful in isolating dinitrobenzene from one of the runs. The diphenyl, benzoic acid, and phenyl benzoate were purified to constant activities, and the results are presented in Table 3.V.

It appears, then, that benzoyl peroxide forms 0.1% diphenyl and 1.5 - 2.0% phenyl benzoate in a cage reaction.

It is not yet possible to say whether or not the benzoic acid and benzene are formed in a cage reaction.

TABLE 3.V

Moles of Product from 100 Moles of 0.003 M. Benzoyl Peroxide in Styrene-Inhibited Cyclohexane Solution at 91°

Product	Yield	
	0.015 M. Styrene	0.12 M. Styrene
Benzene	145	not determined
Benzoic acid	47.8	39.5
Diphenyl	0.14	0.10
Phenyl benzoate	1.8	1.6

The isolation of benzene continues to give trouble. It was reported earlier that benzene can be isolated by distilling it with the solvent cyclohexane from the remainder of the reaction mixture, then nitrating the distillate and isolating the benzene as m-dinitrobenzene. However, when this was tried with a run containing styrene, only a dark oil was obtained. It appears that some styrene distills over with the benzene and cyclohexane and interferes with the nitration. The following modification gave pure m-dinitrobenzene:

A sample containing benzene of known activity treated in this way gave dinitrobenzene with 0.528 the original activity. Had there been no exchange, the dinitrobenzene should have had 0.667 the original activity. This experiment will be repeated several times. If the amount of exchange is the same each time, the method can be used to determine the benzene yield.

The yield of benzene given in the preceding diagram was calculated assuming that the amount of exchange in the isolation run was the same as that in the trial run with benzene of known activity (if there was no exchange, the yield of benzene is 105 moles). (L. J. Schaad)

VI. COMPARISON OF HYDROXIDE AND DEUTEROXIDE ION ISOTOPE EFFECTS

The isotope effect noted in solvolysis reactions employing the deuterioxide ion in heavy water and the hydroxide ion in light water may be attributed to two causes. First, the deuterioxide and hydroxide ions possess different zero point energies and would therefore be expected to undergo reaction at different rates. Second, part of the isotope effect will be due to the fact that the two bases are solvated to different extents by the light and heavy waters. Data have been published which state that large free energy changes are encountered in the transfer of a mole of solute from one solvent to the other.

It is of interest, then, to determine whether the isotope effect in these cases is due to the greater freedom of the deuterioxide ion in heavy water as opposed to that of the hydroxide ion in light water, or whether the effect may be attributed principally to the difference in zero point energies which exists between the two bases.

The most direct manner of assessing the importance of the two effects is to perform the solvolysis reactions in a common, inert medium. The present work is directed upon these lines.
(R. F. W. Bader)

VII. ISOTOPE EFFECTS IN DECARBOXYLATION

Isotope effects are being determined for decarboxylation of dimethylacetoacetic acid (COOH and COOD) in water and benzene solutions at 35° . (R. N. Griffin)

VIII. ISOTOPE EFFECTS IN HYDROLYSIS

The isotope effect for the rate of hydrolysis of benzyl chloride has been determined at 50.45°C . The ratio of the rate in ordinary water to that in heavy water is 1.24. The determination of the isotope effect for benzyl fluoride is now in progress. Preliminary results indicate a larger effect than in the case of benzyl chloride. (A. MacLachlan)

IX. ISOTOPE AND SUBSTITUENT EFFECTS IN OXIDATION OF ALCOHOLS

The oxidation of ethanol by bromine in acidic water solutions is being studied kinetically. The reaction was found to be only about half as fast in heavy as in light water. Trifluoroethanol reacts very much more slowly. (R. A. Wiles)

X. ISOTOPE EFFECTS IN REACTIONS OF HYDROXYLIC COMPOUNDS

Deuterium isotope effects are being determined in reactions of hydroxylic compounds in order to provide an insight into the true nature of the transition states.

The first reaction to be investigated using this technique is between triphenylmethyl (trityl) chloride and methanol in benzene solution. The kinetics, first order in trityl chloride and second order in methanol, is consistent with a reaction proceeding through either a cyclic transition state or a linear one. The isotope effect clearly distinguishes these two mechanisms; the former requires that methanol react at least ten times faster than methanol-d, whereas, the latter would predict only a slight effect. The rates of reaction of methanol and methanol-d with trityl chloride in benzene solution have been determined at 25°. Although acceptable rate constants have not yet been obtained because of experimental difficulties, the isotope effect (k_H/k_D) cannot be large and is probably less than two.

The reaction is especially difficult to follow because all traces of water must be excluded. For this reason, the rates will be followed using tritium-labeled methanol with a large excess of trityl chloride, and the product, tritylmethyl ether, determined by scintillation counting. This technique is especially valuable because the kinetics can be accurately followed for methanol concentrations down to 10^{-5} M where a change in mechanism is expected. Methanol with tritium substituted on carbon has been prepared.

XI. INTRAMOLECULAR HYDROGEN TRANSFER

The study of the o-methylbenzyl system has been undertaken with the view of evaluating the involvement of the hydrogens of the O-methyl group in reactions occurring at the benzoyl position.

The preparation of o-methylbenzyl alcohol has been carried out by the carbonation of the Grignard reagent derived from o-bromotoluene to yield o-toluic acid, and reduction of the acid to the alcohol by lithium aluminum hydride. Conversion of o-methylbenzyl alcohol to the corresponding tosylate has been achieved to give 59% of pure material. Solvolysis of the highly unstable tosylate in formic acid afforded o-methylbenzyl formate, which was converted in two steps to the crystalline phenylurethane of o-methylbenzyl alcohol. When procedures for the oxidation of o-methylbenzyl alcohol to o-toluic acid and for the decarboxylation of o-toluic acid have been perfected, the above sequence will be repeated with radioactive carbon dioxide (C^{14}) in the initial carbonation reaction. (V. Zale)

XII. STUDY OF ION PAIR FORMATION IN THE DECOMPOSITION OF ALKYL CHLOROSULFITES

The decomposition of alkyl chlorosulfites to alkyl chlorides, a reaction of ionic character and greatly influenced by solvent, is being studied to elucidate the conditions under which the reaction

is intramolecular or intermolecular. The decomposition of sec.-alkyl chlorosulfites is of particular interest since this reaction has been shown to proceed with inversion of configuration. The preparation and purification of the alkyl chlorosulfites have been difficult because of the instability of the compounds but the following compounds have been prepared in analytical condition: n-butyl, n-octyl, sec.-butyl, and sec.-octyl chlorosulfites. Sec.-Butyl chloride was isolated in 32% yield from the decomposition in toluene and in 42% yield from the decomposition in dioxane. After the conclusion of the current phase on the decomposition of sec.-octyl chlorosulfite in these solvents, work will be directed towards the preparation of sec.-butyl chlorosulfite containing radioactive chlorine (Cl^{36}). (P. Zanet)

XIII. METHYL ACTIVATION IN COENZYME A-TYPE COMPOUNDS

Coenzyme A is of great current biological interest as the compound responsible for the transfer of acetyl groups in fatty-acid synthesis and possibly in protein synthesis. F. Lyman found that the activated acetyl group was present in the form of a thiolester and postulated it as a key intermediate in the fatty acid cycle. The present investigation was concerned with the mechanism of this transfer reaction, particularly the features important in "methyl activation".

Two thiazoline-type compounds, 2-methyl-2-thiazoline and 2, 3-dimethylthiazolonium iodide, which are structurally related to coenzyme A, were prepared and equilibrated with tritiated water. However, all the compounds tested, showed no detectable exchange with the tritiated water, under conditions of the reaction, thus indicating that these simple models of acetyl CoA do not possess unusually "active" or acidic hydrogen atoms on the methyl group of the acetyl function.

(G. F. Holland)

J. C. Sheehan
C. G. Swain

Cosmic Ray Group

I. INTRODUCTION

During the past year the activities of the cosmic ray group have been approximately equally divided between two fields of investigation. The first concerns high-energy nuclear interactions, with particular reference to the unstable particles produced in such interactions; the second concerns air showers. The experimental work concerning the first item has been done using both "natural" cosmic rays and artificially accelerated particles produced by the Brookhaven Cosmotron. It has been supplemented by some theoretical work concerning the interpretation of the "strange" particles and their relationship to the properties of nucleons.

With regard to the second item, it should be mentioned that the extensive experimental work has also been supplemented by theoretical computations relating the observable properties of the showers to the energy of the primary particles and to the character of their nuclear interactions.

II. OPERATION OF THE MULTIPLATE CHAMBER AT ECHO LAKE

During the past three years the primary purpose of the multiplate chamber experiment at Echo Lake, Colorado, has been the study of the properties of K-mesons; more specifically, the properties of the $K_{\mu 2}$ - and $K_{\pi 2}$ -decay modes. These are now well known and, consequently, the activity devoted to this experiment has been greatly reduced. The operation of the chamber was discontinued in February 1956, and the experimental program up to that time is described below. It is planned to resume operation of the chamber on an exploratory basis during the coming winter.

In the summer of 1955, two scintillation counters were installed inside the cloud chamber, one at the top and the other at the bottom of the illuminated region. These counters can be operated in conjunction with external counters so as to select nuclear interactions inside the chamber or μ -mesons of known energy which traverse the chamber. The nuclear interactions serve as a source of unstable particles and the μ -mesons as calibration tracks for ionization estimates. It is also possible, by the use of delayed coincidence techniques with this counter system, to select unstable particles which decay in the chamber after they have lived 10^{-9} - 10^{-8} sec. The detection system is described in detail in the Laboratory for Nuclear Science Progress Report for August 31, 1955.

In order to use the μ -meson tracks for calibration, it was found that more complete temperature control of the chamber was required. This was achieved by a water jacket around the entire chamber (see L.N.S. Progress Report for November 30, 1955).

Several thousand pictures have been taken in which the chamber is triggered by the nuclear interaction detector for about one hour, and then by the μ -meson detector for several frames. In

this way a continuous calibration of the records with respect to ionization measurement is obtained. A preliminary analysis shows that the method is a very satisfactory one, and that the operation of the chamber was greatly improved by the temperature control.

We expect that the use of calibration tracks obtained in the above way, and combined with the method of ionization measurement developed by Caldwell and Pal, Section III, will greatly extend the usefulness of the multiplate chamber. (H. S. Bridge, H. C. DeStaebler, Jr., A. Pevsner, R. A. Hewitt, G. Sandri, L. Jauneau, and W. B. Smith)

III. PHOTOMETRIC IONIZATION MEASUREMENTS

Work has been completed on a method for determining photometrically the ionization of multiplate cloud chamber tracks. A projection type of photometer is used to measure the track opacity, from which the ionization of the track is obtained by comparison with the opacity of a track of known ionization. The ratio of the properly normalized opacities of the two tracks is related to the ratio of their ionizations by a simple power law. The technique has been employed, with geometric residual range determinations, to find particle masses. It has also been used, when the mass is known, to ascertain the residual range in the plate in which the particle stops. By determining both the ionization and the change in ionization occurring in a plate traversal, both the mass and the residual range of particles have been found.

The method has been applied to measuring the range of the secondaries from K-meson decays. For four $K_{\mu 2}$ and three $K_{\pi 2}$ secondaries, the ranges in copper were 78.6 ± 1.6 and 44.4 ± 1.7 g/cm², respectively (all errors being standard deviations). These ranges yield for the masses of the primaries, $K_{\mu 2} = 952 \pm 11$ and $K_{\pi 2} = 956 \pm 11$ m_e.

The technique has been used also to determine directly the mass of a particle which was observed¹ to traverse five 1/2-inch brass plates, stop in the sixth, and give rise to three electron showers having a total energy greater than 1.6 Bev. From the energy release, this particle had to be either a very heavy boson (mass > 3200 m_e), or an antiproton (mass = 1836 m_e), or possibly an antihyperon. The mass determination from the ionization and residual range of the particle gave 1610 ± 300 m_e, showing that this particle was almost surely an antiproton, and probably the first example ever observed.

The details of the technique will appear in the Review of Scientific Instruments, and further details of the antiproton event will be found in The Physical Review². (D. O. Caldwell and Y. Pal)

IV. OPERATION OF THE MULTIPLATE CLOUD CHAMBER AT BROOKHAVEN NATIONAL LABORATORY

A. Introduction

The initial setup of the large multiplate chamber at the cosmotron was completed last fall. Since that time, the experimental program has been devoted to improving the operation of the chamber, obtaining satisfactory operation in conjunction with the cosmotron, and to the collection of experimental data.

The illuminated volume of the chamber is about 54" $\times$ 48" $\times$ 20" and it contains 17 plates of 1/2" steel. The experiment is set up in a shielded, temperature-controlled room approximately fifty feet from the machine, and it is possible to direct a beam of protons or of π^- -mesons through the chamber. The particles pass through the fringing field of the cosmotron and emerge via a collimating channel in the shielding of the machine. Close to the exit of this channel there is an analyzing magnet which deflects the beam about 70° so that particles of the desired energy are directed through the chamber. During normal operation the cloud chamber operates in conjunction with other experiments and accounts for 2 to 4% of the total operation time of the cosmotron.

For example, in a typical run the chamber is expanded every three minutes or roughly once every 25 machine pulses, and the operating conditions of the cosmotron are adjusted to the cloud chamber requirements for the particular pulse which precedes the expansion of the chamber. Usually this "programming" operation controls the following parameters: target position, machine energy, pulse length and intensity.

During the past six months an additional multiplate chamber has been installed at the cosmotron by the Princeton group. The two chambers are usually operated during the same cosmotron time and their functioning is closely interrelated.

This arrangement can be used because the chambers are located about 12 feet apart. It is thus possible to use the "same beam" of particles for both chambers simply by reversing the field of the analyzing magnet so as to deflect the beam into the desired chamber. In practice, the polarity and current of this magnet are controlled by the "programming" control of the cosmotron.

B. Technical Problems Concerning Cloud Chamber Operation

There have been three main problems associated with the operation of the cloud chamber itself: 1) the illumination was unsatisfactory; 2) a great deal of difficulty has been experienced in constructing a piston which operates for a long time and remains gas tight; and 3) during continuous operation the temperature gradient across the chamber increased to a point at which satisfactory operation could not be maintained. A brief account of the work done on these problems during the past year is given below.

1. Illumination.

The chamber is illuminated from the sides, using two sources on each side. Each source consists of a flash lamp 60" long, operated at an energy input of between ten and fifteen thousand joules. Behind each lamp there is a cylindrical reflector of parabolic cross section formed from high reflectivity aluminum sheet (Alzak).

After the first run it was apparent that particle tracks at minimum ionization could not always be followed with certainty, and that this difficulty was caused by lack of contrast rather than by insufficient illumination. This lack of contrast resulted from light scattered from the metal surfaces of the reflectors onto the velvet and front glass; to remedy the trouble the light sources were moved back 14 inches. At this position the surfaces of the reflectors cannot be seen from the piston or front glass and the contrast of the pictures is much improved.

The optical system used to illuminate the chamber employs cylindrical rather than spherical symmetry and, consequently, the light beam shows convergence only in the vertical plane, in the horizontal plane the beam diverges. Therefore, moving the light source away from the chamber is inefficient from the standpoint of intensity, since a large amount of light escapes from the two ends of the source instead of entering the chamber. This light can be reflected back into the chamber by using mirrors at the top and bottom of the source, but the reflector surface is then partially visible from the velvet and front glass. A more promising approach is to use reflectors which scatter a negligible amount of light. The only practical material which is smooth enough for this purpose is polished glass, and since the precise optical figure is not of primary importance, we are investigating the possibility of fabricating reflectors by bending plate glass over a suitable mold. The work is being done commercially, and an experimental reflector is being tested.

2. Pistons.

During the past year a large amount of work has been done in an effort to construct a satisfactory piston. Although the first piston developed operated well for several months, additional pistons constructed in a similar way proved unsatisfactory because of leaks, and we have not yet arrived at a really good design.

In general, two methods of constructing pistons for expansion chambers have been used by various workers. Both employ a rigid piston which is connected to the chamber at its edges by means of a rubber ring. The ring provides a gas-tight seal and allows the piston to move the required amount. In one design the ring is a separate piece of rubber bonded or clamped to the piston along one edge and to the chamber walls along the other edge. The other method of construction is to sandwich a metal plate between two slightly larger rubber sheets. So far we have used only the first method of construction.

Most of our difficulties with these pistons have resulted from the fact that large single sheets of rubber (60 × 72 inches) have been unavailable and we therefore made use of spliced sheets which almost always failed at the vulcanized joints after a short period of operation.

However, we have recently obtained a rubber sheet of the necessary width and with it are constructing several pistons which should prove satisfactory.

In addition to problems connected with the mechanical construction of the piston, we have made some studies of the behavior of rubber-edge ring during the expansion. Under some conditions the motion of the ring gives rise to localized fog which does not affect the picture quality but is undesirable, since additional cleaning expansions are required for its removal.

Suppose we denote the direction of piston motion during the expansion by χ and call the origin of the coordinate system the position at which the rubber ring is clamped into the chamber walls. Then, according to the original design, the piston moves during an expansion symmetrically about the origin from $-\Delta$ to $+\Delta$. At $\pm \Delta$ the rubber is stretched about 50% of its original length and is under considerable tension, while at the position 0, it is unstretched and essentially free. Now consider the motion of the rubber during the expansion and neglect the tension forces. The pressure over the piston and ring is essentially constant during the expansion but the mass per unit area of the piston is greater than that of the rubber by a factor of about four. Thus one expects that the acceleration of the rubber will be about twice that of the piston. The tension forces reduce this effect at the beginning and end of the expansion but in the region $\sim \chi = 0$, the rubber apparently moves faster than the piston and gives rise to fog. It was pointed out to us that this effect could be controlled by proper mass loading of the rubber³. We have made some tests of this method with encouraging results.

However, we have also been able to control the motion of the rubber by allowing the expansion to take place from 0 to $+2\Delta$ rather than from $-\Delta$ to $+\Delta$. In this way the tension in the rubber does not change sign, and the ring does not tend to "snap" as the piston passes 0. In order to make this change in operation, additional depth behind the piston was required. This was obtained by installing a spacer ring of the proper thickness. Although the operation of the chamber has been improved by this change, difficulties with the piston construction have increased because ~ 100 percent elongation of the rubber is necessary.

3. Temperature gradient.

During the first period of extended operation with the cosmotron, it was noticed that to obtain satisfactory tracks the expansion ratio had to be increased with time and that the chamber operation became unsatisfactory after four to six hours. A temperature gradient was suspected, and thermocouples were installed on the chamber to check this possibility.

There are two causes of such a temperature gradient. Under the influence of gravity, drops fall to the piston and evaporation of liquid at this point cools the bottom of the chamber. In addition, the energy input from the flash lamps heats the plates and gas. Using the thermocouples, it was found that a gradient of 0.75°C resulted from the mass transfer and that an additional rise of 1.0°C resulted from operation of the lamps. These figures are for a 2.5 minute cycle. It is completely impossible to operate the chamber satisfactorily with a temperature gradient greater than 0.75°C ,

and, accordingly, sheets of heat absorbing glass were installed in front of the flash lamps and were air cooled by blowers. This technique eliminated the 1.0°C temperature rise caused by the lamps and greatly improved the operation of the chamber.

4. Optical system and reprojection equipment.

The cameras have been slightly redesigned so that vacuum backs could be installed. This ensures that the film plane is flat and reproducible.

Two sets of reprojection equipment, each consisting of three projectors, were constructed. Initially, one apparatus was set up at M.I.T. and one at B.N.L. In preparation for the expanded analysis program this summer both sets of equipment have now been installed at B.N.L.

C. Experimental Data and Machine Conditions During Operation.

Actual operation of the chamber during the past year has been divided roughly into three periods. During the first period approximately 600 pictures were taken using the proton beam (energy 2.6 Bev) and during the second two periods about 3000 pictures were obtained using π^- mesons. In the first run the picture quality was extremely variable and most of the data was not useful for analysis. Since then, the technical quality of the photographs has been gradually improved and at present, from the standpoint of quality, most of the pictures are satisfactory for analysis. In spite of this fact only about half of the data in a run (during which the cloud chamber operation is completely satisfactory) is useful because the beam intensity of the cosmotron fluctuates so much that there are either too few or too many particle-tracks in the chamber. The intensity of the cosmotron can be controlled via a circulating beam monitor and proportional noise feedback into the rf accelerating voltage to produce a constant circulating beam. Unfortunately, this system does not always operate well in the region of low intensity required for satisfactory cloud chamber operation (10^7 to 5×10^8 protons per machine pulse), and it also fails if the external beam intensity is critically dependent on other variables than the intensity of the circulating beam. A more detailed account of the experimental conditions during the proton and negative π meson runs follows.

1. Proton runs.

The so-called proton "blow-up" beam is obtained by causing the radius of the circulating proton orbit to increase suddenly at the end of the accelerating cycle, while introducing an asymmetry in the magnetic field by shorting the correcting windings in one quadrant. Under these conditions a small fraction of the internal beam escapes tangentially from the vacuum chamber near the south straight section. Several hundred Mev are lost because the particles pass at glancing angles through the vacuum chamber walls. The final proton energy was determined to be around 2600 Mev.

The characteristics of this beam were measured by a scintillation counter telescope, which was also used during the actual running time for an intensity monitor. Monitoring is required because the number of protons thrown from the internal orbits depends markedly on the cosmotron

operating conditions.

The beam was found to be quite homogeneous in energy with very low background, and was emitted within a very short time interval at a point in the acceleration cycle which depended on the exact operating conditions. The time at which the protons were emitted was frequently checked, and the chamber set to expand 30 milliseconds in advance of this for optimum tracks.

The orbits of the protons as they leave the machine and are slightly deflected by the fringing field have been calculated by R. M. Sternheimer, so that it is possible to select with a six-inch collimator in the main shielding that part of the beam which suffered the least amount of degradation in the vacuum chamber walls. The beam is deflected by a magnet outside the shielding through an angle of 7° and enters the chamber 35' away with a width of 12 inches. The intensity of the circulating beam is adjusted to give about 12 protons in the chamber per expansion; however, this number often exhibits severe fluctuations. Because of the very low internal intensity required, and because the blow-up proton intensity changes with respect to the internal intensity, it was not possible to use the feedback intensity control during the proton runs.

2. Meson runs.

Pi-mesons are obtained from a rammed target located in pump station No. 10 (downstream from the south straight section) which is bombarded by protons in the usual manner by collapsing the internal beam onto the target. Forward π -mesons of 1.9 Bev are deflected outward and partially analyzed by the internal magnetic field of the machine. The beam is collimated by a 12" channel in the main shielding and deflected about 7° by a magnet. Because the angle and location of this beam differs from those for the proton beam, it is necessary to relocate the chamber (relative to the position for proton operation) to allow 7° deflection and to insure that there is no direct path from the cosmotron to the chamber.

The π^- target consists of aluminum, one-inch square in cross section, and four inches thick in the beam direction mounted on a solenoid operated ram which had a stroke of 1-1/2 inches. The solenoid was later replaced by a pneumatic cylinder with a 5-inch stroke. The longer stroke permits operation with the external proton beam deflecting magnet in place at a radius several inches greater than the inside wall of the vacuum chamber. Because of the increasing amount of running concurrent with external beam experiments, this facility is quite important.

The π^- beam emerges from the machine consistently 10 milliseconds after the rf accelerating voltage turnoff and the chamber receives a trigger pulse 30 milliseconds before beam particles are expected to enter the chamber. The intensity of the mesons is directly related to the internal circulating proton intensity, so that a certain measure of control can usually be obtained by means of the feedback internal intensity control.

In the past three months approximately 2400 pictures taken with the π -meson beam have been scanned carefully once through. Eighty-five certain neutral V-particles have been found, while no charged K meson has been surely identified; of the 85 events mentioned above, 5 involved

production of two neutral V-particles. Preliminary Q-values have been obtained for some of the Λ^0 -events and further analysis is in progress. (H. Blumenfeld, H. S. Bridge, E. Boldt, L. Jauneau, and B. Rossi - M.I.T., in collaboration with C. Leavitt - B.N.L.)

V. SOUTHERN HEMISPHERE AIR SHOWER MONITOR

Installation of the equipment to monitor air showers of total energy around 10^{14} ev to 10^{15} ev was completed at Chacaltaya (Bolivia) in the fall of 1955. Hourly records of three-fold and four-fold coincidences of Geiger trays, and the individual rates of two of the trays, are made photographically, along with time, pressure, and temperature. The usual difficulties of start-up were encountered and have mostly been overcome, except that the source of fluctuations in the single rates has not been found (see below).

The most interesting result so far has been the information afforded by this apparatus on the great cosmic-ray increase of February 23, 1956. We know of only one other station (Huancayo) which has a similarly low geomagnetic latitude and high altitude.

(a) The shower rate showed no noticeable change at the time of the flare; the rate of three-fold coincidences is ~ 560 c/hr. and is recorded hourly, so this merely means that any increment, averaged over one hour, was less than $(\sim 300/\sqrt{560}) = 13$ percent for events of $\sim 10^{14}$ ev. No increase was expected at this energy, of course.

(b) As previously mentioned, the monitor also records hourly the total component of cosmic rays as indicated by the total counting rate in two of the (unshielded) trays, each of 0.11 m^2 area. As shown in Table 4.I, both trays showed an increase of 3.8 percent in the hour from 0300 to 0400 UT February 23, with the following hour being nearly back to normal (0.7 percent above the rate for the hour from 0200 to 0300). The flare maximum was at 0350. The statistical standard deviation is 0.16 percent, and the barometer correction (which has not been made) would be less than $1/2$ percent over the period covered. However, the apparatus is not yet entirely reliable and its behavior is not well understood -- these single-tray rates fluctuate far beyond statistics, more or less as though some variable radioactive background might be present (as it often is in the mountains). We have included in Table 4.I a huge fluctuation (~ 3 percent) of this kind for which we have at the moment no other explanation. We therefore feel that the flare indication is not reliable, and we do not plan to publish it. It serves as weak confirmation of the Huancayo results. Our 3.8 percent should presumably be multiplied by about 5 or 6 to give the increase at the flare maximum, since there was about 12 minutes of activity in that hour. At these altitudes the total component has a latitude effect of $(I_{50^\circ}/I_{0^\circ}) = 1.3$, so we look at a much higher average energy than does the nucleonic component.

We, therefore, confirm the observations at the Huancayo laboratory that there was an appreciable source of cosmic rays of at least 2×10^{10} associated with this flare. There was no measurable source at $\sim 10^{14}$ ev.

The monitor in Colorado, which is similar to the Chacaltaya one, has been inactive, awaiting the return of intense solar activity. We plan to reactivate it this summer.

TABLE 4.I

Counting rate, counts per hour divided by 256, for two independent unshielded Geiger trays at 5,300 in elevation, geographic latitude 16°S , longitude 68°W on February 23, 1956.

<u>Time (UT)</u>	<u>Tray I</u>	<u>Tray II</u>
0000 to 0100	1584	1661
0200	1563	1639
0300	1560	1635
0400	1620	1697
0500	1569	1648
0600	1532	1617
0700	1530	1616
0800	1534	1621
0900	1535	1616
1000	1533	1613
1100	1529	1607
1200	1538	1616
1300	1531	1620
1400	1564	1643
1500	1599	1665
1600	1606	1673
1700	1607	1676

(R. W. Williams in collaboration with I. Escobar and R. Palmeira of the Laboratorio de Fisica Cosmica of Bolivia)

VI. A LARGE MESON TELESCOPE

We have proceeded with the design and construction of a large meson telescope, about 10 m^2 in area, consisting of polystyrene-terphenyl scintillator disks, cast in 1 m^2 sections as described elsewhere in this report. Our expected counting rate of ~ 1000 counts/sec. will give us a statistical accuracy of about 0.3 percent in each 120 second interval.

We have designed, and for the most part constructed, the circuitry for the counting rate recording apparatus, and are now testing the various components.

The coincidence signals over successive electronically timed intervals are totalled on three binary scalers connected in series, and electronically reset at the end of each interval. The second of these scalers can produce at a given signal a voltage accurately proportioned (by better than 1/4 percent) to the total number of counts recorded by this scaler at the instant (within 1 μ sec.) of the "record" signal. The third scaler gives an indication whenever it runs over the expected number of counts for an interval. The voltage levels produced by the second scaler and the over-scale indications of the third scaler are recorded by a moving pen-type indicator.

Let us take, as an example, our expected counting rate of 1000 c/sec. totalled over 120 seconds, by our three scalers, of 128, 128, and 64 respectively. The first scaler will record from 1 - 127, the second from 128 to about 16,000, and the third from about 16,000 to about 10^6 counts. With the expected average number of counts being 120,000 in each interval, the third scaler will usually total about 115,000 counts, letting the second scaler count and record to better than 1/10 percent of the total, the number of counts in excess of 115,000, up to 131,000. If the number of counts runs over 131,000, the second scaler will instead record this excess from 131,000 to as high as 147,000, and the third scaler will record the overrunning. Thus the recording system can never run off scale, and has a counting range of about 14 percent without rescaling.

Amplifiers, discriminators and a coincidence circuit have been obtained, and it is hoped that we can commence counting with a small (1 m²) telescope shortly, so as to record any further large cosmic-ray increases such as that of the solar flare of February 29 of this year.

Work is continuing on determining the optimum final counter geometry and in checking and improving the accuracy and reliability of the counting circuitry. (R. D'Arcy, R. Morley, and R. W. Williams)

VII. HIGH-ENERGY CROSS SECTIONS

The equipment described in the last Laboratory for Nuclear Science Annual Progress Report (May 31, 1955) to measure the collision cross section of Fe for protons at energies $\sim 10^{11}$ ev was set up and operated during the summer of 1955. A diagram of the apparatus is given in the L.N.S. Progress Report of November 30, 1955; essentially the principle is that of the collision cross section measurements which have been made at lower energies, depending on Geiger-counter hodoscope discrimination to analyze the events. Our energy discrimination depends on the use of the large rectangular ion chamber described in the previous Annual Report.

The results of the summer's run have yielded a preliminary cross section, for Fe, which is smaller than we had anticipated on the basis of other results. In terms of mean-free path, if E is the energy released in a nuclear collision and t is the elasticity of the collision, and therefore $\frac{E}{1-t}$ is the energy of the initiating particle, we find

$$\begin{aligned} 60 < E < 120 \text{ Bev: } \lambda &= 151 \pm 19 \text{ g/cm}^2, \\ E < 120 \text{ Bev: } \lambda &= 127 \pm 25 \text{ g/cm}^2. \end{aligned}$$

The number which would correspond to the "standard" result for Pb (164 g/cm^2) is 115 g/cm^2 of Fe.

The experiment is now being commenced, with some improvements, to obtain sufficient statistics this summer for a decisive answer to the question whether or not the cross sections experience a pronounced rise at high energies. (A.E. Brenner, A. J. Morency, and R. W. Williams)

VIII. AIR SHOWER EXPERIMENT

It will be recalled that the original experiment was designed to detect air showers having numbers of particles in the region $3 \cdot 10^5$ to 10^8 particles. For this purpose 20 one-square-meter liquid scintillation detectors were disposed over an area of some 40 acres. A year ago the principle items of equipment had just been installed at Agassiz Station at Harvard, Massachusetts. Before the experiment could start, considerable effort had to be spent on calibration and in learning how to monitor the equipment. The experiment started in July 1954 and ran for a short period. Following a fire in August 1955, the number of detectors was reduced to eleven. The sensitivity of the experiment to large showers was unimpaired by this change, but showers in the region $3 \cdot 10^5$ - $5 \cdot 10^6$ particles were too small for satisfactory measurement.

Operation, with the eleven detectors, was resumed in late January, 1956. Pulses indicative of ten or more particles per square meter in at least three of the eleven detectors serve to trigger the apparatus, and the pulses from each of the eleven detectors are displayed on oscilloscopes and photographed. From measurement of the relative time of each pulse, we deduce the direction of arrival of the shower, and from the pulse heights we deduce the location of the shower core and number of particles in the shower.

Hence, data taken to date pertain to large showers. Four additional detectors are currently being added, and a month's running should give us all the information we desire on small showers.

Discussed below are first, some details of the equipment operation and instrumentation, and secondly a preliminary analysis of a portion of the data.

To calibrate a detector we measure the average size of the pulses produced when single cosmic-ray particles go through the scintillator. Geiger counter trays are placed above and below the tank to select the single particle events. A portable circuit transmits a signal to headquarters when it detects a coincidence, and that signal causes the accompanying detector signal to be measured.

It had been planned to transmit the coincidences by radio, but noise interference was more of a problem than had been expected. The idea of radio telemetering was dropped, and inexpensive parallel-wire cables were installed to provide a second link between each detector and headquarters. The change proved to be more than worth-while. Besides solving the problem of transmitting coincidence signals for calibration, the auxiliary lines allow communication by sound-powered telephone.

between all points on the array. Recently the portable coincidence circuit has been rewired so that it receives most of its power from headquarters via the same auxiliary line over which it is transmitting.

At headquarters, the individual pulse-height measurements and most of the arithmetic involved in finding an average pulse height are performed electronically by an instrument we developed for the purpose, a "pulse height integrator". When gated by a coincidence pulse, it converts the accompanying voltage pulse from the detector to a time interval, measures the time interval, and adds the result to the sum of previously measured pulse heights, using binary arithmetic.

The integrator has given good service. However, calibrating eleven detectors by the present method is not trivially easy, and the accuracy of the results is not all that we could wish for. We can only afford to calibrate every two or three weeks. Figure 4.1 shows typical results on calibration for a period of about three months. Perhaps the simplest interpretation is that individual calibrations have a probable error of about 10 percent. That figure would not be unreasonable. It is possible that there are real secular variations in detector sensitivity. As to that, we can only say that the average fluctuation or drift over the three-month period was less than we could measure.

Figure 4.1

Calibration record for ten air shower detectors, February 17 - May 18, 1956.

The detectors will soon be improved by substituting 5-inch photomultipliers for the present tubes, which have photocathodes 2 inches in diameter. The change will make possible a simpler and more accurate calibration technique.

It was mentioned in a previous report that space charge limiting in the photomultipliers will cause systematic errors in shower density measurements for large densities. It was found that under the present conditions of operation, the error should be negligible for densities less than 100 particles/m². However, measurements of density larger than 1000 particles/m² could be seriously in error. Because shower cores rarely strike very near our widely spaced detectors, most of the pulses we record correspond to densities less than 100 particles/m². But the larger the shower, the more we need to rely on measurements where the density is larger than that.

To remedy the situation we must reduce the photomultiplier gain. Improving the impedance match between multiplier and coaxial cable would allow us to do so and still retain an acceptable ratio of signal to noise. At present, 98 percent or more of the signal is lost because of the poor impedance match. The possibility of using pulse transformers is being investigated.

The main instrumental problem in determining directions of arrival for air showers was to equalize the time delays between production of a pulse in one of the detectors and deflection of the trace on the corresponding cathode-ray tube. Appreciable delays occur in the coaxial cables and in various delay lines associated with the amplifiers. Altogether there are four sets of delays that had to be made equal. One line of a set was chosen as a standard and the others trimmed to give equal delay within $\pm .02$ microsecond.

As soon as the large array was put into operation trouble was encountered from radio noise picked up by the coaxial cables. Most of the time the noise picked up by the coaxial cables is about equal to the noise that originates in the amplifiers, but there are occasional bursts of "static" much larger. Like the pulses from an air shower these noise pulses arrive coherently from the various cables. Thus they could trigger the equipment and get recorded. The distribution of Fourier components in the noise pulses is so unlike that in the scintillation counter pulses that the possibility of mistaking one for the other is very remote, but at times the noise could trigger the equipment at an intolerable rate.

To avoid this, we added to the equipment a noise blocking device. A dummy cable is used to detect the noise. Pulses large enough to cause trouble generate a gating signal which lasts for a few milliseconds, about the duration of individual bursts. While it lasts, the gating signal prevents the air shower equipment from triggering. The device has proved to be quite efficient. False triggers can be held to a rate of less than one per hour during periods when the noise rate is greater than one per second, and even during such a noisy period the equipment remains sensitive to air showers about 98 percent of the time.

The periodic calibrations are supplemented by a continuous record of the behavior of each detector. In order to trigger the equipment, a shower must produce signals exceeding a certain

size in three or more detectors. Thus, in each channel there is an amplitude discriminator set to trigger on signals that correspond to densities of 10 particles/m^2 or more. To monitor the detectors those discriminators are connected to a multi-channel pen recorder. The counting rate for "ten particle" pulses is about 3/minute. We are reasonably sure that most of the pulses are produced by cosmic rays, although in some cases there may be a contribution from noise of one kind or another. So far, gross irregularities in the monitor record have usually been traced to faults in the monitor circuits, but on other occasions they have given valuable early warning of more serious troubles. It is possible, and even likely, that the monitor rate is a quantitative measure of detector sensitivity; that for equal counting rates the sensitivity is proportional to the bias voltage. The rapid variation of counting rate with bias in this region, which might be used to advantage if that were known to be true, is an obstacle to testing whether it is indeed true. So is the slow rate.

While the experiment was designed primarily with the purpose of investigating problems related to cosmic ray origin, the data accumulated and analysis made to date bear mostly on shower structure.

Particularly interesting are the measured structure functions, or lateral distributions of electrons in the showers. So far as we know, these are the first measurements of shower structure that pertain to individual showers. That is, measurements of shower structure in the past have relied upon statistical arguments and have involved averages over many detected showers. Furthermore, our measurements refer to the electron density distribution in a plane perpendicular to the shower axis. We are able to present the data in this form, of course, because we measure the direction of the shower axis in every case.

Measured electron densities as a function of the distance from the shower core for six showers that arrived from near the zenith are shown in Figure 4.2. Figure 4.3 is similar to Figure 4.2, but these six showers arrived from rather large zenith angles. The solid curves drawn on each graph are theoretical distributions for pure electron or photon initiated cascades, and were obtained by Nishimura and Kamata for a shower age parameter, S , of 1.4. (The choice of this value of S was somewhat arbitrary, and probably fair fits could be obtained also for $S = 1.2$.) One shower, it will be noticed, has a lateral structure that is much less steep than the others. If heavy nuclei rather than protons were responsible for these large showers, one would expect such flattened electron distributions. But there are many other possible causes of such flattening.

The zenith angle distribution for a group of showers having $N_0 = 2 \times 10^6$ or more particles is shown in Figure 4.4. (See p. 74.) We have fitted this observed distribution to a function of the form $\sin \theta \cos \theta \exp(-K/\cos \theta)$, and find K to be about 9. A simple interpretation of the physical significance of K is possible if one makes a few rather reasonable assumptions. Under these assumptions K is $n x_0/\beta \lambda$, where n is the exponent in the primary integral energy spectrum, x_0 is the (vertical) atmospheric depth, and β and λ have meanings that are made clear by noting that we have assumed that the number of electrons in a shower is proportional to $U^\beta \exp(-\frac{x_0}{\lambda \cos \theta})$ where U is the

Figure 4.2

Measured lateral distribution of electrons in six large showers that arrived near the zenith. The solid line is the theoretical distribution for pure electron cascades with $S = 1.4$.

Figure 4.3

Measured lateral distribution of electrons in six large showers that arrived at large zenith angles. The distributions are in a plane perpendicular to the shower axis, and the solid lines are for $S = 1.4$ as in Figure 4.2.

primary energy. If we take $K = 9$, $n = 1.7$, $\beta = 1$ and $x_0 = 1045 \text{ g cm}^{-2}$, we find λ to be about 200 g cm^{-2} , corresponding to a shower age parameter, S , of 1.2. The showers we detect, then, are relatively "young", and certainly do not originate from a single high-energy electron or photon at or near the top of the atmosphere. These measurements are consistent with the physically more reasonable view of high energy electrons and photons being fed into the shower by the nuclear interacting particles as they cascade down through the atmosphere.

Additional information on the nucleon cascade can be obtained from a study of the μ mesons that accompany the electrons in the showers. The μ mesons are one step less far removed from the fundamental nuclear interactions than are the electrons and photons. This is not to say that the μ mesons are as directly related to the nucleon interactions as one would wish, but they do seem to offer one of the very few tools we have for the study of the very high energy interactions. Apparatus has been prepared for the study of these μ mesons and their lateral distribution in the showers. It consists of a very large hodoscope, 1 square meter in area, embedded in lead. It is being located near the center of the existing shower array.

One of the first uses of this hodoscope will be to make a direct comparison of the response of our plastic or liquid scintillation detectors with G.M. counters for shower electron density measurement.

In the course of analyzing a portion of the shower data, we have considered the measured response of detectors that were at roughly equal distances from cores. Averaged over many showers, these responses should be, and were, the same. In individual cases there were fluctuations, and we find that these fluctuations are not greatly different from pure Poisson. The particles in a shower, of course, are genetically related and so fluctuations on the one hand might be expected to be greater than those for a Poisson distribution. On the other hand, our detectors respond to photons as well as electrons, and a pulse indicative of the passage of say 50 electrons through the detector may in fact be due to a smaller number of electrons and a rather large number of low energy photons that are converted in the scintillation material. This could tend to produce fluctuations less than those for a Poisson distribution. This matter is largely of technical interest, since it affects the design and inherent resolution of our and other experiments.

As mentioned previously, each of the scintillation detectors in the main experiment is connected to recording equipment to give a permanent and continuous record of the performance of the apparatus. Recorded for each detector is the rate of events indicative of more than some 200 Mev energy dissipation, which for shower measurements means a nominal 10 particles per square meter. The very large solar flare that occurred at about 0340 (UT) on February 23 produced a large increase in the rate of events recorded in our detectors. The increase started at 0350, and reached a maximum amplitude of 3 to 4 times the normal background rate. The increase was not unlike those recorded in other parts of the world. It is believed that the particles responsible for the cosmic ray increase were protons (1 - 20 Bev) and if this is so, our detectors

were probably detecting stars and other relatively low energy nucleon phenomena. (B. Rossi, G. W. Clark, J. Earl, W. L. Kraushaar, J. Linsley, and F. Scherb)

IX. ARRIVAL DIRECTIONS OF AIR SHOWERS

The arrival directions of over 3,000 air showers have been determined in a continuing survey at M.I.T. with fast timing equipment. So far no statistically significant celestial anisotropy has been found.

An improved version of the fast timing equipment has been completed and shipped to Kodaikanal, India, where the survey of arrival directions will be extended to 20° south latitude in a cooperative program with Dr. Vikram Sarabhai of the Physical Research Laboratory at Ahmedabad. The improved version utilizes plastic scintillators and high gain photomultipliers and these features have made possible a considerable simplification in the associated electronic equipment through the elimination of fast amplifiers. Figure 4.5 is a photograph of the new apparatus. A block diagram of the electronic arrangements and the circuit used for the detection of 4-fold coincidences and for the addition of the pulses are shown in Figure 4.6.

Figure 4.6

Block diagram of the electronic arrangement of the apparatus described in Figure 4.5.

(G. W. Clark, and R. A. Hewitt)

X. CALCULATIONS ON HIGH-ENERGY COSMIC-RAY CASCADES

1. Longitudinal Development of Large Air Showers.

The general solutions describing the longitudinal development of the high-energy N-component (see L.N.S. Annual Progress Report, May 1955) have been employed for numerical

Figure 4.5

Photograph of the new apparatus for the determination of shower arrival directions by part timing. This apparatus is currently being installed at Ahmedabad, India.

computations of various measurable quantities. The calculations have been carried out for several variants of the two general classes of models: the first class assumes totally inelastic nucleon-nucleon collisions with a Fermi-type multiple production of mesons, the second class assumes partially elastic collisions, allowing not only for a (reduced) multiple meson production, but also for retaining of a sizable (constant) fraction of the collision energy among the colliding particles. Among the computed quantities the following two have been studied in most detail: (a) the relation between the sizes of the large vertical air showers and the energy of the primary initiating particle; (b) the zenith angle dependence of large air showers. The results pertaining to the first relation turned out to be quite similar for all models considered. In the region of the primary energies, E_0 , between 10^{16} ev and 10^{19} ev, the size of the vertical shower, N , increases with E_0 as E_0^σ where σ is in the vicinity of 1.10 with some slight model-dependent variations. Also, the energy per electron, ΔE (defined so that $\Delta E \cdot N = E_0$) ranges only between 5 Bev and 8 Bev at $E_0 = 10^{16}$ ev for all models. On the other hand, the zenith angle dependence of large air showers, initiated by primary particles of the same energy, displays a quite different behavior for different models. The experimental data of the zenith angle dependence of N allow one to derive directly the fraction of electrons absorbed per radiation length $-(1/N)(dN/dt)$. The theoretical expression of this quantity turned out to be particularly sensitive with respect to the elasticity parameter characterizing the nucleon-nucleon collisions. The existing experimental data on $-(1/N)(dN/dt)$, although very crude at present, seem already to be sufficient to rule out the possibility of totally inelastic collisions of the Fermi type. However, in order to obtain a precise value for the elasticity parameter, one needs also some additional (still lacking) experimental data on the energy distribution of the N -component. If these data were available, one could narrow down the ambiguity of choice between the remaining possible variants of the partially elastic models.

2. Lateral Distribution of μ -Mesons Associated with Large Air Showers.

In addition to the quantities mentioned in the preceding paragraph, the lateral distribution of μ -mesons associated with large air showers has been studied theoretically in some detail (see LNS Progress Report, February 29, 1956). Explicit numerical results have been obtained thus far for the limiting model, in which we assumed that the observed lateral spread of μ -mesons is due entirely to their multiple coulomb scattering in the atmosphere. This assumption should be valid to a high degree of accuracy for models of π -meson production suggested by Heisenberg and Landau, because they predict an exceedingly small angular spread of π -mesons in the laboratory frame of reference (a fraction of a meter at sea level). The normalized lateral distribution of μ -mesons thus obtained turned out to be considerably broader than the Nishimura-Kamata distribution for electrons. Its broadness and shape seem to be in agreement with the existing experimental data. Among other features of the distribution, the following are worth mentioning: It is almost completely independent of the energy of the primary particle initiating the shower, and it depends only weakly on the assumed longitudinal behavior of the source function for μ -mesons (i.e., the decaying π -meson spectra associated with large air showers).

The summary of the topics outlined in the above paragraphs has been prepared for publication. (S. Olbert)

XI. HEAVY MESONS AND THE ELECTROMAGNETIC PROPERTIES OF NUCLEONS

The hope that the unstable hyperons and K mesons found in cosmic radiation may contribute in a significant way to our understanding of nuclear phenomena is strikingly supported by an analysis of the electromagnetic properties of nucleons. The charge and current distributions in the neighborhood of the proton and neutron have been probed with great ingenuity by means of external electric and magnetic fields ⁴⁻⁹ yielding accurate values for the "anomalous" magnetic moments and the electron-nucleon interactions.

These anomalous properties of the neutron and proton cannot be understood on grounds of the Yukawa theory alone, but a consistent use of the known properties of the "new unstable particles" allows for a very natural interpretation of the available information.

The outstanding properties of hyperons and K mesons are the conservation of strangeness and the symmetry in the two possible parity eigenvalues in the strong interactions responsible for their production¹⁰.

Conservation of strangeness and of the parity symmetry quantum number¹¹ permit the following virtual disintegrations of the nucleons.

$$\begin{array}{l}
 N \rightarrow \left\{ \begin{array}{l} p^+ + \pi^- \\ \Sigma^- + \theta^+ \\ \Sigma^{-'} + \tau^+ \end{array} \right\} \text{P state} \\
 \left\{ \begin{array}{l} \Sigma^- + \theta^+ \\ \Sigma^{-'} + \tau^+ \end{array} \right\} \text{S state} \\
 \left\{ \begin{array}{l} \Sigma^{-'} + \theta^+ \\ \Sigma^- + \tau^+ \end{array} \right\} \text{P state}
 \end{array}
 \qquad
 \begin{array}{l}
 p^+ \rightarrow \left\{ \begin{array}{l} N + \pi^+ \\ \Sigma^+ + \theta^0 \\ \Sigma^0 + \theta^+ \end{array} \right\} \text{P state} \\
 \left\{ \begin{array}{l} \Sigma^0 + \theta^+ \\ \Sigma^{0'} + \tau^+ \end{array} \right\} \text{S state} \\
 \left\{ \begin{array}{l} \Sigma^{0'} + \tau^+ \\ \Sigma^{+'} + \tau^0 \\ \Sigma^{0'} + \theta^+ \\ \Sigma^0 + \tau^+ \end{array} \right\} \text{P state}
 \end{array}$$

while the reactions

$$N \rightarrow \begin{cases} \left. \begin{array}{l} \Sigma^+ + \theta^- \\ \Sigma^+ + \tau^- \end{array} \right\} \text{S state} \\ \left. \begin{array}{l} \Sigma^+ + \theta^- \\ \Sigma^+ + \tau^- \end{array} \right\} \text{P state} \end{cases}$$

are forbidden.¹²

The experimental results of Hughes, et al. on the scattering of slow neutrons by electrons, in conjunction with Foldy's phenomenological analysis, indicate that most of the electron neutron interaction is due to the neutron magnetic moment, the effect of the charge distribution lying between $-.2$ and $+.6$ kv. On the other hand, the relativistic perturbation treatment with PS(PS) coupling of π mesons to nucleons yields an electrostatic contribution of -1.3 kv, if the coupling constant is adjusted to give the observed magnetic moment of the neutron.

Interactions leading to the processes (1) are expected to reduce the electrostatic contribution to the electron-neutron interaction while maintaining the interpretation of the experiments of Hofstadter, et al. on electron-proton scattering in terms of extended charge and moment distributions. Assume for simplicity that the K particle has spin 0. The K, therefore, interacts with the Σ -nucleon fields with a scalar or with a pseudoscalar coupling, depending on the relative intrinsic parities of the K, Σ , and nucleons.

The desired cancellation of the π cloud of the neutron is possible with scalar coupling in spite of the large mass of the K ($M_K \approx 3M_\pi$) because the r.m.s. radius of the charge density for mesons with a scalar coupling is larger by a factor of about 1.6 than the r.m.s. radius of the charge density for mesons of the same mass interacting with derivative pseudoscalar coupling. With a S(S) coupling constant of $g^2 \approx .4$, an electron-neutron interaction of $+1$ kv. is obtained in a second order perturbation calculation with fixed source.

The magnetic moment calculation¹³ gives too high a value for the isotopic scalar part of the magnetic moment. This is remedied by adjusting the coupling of the P-wave K mesons to the baryons to $g_2 \approx .3$ (corresponding to $\mu_S \sim +.5$).

It is suggestive that whatever is known about the scattering of K mesons is quite compatible with the assumptions accepted here.

While we have discussed only the electromagnetic properties of isolated nucleons, the properties of nuclei are also affected. For example, the known statement that mesons do not contribute to the exchange quadrupole moment of deuterium is incorrect if K mesons interact strongly with nucleons. The contributions are of the type:

(G. Sandri)

XII. PREPARATION OF LARGE PLASTIC SCINTILLATORS

Equipment has been built for the large scale polymerization of styrene and approximately three tons of plastic scintillators have been produced.

On the basis of information furnished us by E. Fullman¹⁴, and of small scale tests of our own, we adopted for our production a mixture of styrene monomer (2-3 ppm inhibitor), 1 percent p-terphenyl, about .05 percent popop, and about .03 percent zinc stearate. Polymerization is carried out in a large stainless steel vat fitted with reflux condensers and heated in an oil bath. Violent exothermic polymerization occurs when the monomer reaches a temperature of 150°C. After the reaction subsides, heating is continued for 24 hours at about 150°C under thermostatic control. The vat is then shock-cooled in a water bath in order to break the adhesion of the plastic to the vat walls. The plastic disc is knocked from the vat and placed in a thermostatically controlled oven for annealing. The temperature of the plastic is brought back up to about 120°C over five hours and then allowed to cool to 50°C over 20 hours.

The finished product is easily machined and has shown no sign of deterioration over a period of three months. These plastic scintillators have a scintillation efficiency which is comparable to the best commercial plastics available. They have given greatly improved performance over liquid scintillators in large area cosmic ray detectors in addition to affording greater convenience and safety.

A complete description of this work will be given in a forthcoming Technical Report.
(G. W. Clark, F. Scherb, W. B. Smith)

XIII. A STRUCTURED PICTURE OF THE NEW UNSTABLE PARTICLES

So far, the heavy mesons and hyperons have been interpreted either as the manifestation of a new quantum number, which provides for the generation of a new group of fundamental particles, or as one new fundamental particle and the compounds it can form with nucleons. A third possibility has been examined: that none of the hyperons and heavy mesons are fundamental particles, but rather that they arise from a new type of interaction among nucleons. It is proposed that (1) two nucleon-antinucleon pairs can exchange one-half unit of isotopic spin, (2) each pair can then exist in a bound state (the K mesons), and (3) the pair acquiring the extra isotopic spin can then bind to a nucleon (forming hyperons), or to another pair similarly enhanced in isotopic spin (forming a heavier meson).

From these assumptions, and assuming the separate conservation of charge (Q) and z -component of isotopic spin (I_z), the Q and I_z of each particle is found. These Q and I_z values correspond to those previously proposed for the Σ , Ξ , and Z hyperons and the K mesons. In addition to these, the only other particles which can be formed are one heavier meson (B^-) and the

Λ^0 , which turns out to be another form of the Σ^0 with a lower mass, due to electromagnetic effects. By roughly taking into account similar electromagnetic effects and by making the simplest possible assumption about the binding forces, the masses of all the heavy mesons and hyperons can be found from a simple relation involving just two adjustable constants.

A natural consequence of this point of view is the appearance of two kinds of K mesons, the θ and the τ . Depending upon the spin of the θ meson, two types of bindings are considered, each of which leads to the assignment of the spins and parities of all the particles. For these bindings it is reasonable that the charged θ and τ mesons have about the same mass, but it is predicted that the θ^0 and τ^0 may have rather different masses.

If the π meson is pictured as a bound nucleon-antinucleon pair, the strange-particle-producing reaction mentioned above may also be written as $\pi + \pi \rightarrow K + \bar{K}$. Such a π - π reaction would predict that strange particles are produced largely through the intermediate creation of pions when nucleons are incident, and would explain why K^- 's are seldom, if ever, captured by two nucleons instead of one, and also why K's are produced predominantly forward and hyperons backward. In addition, the second resonances in π -P scattering are accounted for by the $\Lambda^0 + K$ bound state, which gives a resonance in the π - π interaction at just the right energy. Also, it is suggestive that the cut-off in Chew's meson theory is given precisely by the threshold for the $\pi + \pi \rightarrow K + \bar{K}$ reaction. (D. O. Caldwell)

XIV. HIGH PRESSURE RECTANGULAR IONIZATION CHAMBER

This experiment has been concluded; the results, which are being prepared for publication, are presented in detail in the L.N.S. Progress Report of November 30, 1955. The principal conclusions on the high-energy nucleons in the atmosphere are outlined here.

It was estimated that the nucleons studied in this experiment ranged from 200 to 2000 Bev, which was a higher energy region than had been investigated previously in this type of experiment. The absorption mean-free path for protons was found to be 125 ± 2 g/cm² and for neutrons 105 ± 6 g/cm², as compared with the geometric mean-free path of 65 g/cm². The charge-to-neutral ratio was $1.54 \pm .15$. These values were in good agreement with previous altitude variation experiments. There seemed to be no change in the mean-free path with energy.

These results were compared with the calculations of Olbert and Stora, who consider the Fermi model for nuclear interactions first with the assumption of nucleon-antinucleon pair production and no elasticity for the collision and second with the assumption of no nucleon-antinucleon pair production and partial elasticity for the collision. It was found that the experimental values fit fairly well into either picture, suggesting the need for further refinement of the theory.

Evidence was found for the presence of high energy nucleons near the core of air showers, in agreement with previous work. If a power law were fitted to the density spectrum for air showers

associated with nucleons, a crude value of .64 would be found for the exponent. Considering the scarcity of the data on which the evaluation of this particular quantity was based, the result may be considered in reasonably good agreement with the only previous determination which was equal to .5. (L. Altman)

XV. SEARCH FOR LONG-LIVED K-MESONS USING THE COSMOTRON

The equipment associated with a search for long-lived mesons, as described in its initial form in the L.N.S. Annual Progress Report 1954-55, has been at the Cosmotron, Brookhaven National Laboratory, since July 1955. Preliminary observations of delayed activity in the millisecond range have been made. These data indicated that the delayed coincidence method of selecting light mesons by requiring two pulses within a time characteristic of the μ -meson-electron decay was probably useless because of the large amount of radioactivity induced in the detector. In particular, to rise above the rate of accidental coincidences would require that the production of long-lived mesons be comparable to that of K-mesons. Much of the data associated with this "background" activity was consistent with a known beta emitter ($N^{12} \rightarrow C^{12} + e^+$, half-life: 12.5 milliseconds, end point energy: 16.6 Mev)¹⁵. Thus, it became necessary to shift the emphasis in this experiment from discrimination via delayed coincidence selection of light mesons to discrimination in terms of energy selection, with a much sharper energy resolution than could be obtained with the apparatus used for the preliminary observations. The required changes in equipment have recently been completed, and this new mode of observation is now underway.

The geometry of the detector was altered in an attempt to make the light collection at the phototubes independent of the source location within the scintillator. In addition to the detector itself, the associated circuitry was altered to help attain an energy response with a sharp cutoff at the upper end. This situation was obtained by requiring a coincidence between two independent pulse-height discrimination channels, where each channel is associated with a different pair of phototubes.

The program, at the present time, consists of studying delayed events with energies above the end point for the nitrogen activity. If the amount of activity in this region appears sufficiently low, we shall then attempt to supplement the energy discrimination with the method of delayed coincidence needed for identification of light mesons. (E. Boldt, H. Bridge, D. Caldwell, and B. Rossi)

Figure 4.4

Zenith angle distribution of a group of showers having 2.10^6 or more particles.

REFERENCES

1. Bridge, Courant, DeStaebler, and Rossi, Phys. Rev. 95, 1101 (1954).
2. Bridge, Caldwell, Pal, and Rossi, Phys. Rev. 102, 930 (1956).
3. B. D. Hyams, private communication.
4. D. J. Hughes et al., Phys. Rev. 90, 497 (1953). (e - N.)
5. E. Melkonian et al., Bull. Am. Phys. Soc., Series II, 7, 62 (1956). (e - N.)
6. R. Hofstadter et al., Phys. Rev. 98, 217 (1955). (e - P.)
7. F. Bloch et al., Phys. Rev. 74, 1025 (1948). (μ_N .)
8. R. Thomas et al., Phys. Rev. 75, 902 (1949). (μ_P .)
9. J. H. Gardner and E. M. Percell, Phys. Rev. 76, 1262 (1949). (μ_P .)
10. T. D. Lee and C. N. Yang, Phys. Rev. 102, 230 (1956).
11. Dashed and undashed symbols represent hyperons with opposite parity.
12. Other reactions are possible but are not relevant for our present purposes.
13. H. Miyazawa, Phys. Rev. 101, 1564 (1956).
14. E. Fullman, Los Alamos, private communication.
15. L. W. Alvarez, Phys. Rev. 75, 1815 (1949).

B. B. Rossi
H. S. Bridge

Elementary Particle Scattering Group

I. PHOTO EMULSION RESEARCH

A. Introduction

In the period covered by this report, relatively intense well-focussed K-meson beams became available at the Bevatron and Cosmotron. The specific properties of emulsion stacks, notably their very high resolving power, the possibility of making very accurate range measurements, the fact that they can be used in regions of excessively high background, coupled with their mobility and the small amount of time needed for setting up an experiment, make this technique of observation the ideal "reconnaissance" technique in high energy nuclear physics.

These properties were utilized in a series of experiments designed to explore the general properties and inter-relationships of the K-meson family. Specifically explored were the masses of K's based on range momentum measurements, secondary mass values and frequencies using the ranges and identities of the secondaries, lifetimes from the decays in flight, absence of high mass secondaries from the beam, spin parity properties of the tau-meson, interaction properties of K-mesons in flight with nucleons, and relative scattering cross sections for tauons and thetons.

Some of the possible directions of future activity in the coming year are now clear, and can be summarized.

- (1) Experiments to extend K^+ interaction cross sections to higher energies to get a clearer idea of the importance of p-wave interactions to the cross sections. This experiment has already been started.
- (2) Experiments to try and detect long-lived neutral strange particles by their materialization in charge exchange reactions in emulsions. Current theory (Gell-Mann-Pais) demands the existence of such particles. Their presence would add considerable support, their absence lead to radical revision of current basic theoretical concepts. First trial exposures have been made for this experiment.
- (3) On the technical side we are developing a pulsed magnet of $\sim 300,000$ gauss with the hope of focussing very short-lived particles (for instance Σ^- and Ξ^-) in distances of a few cms.
- (4) We are investigating the use of emulsion, liquid hydrogen (or deuterium or helium) sandwiches for use in stopping K^- or antiprotons in a known substance. The specific properties of emulsion may allow this technique to be used to particular advantage for certain experiments. It is hoped to obtain an exposure at Berkeley in the next few months. (D. M. Fournet, A. Pevsner, D. M. Ritson, R. A. Schluter)

B. Characteristics of K^+ Particles

1. Measurement of primary masses.

Among the positive strange particles there have been identified phenomenologically six types of heavy mesons: the τ , τ' , $K_{\mu 3}$, $K_{e 3}$, $K_{\pi 2}$, $K_{\mu 2}$. Experimental evidence indicated masses for these particles in the 900-1000 m_e range. There immediately arises the question as to whether we are dealing with up to six separate new fundamental particles with different decay modes. Cosmic ray evidence suggested that the τ and $K_{\mu 2}$ masses may differ by more than 30 masses of the electron. Further, analysis of the decay spectrum of the τ suggested that the τ and $K_{\pi 2}$ could not be identical particles. It is, therefore, of great interest to differentiate between the heavy mesons by investigating the mass differences that might be expected to exist between different fundamental particles.

With the availability of K-meson beams at the Berkeley Bevatron (see Figure 5.1) it became possible to measure the K-masses with greater precision than previously.

The τ meson decays into three low energy π -mesons. This has allowed a very accurate determination of the τ -mass viz. $966 \pm 1 m_e$. Hence, it is possible to use the τ -mass as a reference point in measuring the K-masses. In attempting to do these experiments we exposed a stack of

Figure 5.1

Experimental arrangement of the strong-focusing channel used in the exposure.

100 emulsions $10'' \times 16'' \times 400\mu$ to the focussed and magnetically analyzed K-meson beam at Berkeley. The stack was so oriented that only particles of a constant momentum, and hence for a given mass of constant range, stopped in each pellicle. The region in which particles of 900-1000 times the mass of an electron would stop was area-scanned for particles that stopped and decayed. The ratio of the mean range of the K^+ -mesons to that of the τ^+ -mesons can be used to determine their relative masses. The results for 743 K^+ -mesons and 65 τ^+ -mesons yield for this determination:

$$m_{\tau^+} - m_{K^+} = (4 \pm 4) m_e$$

As this result is determined from the ratio of two ranges very nearly equal, the result is very insensitive to variations in the range-energy relations or other corrections, since to first order the correction to the K^+ -ranges equals those to the τ^+ -ranges.

It is also possible to calculate the absolute values of the masses from the ratio of the mean ranges of the K^+ particles to the mean ranges of the protons. The result, using the range energy relation of Barkas, was

$$m_{K^+} = (965 \pm 4)m_e \quad m_{\tau^+} = (969 \pm 7)m_e$$

The plates were searched for higher mass groups 1100-1450 m_e . After eliminating all K's which had orientations such that they had probably scattered from the collimator walls, we could set an upper limit of $< 1/2\%$ of the intensity of the K-meson group for any high mass group present in the beam.

2. Measurement of K masses from their secondaries.

The above results were obtained by measuring the mass of the primary K before decay. However in certain suggestions (Lee and Orear scheme) it is possible that there be only one primary particle which can decay into another type K of a slightly different mass. This mass difference would not show up on a primary measurement but could be detected by measuring mass through the secondary, i.e. the mass is calculated from the rest mass of its decay products plus their kinetic energies, the Q-value of the reaction. Hence an attempt to determine the mass by this method was made by following flat tracks to the end of their range. Figures 5.2 and 5.3 are plots of some of these results. The mass of the K's from the Q-value is listed in Table 5.1.

Figure 5.3

Ranges of gray secondaries of K-mesons.

Figure 5.2

Ranges of secondaries of K_L -mesons.

TABLE 5.I

Average Mass Values for K-Particles

Decay Mode	From Q of Decay	K-Particle Mass Values (m_e) from Range Relative to Mean τ Range, with $m_\tau = 965 m_e$ (a)
$K_{\mu 2}^+ \rightarrow \mu^+ + \nu + Q$	964 ± 6	960 ± 7
$K_{\pi 2}^+ \rightarrow \pi^+ + \pi^0 + Q$	964 ± 4	963 ± 9
$K_{e 3}^+ \rightarrow e^+ + ? + ? + Q$	—	983 ± 25
$K_{\mu 3}^+ \rightarrow \mu^+ + \pi^0 + \nu + Q$?	—	955 ± 9
$\tau^+ \rightarrow \pi^+ + \pi^0 + \pi^0$	—	967 ± 8

(a) The masses of the K-particles obtained from momentum-range relative to $m_\tau = 965 m_e$ agree within the errors with the results given by Birge et al.

These masses show no difference between the primary and secondary method of mass differences.

TABLE 5.II

Relative Frequencies of Occurrence of the Various Modes of Decay

Source of Data	Proper time of Flight (sec.)		K _L -Mes- ons				
			$K_{\mu 2}$	$K_{\pi 2}$	$K_{e 3}$	τ/K_L	τ/τ'
The present experiment	1.5×10^{-8}	Numbers observed	13/21	7/21	1/45	1/12	4.6/1 ^a
		Percentages	63%	34%	2%		
G-stack ^b	$\sim 10^{-9}$	Numbers observed	21	17	5	—	—
		Percentages	49%	39%	12%		
Ecole Polytechnique ^c (emulsion)	$\sim 10^{-9}$	Numbers observed	16	9	2	1/18	—
		Percentages	59%	33%	7%		
M.I.T. cloud chamber data ^d	$\sim 2 \times 10^{-9}$	Numbers observed	24	9	—	—	—
		Percentages	$\sim 70\%$	$\sim 30\%$	—		
Birge et al. ^e	$\sim 10^{-8}$	Numbers observed	—	—	—	1/11	4.1/1
		Percentages	—	—	—		

^a This ratio has been corrected to take account of relative scanning efficiency for τ and τ' particles.

^b A. Bonetti et al., Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

^cCrussard, Fouche, Kayas, Leprince-Ringuet, Morellet, Renard, and Trembley, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

^dBridge, DeStaebler, Rossi, and Sreekantan, Nuovo Cimento, Series 10, 1, 874 (1955); H. DeStaebler and B. V. Sreekantan, Phys. Rev. 98, 1520 (1955); H. Courant, Phys. Rev. 99, 282 (1955).

^eBirge, Haddock, Kerth, Peterson, Sandweiss, Stork, and Whitehead, Proceedings of the International Conference on Elementary Particles, Pisa, 1955 (unpublished).

3. Relative frequencies and lifetimes.

The use of a large stack enabled us to follow the secondaries to the end of their ranges in many cases. This gave us not only the masses in the section above, but also a measure of the relative frequencies of the various modes of decay. The result in our experiment and that of other experiments is compared in Table 5.II. In some of the other experiments the proper time-of-flight of the K's before stopping was $\sim 10^{-9}$ sec compared to our 1.5×10^{-8} seconds in our channel. The fact that the frequencies of all modes have not changed under these two very different conditions indicates that the lifetimes of the different decay modes are approximately equal. In a separate experiment the lifetime was determined to be about 1×10^{-8} sec. By scanning along the track we followed K-mesons until they either interacted, decayed in flight, or came to the end of their ranges. By comparing the number of decays in flight to the total time of observation obtained from the slowing down time of a K-meson, it is possible to calculate a lifetime. The result was a lifetime of 1×10^{-8} sec. for both K^+ and K^- lifetime with a statistical error of about $\pm 30\%$.

In conclusion we may say that thus far no evidence has been found for any gross difference in mass, lifetime, or production among K^+ particles. A detailed description of the above work has been published in the Physical Review.¹

C. Spin of the τ^+ -Meson

From an analysis of the energy and angular distributions of 54 τ^+ -meson decays, we conclude that the spin of the τ^+ -meson is either 0^- or 1^+ . Our data favor, slightly, the second choice. However, when combined with the data of other American laboratories, 0^- seems to be preferred. The conclusions are based mainly on the energy distribution of the odd pion, for which we observe appreciable deviations from symmetry about the mean, in the direction predicted by 1^+ . Such deviations could also arise from e.g. an attractive $\pi - \pi$ interaction in the $T = 0$ state for a 0^- tau. (B. T. Feld, A. C. Odian, D. M. Ritson, and A. Wattenberg).

D. $K_{\pi 2}$ and $K_{\pi 3}$ Lifetimes

Current measurements of the $K_{\pi 2}$ and $K_{\pi 3}$ lifetimes indicate one lifetime for the two particles. If one assumes that the $K_{\pi 2}$ and $K_{\pi 3}$ particles are two degenerate states of the same system, it may be possible to understand the behavior of the system with no further gross assumptions. The degeneracy is slightly removed due to the different decay schemes of the states. The energy splitting so induced may be of the order of

$$E = \frac{\hbar}{\tau} \approx 5 \times 10^{-8} \text{ ev.} \quad (1)$$

or larger.

Assume that in the absence of any perturbation the $K_{\pi 2}$ and $K_{\pi 3}$ have decay constants λ_2 and λ_3 respectively. If the states are totally mixed by some perturbing field, the observed decay constant would be the same for both states, namely

$$\lambda_{\text{observed}} = 1/2 \lambda_2 + 1/2 \lambda_3 \approx 10^8 \text{ sec}^{-1} \quad (2)$$

In order to mix the two states one may introduce electric and magnetic fields. The electric field matrix element:

$$H_E' = \int \psi_{K_{\pi 2}} (e E x) \psi_{K_{\pi 3}} d\tau \approx e E \lambda_C \quad (3)$$

is probably of the order of $e E \lambda_C$, where λ_C is the Compton wave length divided by 2π , and E is the perturbing electric field. The magnetic field matrix element is given by

$$H_M' = \int \psi_{K_{\pi 2}} (\mu \cdot B) \psi_{K_{\pi 3}} d\tau \approx \mu \cdot B \quad (4)$$

where μ is about twice the nuclear magnetron and B is the perturbing magnetic field. The spin and parity assignments of the two states determine which matrix element is needed. One may invoke matrix elements involving derivatives of the field if need be. However, in any case, the matrix elements cannot mix the states if the assignments 0^+ and 0^- are correct.

Both H_E' and H_M' are of the order of 10^{-5} ev or larger in ordinary atomic fields. Hence, if the above assumptions are correct, K mesons in emulsions are expected to be in a mixed state, and to exhibit one lifetime. The ratio of the number of these mesons decaying by 2- and 3-meson emission is just

$$\text{Ratio } K_{\pi 2} \text{ to } K_{\pi 3} = \frac{\lambda_2}{\lambda_3} \quad (5)$$

If the currently observed ratio of 4 is correct, then equations (5) and (2) together yield

$$\lambda_3 = 0.4 \times 10^8 \text{ sec}^{-1} \text{ or } \tau_3 = 2.5 \times 10^{-8} \text{ sec} \quad (6)$$

$$\lambda_2 = 1.6 \times 10^8 \text{ sec}^{-1} \text{ or } \tau_2 = .62 \times 10^{-8} \text{ sec} .$$

These two lifetimes should be observable if the K mesons decay in vacuum*. Any attempt to detect the K particles in solids will completely mix the states once again. Hence one should merely count the number of K's of a given momentum traversing varying lengths of vacuum. One then looks for deviations from the exponential decay law. In particular a sum of two exponentials is expected. A vacuum or gas path length of about 15 feet, and a focused beam of monochromatic K mesons can be used.

The mixing of two particle state functions may also be observed with heavier particles. Again the check would be the observation of a non-exponential decay. (R. Weinstein)

E. K⁺-Scattering

1. Cross section.

Two exposures were made with the Berkeley K⁺ beam at ~400 Mev/c energy in conjunction with the Goldhabers at Berkeley. With these exposures it was possible to pick up tracks entering the stack and identify them with high probability as K-mesons by direction and ionization. These tracks were then followed through the stack and all subsequent interactions were investigated. The identities of the interacting K-mesons were checked by measurements of multiple scattering and ionization. The beam contamination was determined by investigating the fraction of tracks which had the same ionization as K-mesons at entry but twice the range and were thus protons.

A total of 38.5 meters of tracks was examined; 60 elastic and inelastic scattering greater than 20° were found. In none of these interactions was there any evidence for absorption of the K⁺-meson and release of the rest mass energy.

The mean-free path for "incoherent" scattering (after eliminating that part due to shadow scattering) was 95 cm (which corresponds to an average of 6 mbs per nucleon). The distribution in angle appeared roughly isotropic, and the cross section showed no marked variation with energy. The ratio of interactions in which the K-meson emerged to those in which no emergent particle was seen, (presumably charge exchange interactions) was 36 to 4. Used in conjunction with the observation of Goettingen and other combined groups of a K⁺ H cross section of the ~15 mbs, the picture indicated by the data is of an S-wave K-meson interaction going through a T = 1 state which would lead to a charge exchange to non-charge exchange ratio of 5:1, and a proton to neutron cross section of 4:1.

It appears a very interesting indication that isotopic spin states also dominate the K-hydrogen interactions as well as the π-hydrogen interaction.

* If the K_{π2} and K_{π3} both decay via the K_{μ2} scheme, the above experiment might require greater accuracy to separate out λ₂ and λ₃.

The complete absence of an absorption cross section is a reflection of the hypothesis of associated production, and is probably the clearest proof that the inverse of absorption, i.e. single production, never occurs. (A. Pevsner, D. M. Ritson)

2. Comparison of θ - τ scattering cross sections.

In view of the probable difference in spin parity of the θ or K_{π_2} (K-meson decaying into two π mesons) and τ (K-meson decaying into three π mesons), an experiment was designed to test if these particles scattered with grossly different cross sections.

A joint exposure with the Harvard group was made at Brookhaven at 330 Mev/c at 2.9 Bev at an angle of 120° to the circulating proton beam. At this angle direct kinematic production even with 25-Mev Fermi energy is forbidden. However, calculating from the previously observed cross sections a large fraction of the produced K-mesons should suffer secondary scattering in the target nuclei (uranium), and appear at a back angle. Accordingly the composition of the beam at this angle should reflect the relative scattering cross sections.

Five hundred K-mesons have been found by systematic on-track scanning and about seventy-five flat tracks have been carefully analyzed by grain count to separate the K_{μ_2} and K_{π_2} components. The results while not completely analyzed show that proportions of τ and θ 's are identical to the order of twenty-five percent.

The very close similarity of the properties of the θ -mesons and τ -mesons, i.e. their relative masses, lifetimes, scattering etc., remains a provoking but unsolved problem. (A. Pevsner, D. M. Ritson, and R. A. Schluter)

3. K^+ -Scattering.

The K^+ scattering events found in nuclear emulsions exposed to the 120-Mev Berkely K^+ beam were analyzed to give the angle of scattering and K^+ energy for each event. A suitable description for these events was found in a model consisting of elastic (or coherent) and inelastic (or incoherent) events. Computations were made to predict the number of events at forward angles (mostly coherent) from the number of events at backward angles, which measure the single nucleon cross section. The results are very sensitive to the assumed sign of the nuclear scattering because of its interference with coulomb scattering. The predictions for an attractive potential for the K^+ -nucleon interaction agree closely with the data.

Recently, we have been able to compare these predictions with other experimental data, in particular that submitted by Professor N. Dallaporta at the Rochester conference.² In this case the cross sections are integrated over the experimental ranges of energies in the plates. Figure 5.4 shows our predicted distributions with the M.I.T.-Berkeley data and the Dallaporta data. (L. S. Osborne)

Figure 5.4

Cross section for K^+ scattering.

F. Heavy Mesons and Hyperons in Nuclear Emulsion

The interactions of K^- mesons of energies between 15 and 100 Mev in emulsion have been studied and compared with existing data on the interactions of K^+ -mesons of the same energy range. An experiment has been started to study the interactions of K^+ -mesons of higher energy, up to 150 Mev, but as yet no results can be given.

A stack of 95 pellicles of Ilford G5 emulsions, each $3'' \times 5'' \times 600 \mu$ was exposed in a focussed K^- beam of the Berkeley Bevatron. The particles entering the stack were those produced in a copper target by a 6.2-Bev proton beam. A magnetic analyzer allowed only particles with momentum of 400 Mev/c to enter the emulsion. Following a total track length of 8.68 meters by along-the-track scanning has resulted in the finding of 137 capture stars of K^- mesons at rest, 23 interactions (other than scattering) of K^- mesons in flight, and 6 decays in flight. From the number of interactions in flight - 23 apparent absorption events and 1 nuclear scattering - the mean free path for K^- interaction is $(36.2^{+9.2}_{-6.1})$ cm. in contrast to (95 ± 16) cm. for interaction of K^+ mesons. If the K^- interactions are divided into two energy regions, the mean free path below 50 Mev is given as 26.7 cm. and between 50 and 100 Mev as 40.9 cm. For comparison, the mean free path corresponding to geometric cross section in emulsion is about 31 cm.

The prong distributions of the stars produced at rest and in flight, and the types of events in both cases are very similar. This similarity indicates that the absorption process $K^- + \text{nucleon} \rightarrow \text{hyperon} + \pi$ which occurs for K^- mesons when they interact at rest also predominates when they interact in flight. This process contrasts to the interactions of K^+ mesons, which are found to only scatter, charge exchange, and occasionally produce small stars. The difference between K^- and K^+ interactions with respect to both the size of the cross section and the types of interaction are in excellent agreement with the requirement of conservation of strangeness in fast interactions. (D. M. Fournet, A. Pevsner, and D. M. Ritson)

G. Immersion of Nuclear Emulsion in Liquid Hydrogen

Described here is the development of a new method that makes accessible to emulsion technique a large class of experiments in elementary particle physics that hitherto could not be done with nuclear emulsion. It is the use of Ilford G-5 nuclear emulsion in contact with liquified light gases, hydrogen in particular. Emulsion assembly methods for a particular experiment, namely the stopping of K mesons in hydrogen, have been studied in detail.

1. Sensitivity.

The aim of the sensitivity experiments was, firstly, to verify sensitivity to minimum ionizing tracks, and secondly, to insure that such sensitivity is not critically dependent on such factors as rate of warm-up, length of time cold, particular batch of emulsion, etc. Several 400-micron pellicles were immersed in a dewar of liquid hydrogen after having been precooled by liquid nitrogen. The cooling took about 5 minutes from room temperature to -259°C . About 1/2 hour after immersion, the dewar was briefly exposed to the γ -ray beam of the M.I.T. synchrotron. Afterwards, the liquid hydrogen was evaporated by means of a wire heat leak so that the emulsion stayed at -259°C . for about one hour after exposure. On depletion of the liquid hydrogen, the warm-up to room temperature occurred in about 2 hours. The pellicles were developed immediately by a standard method (Bristol formula). The minimum grain count determined from electron-positron pairs produced by the 330-Mev γ -ray beam was 20 grains/100 microns, compared to about 28 grains/100 microns measured in the same batch of emulsion exposed at room temperature.

2. Emulsion contact with liquid gas.

Hydrogen at low temperature does not chemically affect the emulsion. Liquid hydrogen wets the emulsion surface, a fact essential to the stack design described in Section 4. The adhesion of pellicles to the mounting glass is not impaired by their having been cooled.

3. Thermal stresses.

A suddenly cooled or warmed pellicle stack will fracture in a pattern suggesting peripheral expansion or contraction relative to the center. Such thermal stress is removed by clamping be-

tween metal plates so that the temperature gradient, if any, is perpendicular to the plane of the pellicles. If so clamped, a pellicle stack of thickness of the order of one centimeter can be cooled from room temperature to -270°C (liquid helium) in five minutes, and rewarmed in ten minutes without damage. Pellicles punched as described in Section 4 are particularly resistant to thermal damage, as might be expected. In these experiments the test stacks contain a thermocouple in order to be sure that the cooling is done continuously. Such steady cooling is done easily by placing metal heat leak tabs on the stack clamping plates and dipping these tabs into the liquid gas. If the emulsion is exposed directly to the vapor stream, superficial cracking at the exposed edges occurs.

4. Assembly.

The first experiment planned is the stopping of K mesons in hydrogen (or deuterium or helium). The basic goal in design of a stack for this purpose is to replace as much emulsion by liquid H_2 as possible and still retain a fine-grained structure through which tracks can be traced without ambiguity. The design evolved consists of pellicles of 100-micron thickness made specially for this purpose by Ilford, clamped between brass plates, and punched with $1/4''$ circular holes in a pattern which would be close-packed except that alternate spaces are unpunched. The pattern alternates from sheet to sheet, one punched pattern being displaced by one unit in both directions from the adjacent patterns. In this way a fraction $\pi/8$ of the volume is filled with the liquid. The pellicles bear a contact printed grid and are aligned on pins as usual. The distortion of a 100-micron pellicle on cooling is such that holes up to about 1 cm diameter could be used without visible buckling of the unsupported region. Thicker pellicles would be easier to assemble but give less spatial resolution. The choice of optimum thickness depends on the density of transverse background tracks. Examples of the "Swiss Cheese" type stack described here have been immersed in liquid helium without difficulty.

A stack of this type having exterior dimensions $2'' \times 3'' \times 1''$ requires about 30 cc of liquid to fill it, if closely sheathed. Therefore, deuterium immersion can be done without arrangements for deuterium reclamation.

Direct immersion can eliminate the need for thin windows on liquid-hydrogen target vessels, and advantage of this is to be taken in an experiment on pion-pair photoproduction near threshold. (D. M. Ritson and R. A. Schluter)

H. High Intensity Pulsed Magnet

Although the production of magnetic fields of several hundred thousand gauss intensity is not new, having been done, for example, by Kapitza and by Cockcroft in the 1920's, the use of such magnets in nuclear emulsion research has only recently been practical, and this is because only recently have unstable elementary particles been produced artificially and therefore concentrated

both in space and in time. High intensity magnets are necessarily small and must also operate with a small duty factor.

Recent technique in the construction of such magnets has been described by K. S. W. Champion³, H. P. Furth and R. W. Waniek⁴, and by S. Foner and H. H. Kolm⁵. The magnet constructed at M.I.T. was designed to give a field of about 250,000 gauss over a volume of 70 cc, with a natural period of 6 milliseconds. The latter was chosen to make the magnet useful with a particle burst of about one millisecond length, as at the Cosmotron at Brookhaven. With the available capacity of about 10,000 microfarads (3,000 volts) such a period requires an inductance of about 100 microhenries, and this dictates a coil of about 70 turns. It was, therefore, considered impractical to use the slit washer method of coil assembly, but rather to cut a deep spiral groove in a cylinder of copper and then compress axially, the method described by S. Foner and H. H. Kolm. An alternative is to wind coils of square magnet wire insulated with glass and formvar. The smaller space factor is compensated by much greater ease of construction. A coil of the first type is under test, and coils of the second are under construction.

A major problem in coil design arises from the very high forces of magnetic origin. In a solenoidal coil this is mainly a radial bursting force reaching a maximum intensity at the equatorial plane and must be contained by a strong jacket. It is just in the equatorial plane that one desires an aperture for admission of particles to the nuclear emulsion inside the solenoid, and the major question in mechanical design is how to provide such access through the jacket without unduly wasting the stored magnetic energy. There are, of course, some experiments that can be done without a side port. An example is the production of short-lived hyperons inside the coil by means of a pencil proton beam directed axially through the coil. However, most experiments demand that particles enter in a plane normal to the field, and the first use of the present coil will be to investigate the mechanical problem of a side port.

A second development project concerns the switch. Initially, this will be a sintered silver-cadmium oxide "bullet" passing between two contacts of the same material. It is hoped to cut off the discharge at the second current node, i.e., after 2π radians of oscillation, so that the condenser bank will retain about 2/3 of its initial energy and the coil will be correspondingly less heated. The maximum current is about 25,000 amperes. Later the switching may be done by a bank of several ignitrons.

The most probable program for this type of magnet is the study of the charged hyperons which live for distances of a few centimeters, and for this purpose it is hoped ultimately to operate with a capacitor bank of 30,000 microfarads, the increased capacity allowing a coil volume increase to 200 cc, with the further advantage of longer time constant and/or coil of fewer turns. (R. A. Schluter)

II. ATOMIC MODEL OF THE NUCLEON AND PION-NUCLEON INTERACTIONS

The "physical nucleon" is approximated as an atom-like configuration of a Dirac nucleon core surrounded by a p-wave single-pion cloud. The ground state has $j = t = 1/2$. The meson density is taken to conform to the observations of Hofstadter on electron-proton scattering. With this model, the computed nuclear magnetic moments are in fair (but not good) agreement with observation. The predicted electrostatic neutron-electron interaction is larger than observed (when corrected by the Foldy term), but is reduced when account is taken of hyperon-K meson configurations, according to the argument of Sandri. However, the atomic model yields a neutron-proton mass difference which is correct both in sign and in magnitude, assuming that all interactions except the electromagnetic are charge-independent.

The physical nucleon is assumed to have an excited, virtual (isobar) state, of $j = t = 3/2$, whose properties are in accord with the observed pion scattering resonance. This state can be excited by magnetic dipole (and electric quadrupole) photon absorption from the ground nuclear state. A straightforward calculation of the transition matrix element then yields an expression for p-wave pion photoproduction which is identical with the expression obtained by Chew and Low by meson-theoretic considerations, except for the substitution of a dynamic moment for the static nucleon magnetic moments assumed by Chew and Low. (B. T. Feld)

III. INTERPRETATION OF THE SECOND PION-NUCLEON SCATTERING RESONANCE IN TERMS OF THE "LOW-ENERGY" ISOBAR

Dyson and Takeda have interpreted the observed 1-Bev π^- -p resonance as indicating a resonant pion-pion interaction. An alternative explanation can be given in terms of inelastic excitation of the $3/2, 3/2$ isobar. The assumption is made that this interaction is resonant when the inelastically scattered pion has $\ell = 1$ and the system of isobar plus pion has $t = 1/2$. On this basis, it is possible to account in detail for the observed π^- -p cross section in the region of 1 Bev, and to make predictions concerning such properties as the ratio of elastic to inelastic scattering, the angular and energy distributions of the reaction products, and the meson charge distributions. (B. T. Feld)

IV. A REMARK ON THE APPLICATION OF CAUSALITY RELATIONSHIPS TO THE INTERPRETATION OF PION-NUCLEON SCATTERING

Anderson, Davidon and Kruse have used the causality conditions of Goldberger to eliminate some of the ambiguity in the phase-shift determinations from pion-nucleon scattering measurements. In particular, they show that these conditions lend strong weight to the $j = t = 3/2$ p-wave resonance solutions. However, it can be shown by a general argument that every "Fermi" solution has an equally good "Yang" solution (neglecting the small $t = 1/2$ p-wave phase shifts) which is

also in equally good (or poor, as the case may be) accord with the causality requirements. This argument strengthens the conclusion that the only means of distinguishing between the two solutions is by observations on the polarization of the recoil nucleons. (B. T. Feld)

V. BUBBLE CHAMBER PROGRAM

Construction of a test model bubble chamber and associated electronic equipment has been started. At this time, a light source with a pulse duration of forty micro seconds has been completed as has the valve powering unit. Also completed is the heating and temperature control unit. The bubble chamber itself is still under construction. The sensitive volume of this chamber is a cylinder 5" long and 1-1/8" in diameter. This model will be used to test various liquids to determine which have the most desirable properties for use in a large instrument. Data from these tests will be used to construct a chamber which will be placed inside an existing cloud chamber magnet.

This model is designed to operate at twelve cycles per second as the first step in a program to develop a chamber which will operate at thirty cycles per second. This fast cycling feature will be adaptable to either organic liquids or to liquid hydrogen or helium. Some preliminary designs and calculations are being made for liquid hydrogen and helium bubble chambers. (I. A. Pless)

VI. LINEAR ACCELERATOR

The research of the Linear Accelerator Group the past year has been directed along three lines of experimentation: a) scintillation spectrometer measurements of photoproton energy distributions, b) time-of-flight measurement of photoneutron energy distributions, and c) measurement of cross sections for coulomb excitation of light nuclei with electrons.

A. Photoproton Energy Distributions

A CsI(Tl) scintillation spectrometer has been in operation at the Linear Accelerator for several months. An x-ray beam is produced by the analyzed electron beam of the accelerator, is collimated, and passes through a scattering chamber as shown in Figure 5.5. The scattering material may be either a gas or a thin foil. The 3/4-inch diameter CsI crystal counts photoprotons emitted at about 90 degrees with respect to the incident x-ray beam and is 3 cm from the center of the beam. The thickness of crystal used depends on the proton energy range which is of interest. For a given crystal thickness, pulses from protons with too low an energy will be indistinguishable from pulses caused by electrons, and protons with too high an energy will not stop in the crystal. The thinnest crystal used is 60 mgm/cm² thick, and is useful for proton energies between 2 and 4 Mev. Overall detector resolution is about 11% for 3-Mev protons.

Figure 5.5

Experimental layout of linear accelerator x-ray beam.

One purpose of the scintillation spectrometer is the measurement of the energy spectrum of the incident bremsstrahlung itself. The chamber has been filled with 5 atmospheres of deuterium and the number of photoprotons per energy interval measured as a function of proton energy and of $E_{\max}$, the energy of the electrons which produce the bremsstrahlung. The proton energy distribution tells the number of photons per energy interval which have passed through the chamber since the cross-section for the photodisintegration of deuterium is known. The photodisintegration reaction kinematics coupled with the rather large solid angle counting geometry contribute about equally with proton detector resolving power to the overall resolution as an x-ray spectrometer. The width at half-maximum is about 1 Mev for incident 11-Mev x-rays.

Uncertainties in resolution obscure the shape of the bremsstrahlung spectrum near its upper end. The interpretation of, say, a sharply rising photoneutron yield curve is quite sensitive to the shape of the x-ray spectrum near $h\nu = E_{\max}$. Measurements are now being made which will in principle measure the shape of the high energy end of the bremsstrahlung spectrum in the region $E_{\max} = 10.5$ Mev in a way which is independent of spectrometer resolution. These measurements make use of the strongly resonant nature of the photon absorption cross section in ^{14}N .

Wright, Morrison, Reid, and Atkinson⁶ have recently measured in a cloud chamber the energy distribution of low energy photoprotons from nitrogen. With 50-keV resolution they find sharply defined groups of protons at 0.51, 1.63, and 2.92 Mev, and a broad group centered at about 1.15 Mev. These groups can be matched with observed resonances in the $^{13}\text{C}(p, \gamma)^{14}\text{N}$ reaction and can be attributed to the resonance absorption of quanta into excited states of the ^{14}N nucleus at 8.06, 9.18,

10.43 and 8.6 Mev respectively. Most of the γ , p cross section in ^{14}N below 14 Mev occurs in these resonances. The threshold for neutron emission from ^{14}N is 10.54 Mev.

The 2.9-Mev protons from the 10.43-Mev state can be observed in the proton scintillation spectrometer above the electron background. The scattering chamber is filled with one atmosphere of nitrogen and the proton group appears centered at about 2.5-Mev energy loss in the CsI crystal, and is about 0.5 Mev wide, principally because of detector resolution. Figure 5.6 shows the pulse-height distribution from runs made at $E_{\text{max}} = 13.6$ Mev. The sharply decreasing spectrum in the first few bins is the electron background. The yield of protons from the 10.43-Mev state should be proportional to the number of photons per energy interval at 10.43 Mev. In Figure 5.7 are plotted preliminary data on the yield of photoprotons from the 10.43-Mev excited state of ^{14}N as a function of E_{max} . The normalization is per "r-unit" as measured by the Beckman ionization chamber (see Fig. 5.5). This r-unit is not the conventional betatron r-unit. The primary abscissa scale in Figure 5.7 is the helipot setting of the voltmeter which measures the output of a rotating coil in the field of the accelerator's analyzing magnet and is inversely proportional to the analyzing field. The other scale is E_{max} , which is the energy at the center of the 4% wide electron spectrum passed by the analyzer slit system. The data of Figure 5.7 are used to correlate helipot units with E_{max} and represent the most reliable calibration to date of the energy scale of the linear accelerator.

Figure 5.6

Energy distribution of photoprotons from ^{14}N .

Figure 5.8 shows the measured bremsstrahlung spectra. Photons per energy unit per r-unit is plotted versus photon energy in units of $h\nu/E_{\text{max}}$. The normal operating rate is about one r-unit per hour

92

Figure 5.7

Yield of photoprotons from 10.43 MeV $^{14}\text{N}^*$ versus E_{max} .

Figure 5.8

Measured bremsstrahlung spectra.

from about 0.3 μ amperes of electron current. The solid curves represent runs made with deuterium at $E_{\max} = 11.55, 13.60, \text{ and } 15.65 \text{ Mev}$. Each curve is based upon about 3000 events. The dashed portion of the curves near $x = 1$ represents that part of the deuterium data which is relatively in doubt because of the uncertainty in resolution. The crystal was not thick enough to obtain reliable data near $x = 1$ for $E_{\max} = 15.65 \text{ Mev}$. The nitrogen data of Figure 5.7 is shown as the points on Figure 5.8. The points are placed by assuming the yield of protons from the 10.43-Mev state of ^{14}N to be proportional to the number of photons per Mev at 10.43 Mev and using the yield at $E_{\max} = 13.60 \text{ Mev}$ to fix the proportionality factor. The yield at $E_{\max} = 13.6$ represents a differential cross section at 90° integrated over the 10.43 absorption line:

$$\int \frac{d\sigma(90^\circ)}{d\Omega} dE = (5.1 \pm 0.8) \times 10^{-28} \text{ cm}^2 \text{-Mev/sterad.}$$

The integrated total cross section of Wright, Morrison, Reid and Atkinson is $(9 \pm 3) \times 10^{-28} \text{ cm}^2 \text{ Mev}$.

The bremsstrahlung spectra of Figure 5.8 should be comparable with theoretical thin target bremsstrahlung spectra for Ta in the forward direction. A detailed comparison with theory has not been made, but the spectrum seems to be in approximate agreement with the Schiff spectrum, except perhaps at the extreme high energy end above $x = .95$.

The proton scintillation spectrometer is also being used to measure the photoproton yields and energy distributions from the separated isotopes of copper. In the same x-ray beam, the photoneutron yields from ^{63}Cu and ^{65}Cu are being measured by coincidence counting the positron annihilation radiation. An experiment has been done with a 4π plastic scintillation spectrometer to check the calculated value of the efficiency of the positron counter. The efficiency is now known to about 15%. The aim of this work is to check the adequacy of the evaporation model for describing photonuclear processes near threshold in middle-weight nuclei. To date, only the photoneutron yield of ^{63}Cu has been measured in detail.

B. Time-of-Flight Measurement of Photo-Neutron Energy Distributions

The general method to be used in this work has been previously described.⁷ After several attempts, a suitable circuit has been built for the conversion of the time interval between two pulses into a proportional pulse of voltage. The output is reasonably linear for time intervals less than 0.7 microseconds and the circuit is usable for times less than 1 microsecond. The time conversion to pulse height operates satisfactorily with input pulses greater than 1-1/2 volts and is independent of pulse size. The circuit is modeled after one reported by J. H. Nieland of Oak Ridge at the January 1956 American Physical Society Meeting. The remaining circuitry and counters have been constructed, and experimenting should begin during the summer.

C. Electron Excitation of Light Nuclei

Instrumentation for experiments on inelastic electron scattering is nearing completion. The 15-Mev analyzed beam from the accelerator will strike a target in an evacuated chamber. The

electrons scattered over a 10 by 3-degree angular aperture about a desired scattering angle will pass through the field of a magnetic spectrometer and, using a scintillation detector, the momentum spectrum of the scattered electrons measured. Monitoring will be done with a large-crystal small-geometry measurement of the elastic electron scattering from the same target.

The method may allow measurement to 10-20% of the differential cross sections for excitation of some levels in light nuclei. For heavier nuclei the continuous background of inelastically scattered electrons which have radiated bremsstrahlung quanta will completely mask the level peaks for any practicable resolving power.

D. Other Work at the Linear Accelerator

An important improvement has been made in the instrumentation of the accelerator. The timing of the application of power to each magnetron may now be controlled from the control room. With these controls analyzed electron beams of 0.3 to 0.4 microamperes are usual, and machine stability is improved.

Work has been finished on the electron gun of a microwave injector for the accelerator. The injector however will not be developed further until there is a definite need for the extra beam intensity it should provide.

A scintillation-type beam integrator has been developed and is in use with the x-ray beam. Beam intensity is still monitored with a Beckman ionization chamber. The Beckman is sensitive to occasional rf breakdown at the accelerator however, and is not suitable as a beam integrator. The scintillation integrator is calibrated frequently with the Beckman. (P. T. Demos, W. Bertozzi, F. R. Paolini, C. P. Sargent, W. R. Sooy, R. C. Smith, M. H. Wachter, and S. Silverstein)

REFERENCES

1. D. M. Ritson, A. Pevsner, S. C. Fung, M. Widgoff, and G. T. Zorn, M.I.T., and S. Goldhaber and G. Goldhaber of Berkley, Phys. Rev. 101, 1085 (1956).
2. Professor N. Dallaporta, Proceedings of the 1956 Rochester Conference.
3. K. S. W. Champion, Proc. Phys. Soc. (London) B63, 795 (1950).
4. H. P. Furth and R. W. Waniek, Rev. Sci. Instr. 27, 195 (1956).
5. S. Foner and H. H. Kolm, submitted to Rev. Sci. Instr.
6. Wright, Morrison, Reid and Atkinson, Proc. Phys. Soc. 69A, 77 (1956).
7. Laboratory for Nuclear Science Progress Report, May 31, 1955.

P. T. Demos, D. H. Frisch, B. T. Feld

Neutron Physics Group

I. INTRODUCTION

All work with the Rockefeller Generator in the year 1955-56 was in the electric excitation field. The major project during most of the year was the measurement of relative transition probabilities for two excited states in odd-A nuclei. This is described in section II.

Since September 1955 work has been in progress on the measurement of magnetic moments of excited rotational states. This work is done in cooperation with the Radioactivity Group and is described in that group's section of the progress report.

In the collective model theory of nuclear structure the electric quadrupole moments of nuclei, static and dynamic, are given in terms of two parameters, one of which is customarily taken as the ground state spin and the other as the quantity defined by Bohr and Mottelson as intrinsic quadrupole moment.¹ It is well known that in many nuclei the spins of the low-lying levels as well as the relative level spacings are predicted correctly and accurately by this theory. Once the spins and positions of the energy levels in any nucleus are known, the theory gives the static and dynamic quadrupole moments in an unambiguous manner. The values of these moments are found to differ considerably from the values predicted from the level spacing. Discrepancies as large as factors of six are not uncommon.^{2,3} However, in some odd-A nuclei electric excitation cross sections have been measured for both the first excited state and the second excited state; and the ratio of the $B(E2)$'s thus obtained is in fair agreement with the collective model value.⁴ The present work is an attempt to measure this ratio of $B(E2)$'s systematically and accurately in the region $Z = 63$ to $Z = 75$ where the rotational level scheme is well developed. The improved accuracy of the method is obtained by measuring the ratio of electric excitation cross sections directly and simultaneously rather than by measuring two cross sections separately, in which case the ratio contains an accumulation of two independent errors.

A. The Experimental Method

The level scheme in an odd-A rotational nucleus is shown in Figure 6.1, where K is a half-integer (in all the nuclei investigated here $K \neq 1/2$). The $K + 1$ level decays by means of photons and conversion electrons of both $E2$ and $M1$ types. The $K + 2$ level decays: a) by the cascade transition $K + 2 \rightarrow K + 1 \rightarrow K$, where $K + 2 \rightarrow K + 1$ is again an $E2$ $M1$ mixture and b) by a direct $K + 2 \rightarrow K$ transition which is pure $E2$. The electric excitation of both levels depends, however, almost entirely on the $E2$ moments. In the present work as in most experiments to date the excitation cross section is determined from the number of de-excitation processes observed. For the $K + 2$ state, evaluation of the cross section required knowledge of both cascade and cross-over transitions. However, in many nuclei the cascade is the predominant mode of decay, and will

generally be so whenever the $M1/E2$ ratio for the $K + 2 \rightarrow K + 1$ transition is considerably greater than unity. In these nuclei the ratio of the number of cascade transition, $K + 2 \rightarrow K + 1 \rightarrow K$, to the number of direct transitions, $K + 1 \rightarrow K$, when bombarded by charged particles of some given energy, is directly related to the ratio $\frac{B(E2, K \rightarrow K + 2)}{B(E2, K \rightarrow K + 1)}$. The measurement of this "cascades to singles" ratio is the essential feature of this method. The influence of the cross-over transition is considered as a comparatively small correction, and this method of evaluating $E2$ moments will be the more accurate the bigger the $M1$ percentage in the $M1 + E2$ transition $K + 2 \rightarrow K + 1$.

Figure 6.1

Level scheme for a typical odd-A rotational nucleus, showing electric quadrupole excitation of the first two energy levels and the subsequent decay. The crossover from the second level to the ground state is pure $E2$ while the cascade transitions are mixed $M1$ and $E2$.

The ratio "cascades to singles" is measured by viewing the target with two γ counters, one counting $K + 2 \rightarrow K + 1$ photons and the other $K + 1 \rightarrow K$ photons. If the latter counts $N_s \text{ sec}^{-1}$ and the number of coincidences in the two counts is $N_c \text{ sec}^{-1}$, then the ratio "cascades to singles" is given by $\frac{N_c}{N_s} \frac{1}{\eta}$ where η is the over-all counting efficiency for $K + 2 \rightarrow K + 1$ gamma rays.

Under the conditions of these experiments, the electric excitation is essentially of the pure $E2$ type. The cross section for this process for any given energy level is given by:

$$\sigma(E) = \frac{2m(E - E_0)}{Z_0^2 e^2 \hbar^2} B(E2) F(\eta, \xi(E)) \quad (1)$$

where E is the incident particle energy in the center of mass system, E_0 is the excitation energy of the nucleus. The other notation is taken from reference 5.

The yield per incident particle of excited nuclei in a target of finite thickness ΔE is given by:

$$Y = \int_{E-\Delta E}^E \sigma(E') \frac{\eta}{\kappa} dE' \quad (2)$$

where η is the number of target atoms per cm^3 and κ is the proton energy loss per cm, $\frac{dE}{dx}$.

The ratio of $B(E2)$'s for the two excited levels can be expressed in the following way:

$$\frac{B(E2, K \rightarrow K+2)}{B(E2, K \rightarrow K+1)} = r \left\{ \frac{N_C}{N_S} \frac{1}{\eta \epsilon_1} \right\} \frac{1 + \frac{\epsilon_1}{\epsilon_2} \nu}{1 - \frac{N_C}{N_S} \frac{1}{\eta \epsilon_1}} \quad (3)$$

here:

$$r = \frac{\int_{E-\Delta E}^E f \left\{ \xi^{K+1}(E') \right\} \frac{E' - E_{K \rightarrow K+1}}{\kappa} dE'}{\int_{E-\Delta E}^E f \left\{ \xi^{K+2}(E') \right\} \frac{E' - E_{K \rightarrow K+2}}{\kappa} dE'}$$

where E is the proton energy, ξ^{K+1} and ξ^{K+2} refer to the transitions $K \rightarrow K+1$, $K \rightarrow K+2$ respectively, ΔE is the target thickness,

ν is the branching ratio: $\frac{\text{number of } K+2 \rightarrow K \text{ photons}}{\text{number of } K+2 \rightarrow K+1 \text{ photons}}$,

ϵ is related to the conversion coefficient α by

$$\epsilon = \frac{\text{number of photons}}{\text{number of photons} + \text{number of electrons}} = \frac{1}{1 + \alpha}$$

ϵ_1 , ϵ_2 relating to the $K+2 \rightarrow K+1$, $K+2 \rightarrow K$ transitions respectively. The factor $\frac{1}{1 - \frac{N_C}{N_S} \frac{1}{\eta \epsilon_1}}$

derives from the fact that the $K+1 \rightarrow K$ photons arise both in direct transitions from the $K+1$ level and from cascade transitions from the $K+2$ level.

1. Coincidence measurements, N_C/N_S .

Protons of about 3 Mev were produced in the M.I.T.-Rockefeller electrostatic generator. At the target the beam spot was less than $1/64''$ in diameter. The γ -counters were $2'' \times 2''$ "Harshaw" NaI (Tl) canned crystals optically bonded to DuMont 6292 photomultiplier tubes. The coincidence counting assembly is shown in Figure 6.2. The crystal faces have been brought as close as possible to the target in order to get high coincidence yields, and to minimize the effects of anisotropic distribution of the γ rays (in most cases the relevant distributions were unknown). With the geometry of Figure 6.2 it can be shown that the uncertainty thus introduced cannot exceed

2 percent. In order to avoid coincidence counts from Compton-back-scattering events the lead and gold double cone shield, detailed in the upper part of Figure 6.2 was introduced.

Figure 6.2

Counting assembly cutaway diagram showing solid angle and lead shielding. The lower inset shows the complete assembly.

Graded and "staggered" absorbers were placed in front of each crystal to absorb atomic x-rays. The "staggering" was done by building up the absorbers from a large number of thin concentric circular foils whose radii were chosen so that a γ ray penetrated the same amount of material in reaching the crystal regardless of its incident angle from the target. The uniformity of absorption thus obtained helps minimize the effects of the anisotropic distribution of the γ rays.

The coincidence circuit was of the "fast-slow" type with a single-channel pulse-height analyzer for each counter. The fast resolving time was $0.2 \mu\text{sec}$.

The number of random coincidences was determined directly by comparing the total coincidence rate at widely differing proton currents.

In the normal runs the random rate was always less than 0.1 of the real coincidence rate.

The coincidence counting technique for measuring N_c/N_s as well as the method of target preparation were described in detail in the August 1955, November 1955 and February 1956 progress reports. The absolute calibration of the γ ray counters has also been described in these reports and it is summarized in section III of the present report.

2. Branching ratio measurement ν .

The measurement of the crossover to cascade branching ratio is the least accurate part of the present work. In principle, a coincidence system such as ours can be used to evaluate branching ratios, and some measurements have been reported using such methods.^{2, 6, 7} This procedure, however, is somewhat uncertain because the conversion coefficient for the $K + 1 \rightarrow K$ radiation must be known. In our work no great accuracy in the value of ν is required and, therefore, we preferred to measure it in the less accurate but more direct way of comparing the $K + 2 \rightarrow K$ and $K + 2 \rightarrow K + 1$ peaks in the singles spectrum. For Ta we used the value for ν as reported by Stelson and McGowan⁸, who had measured it using essentially this latter procedure. For other nuclei we used our own data, with this Ta value⁸ as a calibration point for the $K + 2 \rightarrow K \gamma$.

3. Conversion coefficients.

The M1 to E2 mixing ratio, δ^2 , for the $K + 2 \rightarrow K + 1$ radiation was obtained by comparing the experimental branching ratio ν with the value ν' obtained for pure E2 transitions according to the collective model. This procedure presupposed the validity of the collective model calculations, which is in effect the problem under investigation in this work. Nevertheless it seems to us justified for the following reasons:

a) The final results of this work confirm the validity of the collective model, so that the procedure is in this case consistent.

b) It has been mentioned above that in cases of interest δ^2 is large. In such cases ϵ_1 (of equation 3) is relatively insensitive to δ^2 :

$$\frac{d\epsilon_1}{\epsilon_1} = \frac{\epsilon_1 d\delta^2}{(1+\delta^2)^2} \quad (\alpha_E - \alpha_M)$$

where α_M , α_E are the M1 and E2 conversion coefficients respectively.

The calculations of conversion coefficients by Rose et al.⁹ and Gellman et al.¹⁰ are based on the assumption of point nuclei. For very high Z this assumption may not be valid, especially for M1 transitions. Wapstra and Nijgh¹¹ report the measurement of the conversion coefficient for a transition in Tl, and according to that paper the M1 coefficient is only about 0.6 of the value given by Rose. The general trends of the dependence of this correction factor on Z and on energy are also discussed in that paper, and it appears that for the transitions considered here the correction factor would be closer to unity. We have investigated this problem directly in the following manner: the ratio of coincidence counts to singles counts from the $K + 2 \rightarrow K + 1$ transition could be

determined directly from our data; this ratio is equal to $\eta_3/1 + \alpha_3$ where α_3 is the conversion coefficient and η the counter efficiency for the $K + 1 \rightarrow K$ radiation. Since we know η_3 fairly accurately, we have in effect a measurement of α_3 . In order to get the value of the M1 coefficient we adopted the values of Huus et al.¹² for the M1/E2 branching ratio. Most of these transitions (in the $K + 2 \rightarrow K + 1$ transitions) are predominantly M1 and therefore no accurate value of the mixing ratio is required. Our results are consistent with correction factors p (to the values given by Rose) of $0.8 \leq p \leq 1.0$.

We expect p to be the same for the $K + 2 \rightarrow K + 1$ transitions as for the $K + 1 \rightarrow K$ transitions and for our final results we have adopted the value $p = 0.8$. In order to show the dependence on p the ratios of $B(E2)$ are also given as calculated with the extreme (and improbable) values $p = 1$ and $p = 0.6$.

B. Results

The results are summarized in Table 6.I. We have also included in the table a value

TABLE 6.I

Ratios of $B(E2)$'s calculated from the experimental results using different values for the M1 conversion coefficient. p denotes the ratio between the value used and the value given by Rose et al. The numbers given in the last column are considered accurate to 20%, including the uncertainty in the conversion coefficient. Relative values for different nuclei are accurate to $\sim 12\%$.

Nuclide	Ground State Spin	$\frac{N_c}{N_s} \frac{1}{\eta} = \frac{\text{cascades}}{\text{singles}}$	$\nu = \frac{\text{crossover}}{\text{cascade}}$	$\frac{B(E2, K \rightarrow K + 2)}{B(E2, K \rightarrow K + 1)}$			
				Observed with $p = 1$	Observed with $p = 0.6$	Observed with $p = 0.8$	Calculated
Tb	3/2	-	-	-	-	0.36*	0.555
Re ¹⁸⁷	5/2	0.0760 ± 0.005	0.22 ± 0.05	0.31	0.25	0.28	
Re ¹⁸⁵	5/2	0.0845 ± 0.006	0.23 ± 0.05	0.40	0.30	0.35	0.350
Eu ¹⁵³	5/2	0.0465 ± 0.003	1.3 ± 0.02	0.24	0.21	0.285	
Ta ¹⁸¹	7/2	0.0467 ± 0.003	0.574 ± 0.05	0.24	0.20	0.22	
Hf ¹⁷⁷	7/2	0.0342 ± 0.003	4.3 ± 0.6	0.34	0.30	0.32	0.257
Lu ¹⁷⁵	7/2	0.0484 ± 0.003	0.90 ± 0.15	0.24	0.22	0.23	
Ho ¹⁶⁵	7/2	0.0564 ± 0.004	0.14 ± 0.015	0.22	0.17	0.195	
Hf ¹⁷⁹	9/2	0.048 ± 0.004	0.50 ± 0.07	0.25	0.19	0.22	0.204

* This value was obtained from inelastic proton scattering measurements (Richard D. Sharp, private communication).

recently obtained by R. D. Sharp¹³ by measuring relative cross sections for inelastic proton scattering from Tb. The results indicate that the intrinsic quadrupole moments Q_0 in any one nucleus for two different E2 transitions are remarkably constant. The agreement is certainly better than the agreement between Q_0 's calculated from electric excitation cross sections, and from the level spacings. In particular it is interesting to note that the mean ratio $\frac{B(E2, K \rightarrow K+2)}{B(E2, K \rightarrow K+1)}$ for all the nuclei investigated is 0.267 ± 0.05 whereas the corresponding collective model value is 0.315.

This seems to indicate that the general theory is correct and applicable to a class of nuclei and that the main discrepancy lies in the relation between Q_0 and the moment of inertia (reference 1: V7, VI 2 and II 6a). No regularity could be detected in the discrepancies between experiment and theory in the ratios of $B(E2)$'s. The largest discrepancy is found in Eu^{153} . Hf^{177} is unique in that it has an unusually large branching ratio, ν . Compared to the crossover transition, the cascade transition is 1 ± 0.13 the value predicted for a pure E2 transition. We may therefore conclude that the magnetic moment for this transition is exceedingly small, or in the description of the collective model: $g_\Omega - g_R \sim 0$. The $K+1 \rightarrow K$ transition in Hf^{177} is also reported to be essentially pure E2¹² (see Table 6.II).

TABLE 6.II

M1/E2 ratios. The first column is taken from Huus et al.¹², and the second column gives the values derived from our measurements. The values are normalized in such a way that the collective model theory would give equal numbers in both columns. The values in the last column have been computed under the assumption that Q_0 is constant. The uncertainty thus introduced is not taken into account in the errors quoted in the last column.

Nuclide	$K+1 \rightarrow K$	$K+2 \rightarrow K+1$
	δ^2	δ^2
	$K(K+2)$	$(K+1)(K+3)$
Re^{187}	0.8	1.3 ± 0.3
Re^{185}	-	1.0 ± 0.25
Eu^{153}	0.035	0.2 ± 0.05
Ta^{181}	0.35	$0.22 \pm 0.02^*$
Hf^{177}	0.001	0 ± 0.005
Lu^{175}	1.1	0.15 ± 0.025
Ho^{165}	0.6	1.2 ± 0.2
Hf^{179}	-	0.15 ± 0.025

* This value is derived from the value of reference 8 for ν . From angular correlation measurements (reference 13) one gets the value 0.14.

We believe the relative value:

$$\frac{B(E2, K \rightarrow K+2)}{B(E2, K \rightarrow K+1)}_{\text{Re}^{187}} : \frac{B(E2, K \rightarrow K+2)}{B(E2, K \rightarrow K+1)}_{\text{Re}^{185}} = 0.80$$

to be accurate to ± 0.08 . This ratio for which the collective model value is unity is the most accurate measurement we have of the modification of the mean rotational structure.

In Table 6.II we summarize the information on the branching ratio $M1/E2$. The values for the $K+1 \rightarrow K$ transition are taken from reference 12. The numbers for the two transitions are listed as $\frac{\delta^2}{K(K+2)}$ and $\frac{\delta^2}{(K+1)(K+3)}$ respectively because according to the collective model these two numbers should be equal [being proportional to $\frac{(g_\Omega - g_R)^2}{Q_0^2}$]. Since the measurements are rather inaccurate, the differences between the two values may well be within the limits of experimental uncertainty for all nuclei except Lu and Eu¹⁵³. For these two there seems to be a real and significant discrepancy. (G. Paulissen and G. Goldring)

II. Crystal Efficiency Calibration and As⁷¹ Half Life

As a part of the work being done on rotational levels, it was necessary to determine as accurately as possible the absolute Na(Tl) crystal efficiency for counting the low energy γ rays involved. Nearly monoenergetic γ -ray sources in the proper energy range were calibrated by integrating over the photopeak and the escape peak which were obtained using a 2×2 -inch well-type Na(Tl) crystal, and correcting this value for leakage through the crystal and attenuation in the canning materials. These sources were then placed in the target position (see Figure 6.2) and again counted. The efficiencies measured at 125 kev and 175 kev using Co⁵⁷ and As⁷¹ sources were 26.9% and 27.2% ($\pm 4\%$) respectively. A back-to-back coincidence measurement at 510 kev using Na²² gave a crystal efficiency at $13.3 \pm 2.0\%$. The error estimates are based on considerations of statistics, electronics drift, and background subtractions.

Previously As⁷¹ γ -ray sources were produced through cyclotron bombardment of Ge⁷⁰ and Ge⁶⁹. This method activates many states whose decay tends to obscure the 175-kev γ ray; however, bombardment of Ge with 3.1-Mev protons does not produce these higher states and sources prepared in this manner emit strong 175-kev γ rays with very little background.

Since the literature differs widely on the magnitude of the As⁷¹ half-life, a measurement of this quantity was also carried out, and the half-life of As⁷¹ was found to be 66.7 ± 2.5 hours. This value is based on an analysis of the decay of the 175-kev photopeak. (P. Alexander)

REFERENCES

1. A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 27, No. 16 (1953).
2. H. Mark and G. T. Paulissen, Phys. Rev. 100, 813 (1955).
3. K. W. Ford, Phys. Rev. 95, 1250 (1954).

4. A. Bohr, "Rotational States of Atomic Nuclei", Ejnai Munksgaards Forlag (1954).
5. K. Alder and A. Winther, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 29, No. 19 (1955).
6. G. M. Temmer and N. P. Heydenburg, Bull. Am. Phys. Soc. I, 43 (1956).
7. N. P. Heydenburg and G. M. Temmer, Phys. Rev. 100, 150 (1955).
8. P. H. Stelson and F. K. McGowan, Phys. Rev. 99, 112 (1955).
9. Rose, Goertzel; Spinrod, Harr, and Strong, Phys. Rev. 83, 79 (1951).
10. Gellman, Griffith, and Stanley, Phys. Rev. 85, 944 (1952).
11. A. H. Wapstra and G. J. Nijgh, Nuclear Physics, 1, 245 (1956).
12. Huus, Bjerregaard, and Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 30, No. 17 (1956).
13. R. D. Sharp, private communication.

ONR Generator Group

I. INTRODUCTION

During the past year, we have continued our general program of nuclear spectroscopy. In this period, considerable progress has been achieved along three related lines of activity. In the first place, the level schemes of a large number of nuclei have been investigated and clarified. Many of these nuclei had not been studied previously. We have also continued the study of means for obtaining such information as the spins and parities of the individual levels, both from the stripping reaction and from the variation of yields with bombarding energy. Finally, the mechanisms of certain reactions have been investigated with particular emphasis on Coulomb excitation and the role of the isotopic spin quantum number. The present status of these various researches is outlined in the following sections.

II. ENERGY LEVELS OF S^{32} AND S^{34}

A study of the (p, α) reactions of Cl^{35} and Cl^{37} has been made, using targets of barium chloride. In order to determine the correct assignments of groups, the charged reaction products were observed at 90 and 130 degrees to the incident proton beam, while the energy of these incident protons was kept constant at 7.04 Mev.

The results are listed in Table 7.I. Almqvist, Clark, and Paul¹ recently reported the ground-state Q-value of the $Cl^{35}(p, \alpha)S^{32}$ reaction to be 1.865 ± 0.015 Mev; the ground-state Q-value of the $Cl^{37}(p, \alpha)S^{34}$ reaction was reported as 3.015 ± 0.015 Mev. The $Cl^{35}(p, \alpha)S^{32}$ Q-value can also be computed from that of the $Cl^{35}(d, \alpha)S^{33}$ reaction² and from the $S^{33} - S^{32}$ mass difference given by Li³. This yields 1.858 ± 0.014 Mev, in very good agreement with our value of 1.863 ± 0.008 Mev and with the value of 1.865 ± 0.015 given by Almqvist et al.

The excitation energies found from inelastic scattering of 8-Mev protons on sulfur are reported by Arthur et al.⁴ Their values are 2.25 ± 0.02 ; 3.81 ± 0.02 ; 4.32 ± 0.02 ; 4.50 ± 0.02 ; and 4.74 ± 0.02 Mev, and are in general agreement with our data. The excitation energy of the first level in S^{32} , as found from the $S^{32}(n, n\gamma)S^{32}$ reaction, has been given by Day⁵ as 2.23 ± 0.02 Mev.

The three lower levels found in S^{34} have also been observed from the $Cl^{34}(\beta^+)S^{34}$ decay⁶ (2.10 ± 0.03 , 3.24 ± 0.03 , and 3.9 Mev) and from the $P^{34}(\beta^-)S^{34}$ decay⁷. Levels at (0.7), 2.1, (3.0), and (3.6) Mev are found from the $P^{31}(\alpha, p)S^{34}$ reaction⁸. A level at 0.82 Mev has also been reported from the $S^{33}(d, p)S^{34}$ reaction⁹. No alpha-particle group corresponding to this excitation energy has been observed in the present work, although the region of the spectrum where such a

group could be expected has been carefully scanned.

TABLE 7.I

Levels in S^{32} and S^{34}

The $Cl^{35}(p, \alpha)S^{32}$ Reaction			The $Cl^{37}(p, \alpha)S^{34}$ Reaction		
Level	Q-Value in Mev	S^{32} Level in Mev	Level	Q-Value in Mev	S^{34} Level in Mev
(0)	1.863 ± 0.008	0	(0)	3.026 ± 0.008	0
(1)	-0.374 ± 0.008	2.237 ± 0.008	(1)	0.899 ± 0.008	2.127 ± 0.008
(2)	-1.917 ± 0.008	3.780 ± 0.008	(2)	-0.276 ± 0.008	3.302 ± 0.008
(3)	-2.424 ± 0.008	4.287 ± 0.008	(3)	-0.889 ± 0.008	3.915 ± 0.008
(4)	-2.602 ± 0.010	4.465 ± 0.010	(4)	-1.047 ± 0.008	4.073 ± 0.008
(5)	-2.835 ± 0.010	4.698 ± 0.010	(5)	-1.088 ± 0.008	4.114 ± 0.008
			(6)	-1.595 ± 0.008	4.621 ± 0.008
			(7)	-1.659 ± 0.008	4.685 ± 0.008
			(8)	-1.850 ± 0.008	4.876 ± 0.008

(P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner)

III. ENERGY LEVELS OF P^{31} AND Si^{28}

Since several gamma rays have been reported from the reaction $Si^{30}(p, \gamma)P^{31}$ and the level scheme of P^{31} is not accurately known, a study of the inelastically scattered protons from the reaction $P^{31}(p, p')P^{31*}$ was undertaken. For this work, thin $Pb_3(PO_4)_2$ targets were bombarded with

TABLE 7.II

Levels in P^{31} and Si^{28}

$P^{31}(p, p')P^{31}$		$P^{31}(p, \alpha)Si^{28}$	
Level	E_x	Level	E_x
		(0)	0
(1)	1.267 ± 0.005	(1)	1.769 ± 0.008
(2)	2.235 ± 0.005	(2)	4.615 ± 0.008
(3)	3.131 ± 0.005		
(4)	3.292 ± 0.005		
(5)	3.414 ± 0.005		
(6)	3.508 ± 0.005		

7.04-Mev protons. The emitted proton groups were observed at angles of 90 and 130 degrees. In addition to the proton groups, three alpha-particle groups corresponding to the reaction $P^{31}(p, \alpha) Si^{28}$ were observed. The results of both reactions have been listed in the foregoing table 7.II.

(P. M. Endt and C. H. Paris)

IV. ENERGY LEVELS OF Cl^{35} AND Cl^{37}

In connection with the (p, α) studies described in the preceding section, the Cl^{35} and Cl^{37} (p, p') reactions were also measured. The results are listed in Table 7.III. Level (6) assigned to Cl^{35} and levels (3) and (4) assigned to Cl^{37} certainly result from inelastic scattering on chlorine, but the observed energy shift is not accurate enough to determine the responsible isotope uniquely.

Levels in Cl^{35} are reported at (0.7), 1.1, and (1.7) Mev from the $S^{32}(\alpha, p)Cl^{35}$ reaction⁸. The doubtful level at 0.7 Mev has not been observed in our work, while the levels at 1.1 and 1.7 Mev agree with those of Table 7.III at 1.221 and 1.763 Mev. No accurate measurements exist of excitation energies of levels in Cl^{37} .

TABLE 7.III

Levels in Cl^{35} and Cl^{37}

$Cl^{35}(p, p')Cl^{35}$		$Cl^{37}(p, p')Cl^{37}$	
Level	Cl^{35} Level in Mev	Level	Cl^{37} Level in Mev
(1)	1.221 ± 0.005	(1)	0.838 ± 0.005
(2)	1.763 ± 0.005	(2)	1.728 ± 0.005
(3)	2.645 ± 0.005	(3)	(3.087 ± 0.008)
(4)	2.695 ± 0.005	(4)	(3.105 ± 0.008)
(5)	3.006 ± 0.005		
(6)	(3.165 ± 0.008)		
(7)	4.058 ± 0.005		
(8)	4.113 ± 0.005		
(9)	4.174 ± 0.005		

(P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner)

V. ENERGY LEVELS OF Ni^{58} , Ni^{60} , AND Ni^{62}

The proton groups from thin nickel targets of natural isotopic abundance (Ni^{58} , 67.9 percent; Ni^{60} , 26.2 percent; and Ni^{62} , 3.7 percent) have been studied at angles of observation of 90

and 130 degrees with an incident proton energy of 7.04 Mev. Thus far, the experiments indicate excited states in Ni^{58} at 1.454, 2.460, and 2.520 Mev. Excited states in Ni^{60} are found at 1.335, 2.160, 2.287, 2.507, 2.782, 2.909, 2.949, 3.045, 3.119, 3.268, and 3.428 Mev, while in Ni^{62} the following excited states are observed: 1.174, 3.323, and 3.398 Mev. However, to obtain an unambiguous assignment of the different proton groups to the responsible isotope, a greater angle shift is needed. (C. H. Paris)

VI. ENERGY LEVELS IN Ne^{20} AND Na^{23}

The analysis of the proton and alpha-particle groups observed from the proton bombardment of thin NaI targets has been completed. Accurate measurements of the Q-values for the particle groups corresponding to levels in Na^{23} and Ne^{20} have been made. In Table 7.IV are listed the excitation energies calculated from measurements on eleven proton groups assigned to the $\text{Na}^{23}(p, p')\text{Na}^{23}$ reaction, together with the Q-values and excitation energies determined from five alpha-particle groups assigned to the $\text{Na}^{23}(p, \alpha)\text{Ne}^{20}$ reaction. These results are the averages of measurements made with 7.04-Mev protons at 130 degrees and 7.45-Mev protons at angles of 45, 60, and 130 degrees with respect to the incident beam. The spread in the measured Q-values was less than 4 kev in most cases.

TABLE 7.IV

Levels in Na^{23} and Ne^{20}

$\text{Na}^{23}(p, p')\text{Na}^{23}$		$\text{Na}^{23}(p, \alpha)\text{Ne}^{20}$	
Level	E_x	Q-value	E_x
(1)	0.440 ± 0.003	2.370 ± 0.008	0
(2)	2.078 ± 0.004	0.735 ± 0.008	1.635 ± 0.006
(3)	2.393 ± 0.007	-1.878 ± 0.008	4.248 ± 0.006
(4)	2.641 ± 0.007	-2.599 ± 0.008	4.969 ± 0.006
(5)	2.705 ± 0.007	-3.261 ± 0.008	5.631 ± 0.006
(6)	2.983 ± 0.007		
(7)	3.678 ± 0.009		
(8)	3.850 ± 0.008		
(9)	3.915 ± 0.010		
(10)	4.431 ± 0.010		
(11)	4.778 ± 0.010		

A typical spectrum of the protons observed from a NaI target is shown in Figures 7.1 and 7.2. Figure 7.1 shows the protons elastically and inelastically scattered at 130 degrees with

Figure 7.1

Proton spectrum observed at 130° from bombardment of a thin target with 7.04-Mev incident protons.

Figure 7.2

Spectrum of elastically scattered protons with energies between 2.2 and 5.0 MeV observed at 60° from bombardment of NaI target. The incident proton energy was 7.45 Mev.

7.04-Mev protons incident on a thin layer of NaI on a Formvar film strengthened with a thin layer of gold. Figure 7.2 shows the spectrum of inelastically scattered protons with energies between about 2.2 Mev and 5 Mev. The groups inelastically scattered from Na^{23} are numbered 1 through 11 in the two figures.

The groups arising from elastically scattered protons from various target nuclei are labeled with the symbol corresponding to the target nucleus. Of the three groups labeled Au^{197} , the most intense one at a distance of 55.5 cm is due to elastically scattered protons from the thin gold backing, while the remaining two are due to inelastic scattering from Au^{197} and correspond to levels at 0.277 and 0.550 Mev.* In the region of the spectrum covered by these two figures, the five alpha-particle groups were also observed.

Previous work⁶ on the energy-level structure of Na^{23} had not resolved the pairs of groups (4) and (5), (8) and (9), and (10) and (11). Our present measurement of 0.440 ± 0.003 for the energy of the first excited state in Na^{23} is in excellent agreement with the value 0.439 ± 0.001 Mev¹⁰ determined from electrostatic deflection of inelastically scattered protons.

The level structure up to about 6 Mev in Ne^{20} has been studied previously by inelastic scattering of protons and deuterons from neon, by the $\text{F}^{19}(\text{d}, \text{n})\text{Ne}^{20}$ reaction and by the $\text{Na}^{23}(\text{p}, \alpha)\text{Ne}^{20}$ reaction. The present investigation has revealed no new levels up to about 6 Mev. A particular objective of the present work was to obtain more accurate measurements of the excitation energies in Ne^{20} , especially for the group corresponding to the 4.969-Mev level, which is of importance for astrophysical reasons¹¹. (W. W. Buechner and A. Sperduto)

VII. ENERGY LEVELS IN A^{36} AND K^{39}

The investigation of the proton and alpha-particle groups observed from the proton bombardment of thin KI targets has been completed and accurate measurements made on sixteen proton groups from the $\text{K}^{39}(\text{p}, \text{p}')\text{K}^{39}$ reaction and on two alpha-particle groups from the $\text{K}^{39}(\text{p}, \alpha)\text{A}^{36}$ reaction. The average results of several measurements indicate levels in K^{39} at 2.526, 2.819, 3.018, 3.600, 3.880, 3.936, 4.080, 4.091, 4.121, 4.472, 4.512, 4.679, 4.735, 4.928, 5.010, and 5.258 Mev, with uncertainties in these values of 10 kev or less. Assignment of all the groups was made on the basis of the amount of shift in energy observed with the known changes in angle and incident energy. Bombardments were made with 7.04-Mev incident protons at angles of 60, 90, and 130 degrees; with 7.17-Mev incident protons at 90 and 130 degrees; and with 7.45-Mev protons at laboratory angles 45, 60, 90, and 130 degrees.

A typical spectrum of the protons observed from the bombardment of a thin KI target on a Formvar film with gold backing is shown in Figures 7.3 and 7.4. The spectrum of Figure 7.3 was

*See Section XII.

Figure 7.3

Proton spectrum observed at 130° from bombardment of a thin KI target. The incident proton energy was 7.45 Mev.

Figure 7.4

Spectrum of inelastically scattered protons with energies between about 2.2 and 5.0 Mev observed at 60° from bombardment of a KI target. The incident proton energy was 7.45 Mev.

obtained at 130 degrees with respect to the incident beam and shows the elastically scattered particles from the target nuclei, in addition to the four groups (Nos. 1 - 4) that are due to inelastic collisions. The spectrum of Figure 7.4 was observed at 60 degrees to the incident beam and with the spectrograph field set so as to analyze protons with energies between 2.2 and 5.0 Mev. Both spectra were obtained at a bombarding energy of 7.45 Mev.

The groups numbered 1 through 16 are all due to inelastic collisions and have been assigned to the $K^{39}(p, p')K^{39}$ reaction. Only one other group from inelastic proton scattering was observed in the energy range shown in the figures, and this group was identified with the one corresponding to the 4.431-Mev state in C^{12} .

In addition to these proton groups, there were two alpha-particle groups and one deuteron group observed in the region covered by these two figures. The deuteron group was identified with the $C^{13}(p, d)C^{12}$ reaction ($Q = -2.718$ Mev), while both alpha-particle groups were assigned to the $K^{39}(p, \alpha)A^{36}$ reaction. The higher energy group with a Q -value of 1.286 ± 0.008 Mev corresponds to the ground-state transition, while the lower energy group ($Q = -0.691 \pm 0.010$ Mev) corresponds to a level in A^{36} at 1.977 ± 0.008 Mev.

Except for the present investigation and a recent study by Schwartz et al.¹², there is no other information on the level schemes in either A^{36} or K^{39} . Schwartz et al. investigated the reaction $A^{36}(\alpha, p)K^{39}$ with 8-Mev incident alpha particles and observed proton groups corresponding to levels at 2.48 and 2.87 Mev in K^{39} .

The present measurement of the ground-state Q -value for the $K^{39}(p, \alpha)A^{36}$ reaction is of particular interest in that it closes a gap in linking the nuclear masses between neon and calcium. (A. Sperduto and W. W. Buechner)

VIII. (d, p) REACTIONS OF THE IRON ISOTOPES

Thin targets of natural iron (91.6 percent Fe^{56}) and of iron oxide enriched in Fe^{54} (96.7 percent), Fe^{57} (84.1 percent) and Fe^{58} (75.1 percent) have been bombarded with deuterons and the resulting protons analyzed with the broad-range magnetic spectrograph. Each of the four targets was bombarded with 6.54-Mev deuterons and the proton spectrum observed at 30 and 45 degrees to the incident beam. A set of four bombardments was also made with 7.01-Mev incident deuterons and the spectrograph set at 10 degrees.

For each exposure, the particle energy range covered by the nuclear track plates in the spectrograph extended from about 6.5 Mev to 14.5 Mev. The excitation in the residual nucleus thus studied extends to about 7.5 Mev in Fe^{56} , 6.0 Mev in Fe^{57} , 8.1 Mev in Fe^{58} , and 4.7 Mev in Fe^{59} . The proton spectrum from each isotope was found to be complex with the level density increasing rapidly with excitation. The 10-, 30-, and 45-degree exposures are currently being analyzed to determine the proper isotopic assignment for each of the proton groups observed. This

analysis is complicated for the lower intensity groups because of the presence of small amounts of the less abundant iron isotopes in each of the targets used here.

TABLE 7.V

Energy Levels for the Iron Isotopes

Fe^{54} from $Fe^{54}(p, p')$ E_x	Fe^{55} from $Fe^{54}(d, p)$ E_x	Fe^{56} from $Fe^{56}(p, p')$ E_x	Fe^{57} from $Fe^{57}(p, p')$ $Fe^{56}(d, p)$ E_x	Fe^{58} from $Fe^{58}(p, p')$ $Fe^{57}(d, p)$ E_x	Fe^{59} from $Fe^{58}(d, p)$ E_x		
			(p, p')	(d, p)	(p, p')	(d, p)	
1.41	0.413	0.845	0.015	0.015	0.80	0.799	0.286
2.55	0.932	2.08	0.136	0.139	1.66	1.664	0.473
(2.56)	1.413	2.66	0.365	0.368	2.12	2.125	0.728
2.58	1.93	2.94	0.710	0.711	2.25	2.25	1.026
2.97	2.06	2.96	1.01	1.01	2.59	2.59	1.166
3.18	2.15	3.12	1.20	1.20	2.77	2.77	1.216
3.31	2.22	3.37	1.27	1.27	2.86	2.87	
3.36	2.31	3.39	1.35	1.36	3.07	3.07	
	2.48	3.45	1.63	1.63	3.22	3.23	
	2.55	3.60	1.72	1.73	3.53	3.53	
	2.59		1.99	1.99	3.62	3.63	
	(2.79)		2.12	2.12		3.75	
	2.82		2.21	2.21		(3.79)	
	2.88		2.22	2.23		3.86	
	2.94		2.45			3.88	
	2.99		2.51			3.90	
	3.04		2.55			4.01	
	3.08		2.57			4.12	
	3.12		2.59			4.16	
	3.32		2.69			4.21	
	3.36		2.76			4.24	
	(3.47)		2.80			4.32	
	(3.53)		2.83			4.35	
	3.56		2.92			4.44	
	3.60		3.06			4.47	
	3.66		3.11			4.51	
	3.71		3.12			4.55	
	3.72		3.18			4.59	
	3.80		3.21			4.62	
	3.86		3.24			4.66	
	3.88		3.28			4.72	
	3.92		3.30			4.81	
	3.98		3.35			4.83	
	4.03		3.37				
	4.06		3.42				
			3.45				
			3.47				
			3.53				
			3.55				
			3.61				
			3.66				
			3.75				

Thus far, only about 20 percent of the observed groups have been assigned to the responsible isotope. The Q-values of the (d, p) reactions leading to the ground states of Fe^{55} , Fe^{57} , Fe^{58} , and Fe^{59} were found to be 7.073, 5.418, 7.808, and 4.350 Mev respectively.

In Table 7.V a tentative list has been given of the excitation energies of the groups thus far measured and assigned.

The level structure for some of the low-lying states in Fe^{55} , Fe^{57} , and Fe^{58} has been previously reported¹³. The present investigation confirms all of the known data and further extends the knowledge of the level schemes to higher energies. In the case of Fe^{59} , no previous work had been done. Of particular interest was the measurement of a prominent group only 15 kev above the ground-state group in Fe^{57} . This confirms the previous measurement of a 14-kev gamma ray observed from the K-capture and positron decay of Co^{57} .¹⁴

The level schemes for Fe^{57} and Fe^{58} have also been studied by means of inelastic proton scattering (see the next section of this report), and the results are in agreement with those from the (d, p) reactions on Fe^{56} and Fe^{57} . (A. Sperduto and W. W. Buechner)

IX. INELASTIC SCATTERING FROM IRON

Isotopically enriched targets of Fe^{54} , Fe^{57} , and Fe^{58} (see the preceding section) have been bombarded with protons at 7.01 Mev and the scattered protons with energies ranging from 3 to 7 Mev have been observed at 130 degrees to the incident beam. Thin targets of natural iron were bombarded with 7.01-Mev protons, and the scattered particles observed at 30, 45, 90, and 130 degrees. In addition, natural iron targets were bombarded with 6.65-Mev protons with observations being made at 90 and 130 degrees to the incident beam.

A large number of proton groups caused by inelastic scattering have been observed. Tentative assignment of these groups to the responsible isotope has been made and the corresponding excitation energies are listed in Table 7.V. Since the scattered protons have been observed at only one energy and angle for the Fe^{54} , Fe^{57} , and Fe^{58} enriched targets, the assignment here is based chiefly on intensity considerations. In the case of levels in Fe^{57} and Fe^{58} , the results from the (d, p) reactions on natural iron and Fe^{57} served as a guide in making these assignments.

It is expected that additional exposures at other angles may be made to check these results and perhaps also to extend the investigation to higher excitation energies. (W. W. Buechner and A. Sperduto)

X. EXCITED STATES OF Mn^{55} AND Co^{59}

During the past year a series of bombardments were made with the MIT-ONR generator, and the work of counting the nuclear track plates and analyzing the observed spectra was carried

out by the staff of the University of Mexico with F. Alba and M. Mazari directing the work there.

Thin targets of manganese and cobalt, both monoisotopic elements, were bombarded with 6.5 and 7.5-Mev protons, and the resulting proton groups from inelastic scattering were observed at 90 and 130 degrees at each energy. In addition, the manganese target was bombarded with 7.0-Mev protons with the spectrograph set at 90 degrees.

The results of some preliminary calculations from the Mn bombardments have been received from Mexico, and these indicate a complicated level scheme for Mn^{55} with at least thirty levels up to an excitation energy of about 3.6 Mev. Additional exposures with thinner targets are being planned in order to improve the resolution in the case of a number of weaker groups where the spacing is of the order of 10 kev. The levels in Mn^{55} thus far observed are at 0.127, 0.98, 1.30, 1.53, 1.89, 2.20, 2.26, 2.27, 2.37, 2.40, 2.57, 2.73, 2.75, 2.83, 2.88, 2.96, 2.98, 2.99, 3.01, 3.04, 3.08, 3.12, 3.16, 3.19, 3.27, 3.34, 3.37, 3.42, 3.53, 3.59, and 3.61 Mev.

Previous workers¹³ covering approximately this same excitation region have reported only fifteen groups.

The proton spectrum from the cobalt bombardment also indicates a large number of levels in Co^{59} . Analysis of the results is currently being made, while additional longer exposures are being planned to increase the yield of several of the weaker groups. (M. Mazari, A. Sperduto, and W. W. Buechner)

XI. EXCITED STATES OF Mn^{56}

Although there have been a number of studies of Mn^{56} using the $Mn^{55}(d, p)$ and the $Mn^{55}(n, \gamma)$ reactions, the results have not been in agreement, and in no case has the number of levels reported been so high as might be expected for an odd-odd nucleus in this mass region. No level of energy less than about 1.1 Mev has been reported from the (d, p) studies, while the gamma-ray data indicate low-lying levels at about 0.11, 0.21, 0.27, 0.31, 0.48, and 0.83 Mev, in addition to a number at energies greater than 1 Mev.

In order to study this nucleus, the broad-range spectrograph was used to study the (d, p) reaction. Exposures were made at angles of 10, 30, and 60 degrees, the deuteron energy being 7 Mev. Data from the 30-degree exposure are plotted in Figure 7.5.

It is apparent that the level scheme is of considerable complexity, twenty-nine excited states being observed between the ground state and 2.5-Mev excitation, and approximately 80 more between 2.5 and 7.0 Mev. Excitation energies corresponding to the observed groups have been calculated and are tabulated in the Master's Thesis of Lts. Green and Smith. Particularly interesting is the region below 1 Mev, in which levels have been found at 0.025, 0.108, 0.207, 0.335, 0.449, 0.479, 0.713, 0.753, and 0.835 Mev. At present, it is not clear whether the 7.261-Mev

115

Figure 7.5

Proton spectrum observed at 30° from MN^{55} targets. Incident deuteron energy was 7.006 Mev.

capture gamma ray observed by Bartholomew and Kinsey¹⁵ arises from a transition to the ground state or to the newly discovered state at 0.025 Mev. (J. W. Green and A. J. Smith)

XII. INELASTIC PROTON SCATTERING FROM GOLD

A reduction of the instrumental background of the broad-range spectrograph made it possible to extend inelastic scattering measurements into the range of the heavy elements. Interesting information can be deduced from the cross sections if the inelastic scattering occurs primarily by Coulomb excitation. Therefore, the inelastic scattering from gold was studied at a proton energy of 6.0 Mev, where the calculated cross section for the formation of a compound nucleus is 0.2 mb, compared with an expected Coulomb cross section of 0.8 mb.

At 6.0 Mev the absolute cross section for elastic scattering from gold was found to agree within 7 percent with the Rutherford formula for angles between 50 and 130 degrees. Protons inelastically scattered to the 279- and 550-keV states were observed at angles of 60, 95, 110, and 130 degrees. The inelastic cross sections were obtained by comparing the number of tracks in the inelastic peak with those in the elastic peak. From the inelastic cross sections, the reduced transition probabilities were obtained. Preliminary values of $B(E2)/e^2 = 0.29$ and 0.41 (the errors have not been computed) for the 279- and 550-keV transitions are obtained, which can be compared with the results of Stelson and McGowan¹⁶ of 0.334 and 0.470 respectively. The status of the 268- and 77-keV states is under investigation. (C. K. Bockelman)

XIII. ANGULAR DISTRIBUTION OF PROTONS FROM DEUTERON BOMBARDMENT OF CALCIUM ISOTOPES

The investigation of the angular distribution of the proton groups emitted from calcium targets under 7-Mev deuteron bombardment has been completed. A summary of the results for $\text{Ca}^{40}(\text{d}, \text{p})\text{Ca}^{41}$ is given in Table 7.VI. An arbitrary figure for the maximum intensity and the angle at which this maximum was observed is given; however, these numbers are subject to a correction of about 10 percent to account for the variation of solid angle as a function of radius of curvature. The last column gives the orbital angular momentum quantum number which gives the best fit in the stripping theory of Butler. A radius of 6.0×10^{-13} cm was used. A dash indicates that the angular distributions observed did not show the characteristic stripping distribution.

The results for the ground state and the levels at 1.947 and 2.469 Mev agree with those of Holt and Marsham¹⁷. The gamma rays following slow neutron capture in Ca^{40} observed by Demidov et al¹⁸ can be fitted to a level scheme employing only those levels that show intense stripping-type angular distributions. These levels are tentatively interpreted as being "single-particle" in nature.

The data for the $\text{Ca}^{42}(\text{d}, \text{p})\text{Ca}^{43}$ and $\text{Ca}^{44}(\text{d}, \text{p})\text{Ca}^{45}$ reactions are still being analyzed. The three calcium angular distributions are being studied from the point of view of the shell model by B. J. Raz and J. B. French; a preliminary report of their results¹⁹ was presented at the Washington meeting of the American Physical Society.

TABLE 7.VI

Summary of the Results from the $\text{Ca}^{40}(\text{d}, \text{p})\text{Ca}^{41}$ Reaction

E_x	θ of Maximum	Intensity at θ_{max}	l
0	40	41	3
1.947	20	258	1
2.014	35	5	2
2.469	20	87	1
2.584	-	1.4	-
2.612	-	2	-
2.677	(7.5)	17	0
2.890	-	3	-
2.967	20	6	1
3.056	-	1.5	-
3.206	-	4	-
3.375	-	1	-
3.405	(7.5)	19	0
3.500	-	1	-
3.531	-	1	-
3.619	20	25	1
3.682	-	0.5	-
3.736	20	15	1
3.837	Not resolved		
3.854			
3.921	-	1	-
3.950	20	158	1
3.982	-	3	-
4.023	-	0.8	-
4.101	-	1.8	-
4.194	-	4	-

(C. K. Bockelman)

XIV. INELASTIC SCATTERING FROM SILVER

Targets of natural metallic silver (51.4 percent Ag^{107} and 48.6 percent Ag^{109}) have been bombarded with protons of 7.04 and 7.45 Mev. The scattered particles were observed at 60 and 130 degrees to the incident beam for the 7.04-Mev bombardments and at 45 and 130 degrees for the bombardments at 7.45 Mev.

In addition to the proton groups arising from elastic scattering, there were observed eight proton groups from inelastic collisions from silver. No other groups up to an excitation energy of

about 3.5 Mev in silver were observed.

Fagg et al²⁰ have recently reported some measurements of gamma rays following inelastic proton scattering from separated isotopes of silver. They report gamma ray energies of 0.319 and 0.419 Mev from Ag¹⁰⁷ and 0.306 and 0.412 Mev from Ag¹⁰⁹. Preliminary calculations from the eight inelastic proton groups that we observed indicate levels in silver at the following energies: 0.31, 0.33, 0.41, 0.42, 0.69, 0.79, 0.86, and 0.95 Mev. The first four groups are in good agreement with the gamma-ray measurements. The latter four groups are relatively weak groups and have not been previously reported. Unique assignment of each group to the responsible silver isotope is not possible from our present measurements. We plan to obtain separated isotopes before more accurate measurements are attempted. (W. W. Buechner and A. Sperduto)

XV. Al²⁷(d, p)Al²⁸ STRIPPING ANALYSIS

Angular distribution measurements have been made on proton groups from the Al²⁷(d, p)Al²⁸ reaction with a deuteron energy of 6.0 Mev and reaction angle 5 to 60 degrees. Twenty-two of the forty-two lowest states have angular distributions that more or less definitely indicate contributions from the stripping process. The proton yields for the remaining twenty of the levels studied are comparatively weak, and the angular distributions are, within the limits of error, fairly isotropic.

The numerical calculations of the stripping curves, the tables, and graphs prepared by Enge and Graue²¹ have been used. These are based on the Butler formula in the form given by Friedman and Tobocman²². Examples of theoretical stripping curves fitted to experimental angular distributions are shown in Figures 7.6, 7.7, and 7.8 for three levels with $\ell_n = 0$, $\ell_n = 1$, and $\ell_n = 2$, respectively. (ℓ_n is the orbital angular momentum of the captured neutron in the stripping process.)

In most of the cases studied, stripping seems to occur only or predominantly with one ℓ_n value. When this is the case, strictly speaking, only one more parameter in the stripping formula can be adjusted to obtain a good fit. This is the reduced width γ of the level. Actually, the theory used is based on rather crude approximations, and we feel that this situation can be improved upon by making small empirical adjustments to the theory. This means introducing other adjustable parameters.

One such adjustment we have made is to use target nucleus radius $R = 6.6 \times 10^{-13}$ cm for all $\ell_n = 0$ curves and $R = 5.4 \times 10^{-13}$ cm for all $\ell_n = 1$ and 2 curves in this work. The latter is the radius given by the Gamow-Critchfield formula for Al²⁷. We also feel it justified to add a small adjustable isotropic "background yield" to the theoretical angular distribution to obtain as good a fit as possible. This yield may be due in part to compound nucleus decay to the level in question.

Figure 7.6

Example of theoretical stripping curve with $\ell_n = 0$ fitted to experimental points.

Figure 7.7

Example of theoretical stripping curve with $\ell_n = 1$ fitted to experimental points.

Figure 7.8

Example of theoretical stripping curve with $\ell_n = 2$ fitted to experimental points.

With regard to the reduced width γ , it is well known that the simple stripping theories predict a too high yield when a reasonable value for γ is used in the formula. We have therefore made no attempt to measure absolute cross sections in order to obtain absolute values for γ . We have, however, found γ for the levels on a relative scale, based arbitrarily on a value $\gamma = 100$ kev for the ground state. The γ values thus obtained should give some kind of a relative measure for the capture probability of a neutron with the specific ℓ_n value to the various states.

The information obtained for the various levels is collected in Table 7.VII. The first column identifies the level by excitation energy. The numbers here are averages of the excitation energies obtained from two previous works^{23, 24}. The second column gives an adjusted total number of proton tracks in the peak measured at the angle where it is a maximum. The adjustment is for varying solid angle along the plate. The third column gives the "background yield" mentioned above. For the levels that do not show any stripping effect, the third column gives the average yield in the angular range studied.

TABLE 7.VII
Results of Stripping Analysis on $\text{Al}^{27}(\text{d}, \text{p})\text{Al}^{28}$

E_x Energy Mev	Counts at Max	Backgr Counts	ℓ_n	$(2J+1)\gamma$	E_x Energy Mev	Counts at Max	Backgr Counts	ℓ_n	$(2J+1)\gamma$
0	24,700	580	0	700	3.701	1,600	200	0	35
0.031	12,800	350	0	360	3.876	720	150	1	120
0.973	-	50	-	-	3.900	-	100	-	-
1.015	3,300	230	2,(0)	600	3.933	-	160	-	-
1.369	-	100	-	-	4.030	650	300	2,(0)	300
1.627	-	320	-	-	4.113	-	50	-	-
2.139	8,100	500	0	220	4.241	1,000	70	0	20
2.202	300	100	2	160	4.312	250	120	2	110
2.273	800	300	2,(0)	400	4.380	-	100	-	-
2.486	1,200	100	0	40	4.462	-	110	-	-
2.583	-	300	-	-	4.515	-	70	-	-
2.657	800	250	2	400	4.593	-	120	-	-
2.986	-	130	-	-	4.685	4,800	700	1	650
3.009	-	50	-	-	4.739	-	250	-	500
3.100	-	90	-	-	4.763	4,100	700	1	500
3.293	960	140	0	20	4.842	-	120	-	-
3.345	1,150	80	0	25	4.902	2,800	500	1	330
3.461	2,300	650	1	320	4.924	-	?	-	-
3.535	-	80	-	-	4.994	-	280	-	-
3.589	2,800	550	1	410	5.014	-	120	-	-
3.668	500	70	0	12	5.133	3,200	500	1	340

The fourth column of Table 7.VII gives the orbital angular momentum of the captured neutron. In the case of the 1.015-Mev level, $\ell_n = 2$ is seven times as probable as $\ell_n = 0$. In the other cases of $\ell_n = 2$ and 0, the zero combination is very small. For the levels with $\ell_n = 1$, a comparatively large contribution of $\ell_n = 3$ may be present but was undetected in this work.

The fifth column of Table 7.VII gives the reduced width times the statistical factor $2J + 1$. The spin of the final nucleus J is undetermined for all cases, except for the ground state and the first excited state²⁴, but is of course tied down to within certain limits by the ℓ_n value found. In particular, all levels showing any $\ell_n = 0$ contribution must have either $J = 2$ or $J = 3$.

In Figure 7.9, lower part, the levels are plotted on a horizontal excitation energy scale.

Figure 7.9

Energy spectrum of Al^{28} from two different reactions.

Above the line are plotted the levels showing stripping contributions with relative amplitudes proportional to $(2J + 1)\gamma$. Below the line are plotted the levels that are not formed by stripping, or perhaps the contribution from the stripping process is undetected in this work because of fairly large fluctuations from point to point in the angular distribution for the low-yield levels. These fluctuations are due to various experimental uncertainties, such as subtraction of general background, disturbing proton groups from target contaminations, and so forth. Below the line the levels are plotted with an amplitude proportional to the average yield.

Figure 7.10 shows a schematic diagram of single-particle excitation levels that may be expected to occur in Al^{28} according to the simple shell model. There seems to be some agreement between this oversimplified scheme and the actual situation (Fig. 7.9). Because the amplitude of the peak maximum in an angular distribution goes rapidly down with increasing ℓ_n value, it is conceivable that some of the levels around 3.5 Mev have a comparatively high undetected $\ell_n = 3$ contribution in their wave function.

Figure 7.10

Levels expected to be formed in Al^{28} by adding neutron to a core of Al^{27} in a pure $d_{5/2}$ state.

An attempt to correlate the (n, γ) work of Kinsey et al²⁵ with the present work is made in the upper part of Figure 7.9. Remarkable is the fact that, for the levels that show $\ell_n = 1$ stripping, strong gamma rays are found connecting these levels with the ground state or the neutron capture state ($J = 2^+$ or 3^+). On the other hand, no strong gamma rays are found that can be assigned to transitions between the neutron capture state and the $\ell_n = 2$ levels. (The dotted lines indicate possibilities; none of them coincides with any $\ell_n = 2$ state.) (H. A. Enge, C. C. Angleman, and D. L. Jarrell)

XVI. THE ENERGY LEVELS OF Be^9

The energy levels of the Be^9 nucleus have been the subject of several recent studies^{26,27,28}. These experiments have been concerned with verifying the results of Moak et al²⁹ and of Almqvist et al³⁰ which showed that the $\text{Li}^7(\text{He}^3, p)\text{Be}^9$ and the $\text{B}^{10}(t, \alpha)\text{Be}^9$ reactions displayed a characteristic edge to the proton and alpha distributions that was interpreted as evidence for a state at 1.8 Mev in Be^9 . In addition, the well-known level at 2.428 Mev^{4,31,32} as well as a broad group attributed to a 3.1-Mev state were observed. Lee and Inglis²⁶ saw alpha groups from the deuteron bombardment of boron, which they assigned to Be^9 levels at 1.75, 2.43, and 3.02 Mev. However, Gosset et al²⁷ in a study of the inelastic protons from a Be^9 target carefully measured the edge of a proton distribution, which corresponded to an excitation of 1.675 ± 0.002 Mev. They suggested that these protons, rather than signifying a 1.8-Mev level in Be^9 , might be associated with the (p, pn) reaction, since the edge energy corresponded closely to the (γ, n) threshold in Be^9 , measured as 1.666 ± 0.002 Mev by the Wisconsin group³³ and 1.662 ± 0.003 Mev at Notre Dame³⁴. The small difference between the edge and the threshold was attributed to a barrier effect. Finally, Rasmussen et al²⁸, studying the inelastic scattering of deuterons and alphas from Be^9 , again saw a broad distribution with a maximum in the neighborhood of 1.74-Mev excitation, the sharp state at 2.43 Mev, and the broad state at 3.1 Mev. By analyzing the shape of the distribution, these authors attempted to answer the question of whether the 1.74-Mev maximum is a state or the edge of a continuum from the three-body breakup. The present work was undertaken concurrently with the work described in references 27 and 28. It was felt that the use of the broad-range spectrograph²³, which permits the simultaneous recording of a wide energy range of reaction products might be profitably used to obtain with reasonable accuracy the shape of the distributions involved.

Figure 7.11 shows the proton count for an incident energy of 7.04 Mev, with the spectrograph set at 130 degrees. At a distance of $d = 11$ cm, the edge of a continuous distribution of protons is seen, superimposed on a background attributed to slit-edge scattering. In a following exposure, the bombarding energy was held constant and the magnetic field changed so as to center the expected 3.1-Mev peak on the third photographic plate where the solid angle of the spectrograph is largest. The results of this exposure are shown on the top half of Figure 7.11. The edge is again seen clearly; this time at $d = 40$ cm. The point at which the edge intersects the background can be

124

Figure 7.11

Spectrum of protons inelastically scattered from a beryllium target.

located with good accuracy in both of these exposures. Using an input energy calculated from the Be^9 elastic peak, the relativistic Q-value is computed to be -1.664 ± 0.005 Mev, in excellent agreement with the (γ, n) threshold^{33,34}.

In order to identify the peaks, another exposure was made at 7.01 Mev and 40 degrees. At this forward angle, the instrumental scattering was worse, so that the edge could not be located with as good an accuracy. However, it and the other peaks were observed, and the following identifications justified. The peak at $d = 28$ cm in the upper part of Figure 7.11 is the well-known Be^9 state, the excitation energy of which is here measured as 2.434 ± 0.005 Mev, in agreement with the work of reference 32. The peak of the broad group ($d = 13$ cm) corresponds to an excitation of 3.03 ± 0.03 Mev in Be^9 ; the uncertainty here arises from the inability to locate the peak to any better accuracy. The other two peaks at $d = 21$ cm and $d = 9$ cm arise from protons inelastically scattered, exciting the 3.09- and 3.68-Mev levels in C^{13} . In addition, a few high points are seen at $d = 6$ cm, the location expected for a peak from the 3.86-Mev C^{13} level. The plate taken at 40 degrees did not cover this region.

While there is no doubt of the existence of the broad peak, its width cannot be stated with accuracy because the momentum analysis does not extend to low enough momenta to locate the level of the continuum on which the peak is superimposed. This uncertainty makes it impossible to measure the true shape of the peak from the present data. Nevertheless, these results show that the width, ΔQ , of the level as seen under these circumstances cannot be less than 280 kev. On the 40-degree exposure, the background from slit-edge scattering was sufficiently high that no better measurement of the width was afforded.

The strong elastic peak at mass 14 raises the question of whether any inelastic scattering from nitrogen might be observed. The positions expected for peaks corresponding to the 2.31 and 3.95 levels are indicated by arrows in Figure 7.11. The computed position for the 2.31-Mev state is a distance of 6.5 mm to the right of, that is 22 kev higher energy than, the observed edge; this separation represents over twice the error expected in the computed location. No evidence for inelastic scattering to this level is observed.

No inelastic peaks are expected from C^{12} or O^{16} in the region studied. The elastic peaks for all the contaminants other than carbon, nitrogen, and oxygen are sufficiently small that no measurable inelastic yield is expected from them.

In order to study further the beryllium levels, magnetic analyses of the alpha particles emitted from a thin film of boron under deuteron bombardment were obtained. The result of a bombardment at a deuteron energy of 7.01 Mev is shown in Figure 7.12.

By means of exposures at bombarding energies between 5.0 and 7.3 Mev at angles of 60 and 90 degrees to the incident beam, it was possible to ascertain that the peak at $d = 35$ cm was caused by alpha particles from the $\text{O}^{16}(d, \alpha)\text{N}^{14}$ reaction ground-state group. The peak at $d = 58$ cm shifted in a manner consistent only with the $\text{B}^{10}(d, t)$ reaction, leading to the ground state of B^9 . Since B^{10}

Figure 7.12

Spectrum of alpha particles plus tritons emitted from a boron target under deuteron bombardment.

is 19 percent abundant in natural boron, the group is not unexpected. The track length expected for tritons at this momentum is quite close to that expected for alpha particles, and no distinction was made in counting them. In the interest of increasing the intensity, this experiment was performed under relatively low-resolution conditions; furthermore, observations were taken with the target in such a position that the emitted alphas passed through the target, tending to displace the positions of the peaks by an amount corresponding to the target thickness. Because of these factors, the energy measurements in this experiment were not of the highest precision. The ground-state Q-value of the $B^{10}(d, t)B^9$ reaction is measured as -2.187 ± 0.010 Mev. A calculation using the masses of Li et al³⁵ predicts a value of -2.176 Mev.

The peaks at $d = 69$ cm and $d = 46$ cm and the broad group at $d = 41$ cm all shift with energy and angle as expected for groups associated with states in Be^9 . The Q-value measured on two observations of the ground state is 8.015 ± 0.010 Mev. Four measurements of the separation between the ground state and the sharp excited state yield an excitation energy of 2.424 ± 0.005 Mev in Be^9 , in good agreement with the results reported here, as well as with those of reference 32. The peak of the broad group is located at 3.05 ± 0.03 Mev excitation, the uncertainty arising from the difficulty of locating the peak to any better accuracy. In Figure 7.12 this peak shows a low-energy side somewhat more ragged than expected from the statistical accuracy alone. As a result, the nominal 325-keV difference in the alpha-particle energies at the half maximum points must be assigned a large error of ± 90 keV. Thus, the width, ΔQ , of the state derived from this measurement is 425 ± 120 keV. However, another observation at 6.5 Mev and 90 degrees yields $\Delta Q = 250 \pm 50$ keV. The reason for this discrepancy is not known. It might, of course, be caused by the presence of an unexpected contaminant peak at about 39-cm distance in Figure 7.12.

A continuous background of alpha particles might be expected from the $B^{10}(d, \alpha)Be^8$ reaction. The Be^9 ground-state group is at a position corresponding to about 9-Mev excitation in Be^8 . Little is known of the alpha spectrum from B^{10} in this region; it may cause the background below the Be^9 ground-state peak, as well as the large rise below the $O^{16}(d, \alpha)$ peak. However, the step in the yield observed at $d = 53$ cm on Figure 7.12 shifts, when bombarding energy and angle are varied, in such a way that it must be assigned to Be^9 . Unfortunately, the exposures taken inadvertently place this edge near a junction of the ten-inch plates, which were obscured for a few mm near their edges. Therefore, measurements of this edge were obtained by extrapolating the slope, in itself fairly poorly defined, until it intersected a straight line drawn through the background. In this manner, an excitation of 1.669 ± 0.010 Mev was obtained, in agreement with results reported here and the (γ, n) threshold of references 33 and 34, but with lower accuracy.

The present results confirm the conclusion of Lee and Inglis²⁶ that a state at 3.04 Mev in Be^9 is produced in the $B^{11}(d, \alpha)$ reaction. As these authors have suggested, the previous high-resolution work of Van Patter et al³¹, using a 180-degree spectrograph, which viewed only a small portion of the spectrum at any one exposure, appears to have missed this broad state of relatively low yield at the peak. In Figure 7.12, the peak yield of the 2.43 level is ten times that of the

3.04-Mev level. This state is also observed with inelastic protons from Be^9 , although it was not reported in earlier work⁴. However, it appears possible that peaks (g) and (j) of Figure 1 in reference 4, interpreted there as deuterons from the $\text{Be}^9(p, d)\text{Be}^8$ reaction, may have actually been protons³⁶. If this is the situation, these two peaks correspond to excitations of 1.8 and 3.1 Mev in Be^9 . Since recent experiments do not support the existence of levels in Be^8 at 4.0 and 5.1 Mev, the reinterpretation seems reasonable. From the present observations, the width of the 3.04-Mev state is at least 280 kev.

The edge of the continuous distribution lies at the energy that would be expected for the threshold of the three-body reaction. It therefore appears that it may be incorrect to interpret the rise as evidence for a level. Perhaps the question is best answered by attempting to compute the expected shape by the method outlined by Watson³⁷ and applied to this particular problem by Rasmussen et al²⁸. These authors have pointed out that, for given assumptions regarding the interaction between Be^8 and the neutron, one can compute the relative number of, say, alpha particles per unit momentum interval dN/dp , in terms of the alpha-particle momentum p and the momentum of the neutron relative to the Be^8 nucleus q . For the $\text{B}^{11}(d, \alpha n)\text{Be}^8$ reaction, conservation of energy and momentum give:

$$\frac{q^2}{2\mu} = W - \frac{(M + M_8 + M_n)p^2}{(M_8 + M_n) 2M} \quad (1)$$

where M_n = neutron mass

M_8 = Mass of Be^8

μ = $\frac{M_n M_8}{M_n + M_8}$

M = alpha-particle mass

W = energy available for breakup of the compound nucleus.

In Figure 7.13a a portion of the alpha-particle data shown in Figure 7.12 has been replotted as the number of alphas per 1-mm strip versus distance. In Figure 7.13b a similar treatment has been applied to part of the proton data from the upper part of Figure 7.11. For this reaction, q is also given by Equation (1) if the proton mass and momentum are substituted for M and p , respectively.

The alpha-particle (or proton) momentum distribution in the case of no interaction between alpha (or proton), neutron, and Be^8 is given by $dN/dp \sim p^2 q$. This expression, transformed into the laboratory system and written in terms of the number of particles per unit distance on the photographic plate yields the dashed curves in Figure 7.13. (In the figure, the data have not been corrected for the solid-angle transformation from center-of-mass to laboratory system nor for the variation in solid angle with position on the plate. This variation is essentially linear, the solid angle at 29 cm being approximately 8 percent greater than that at 40 cm.) This expression clearly

does not fit either set of data.

Figure 7.13

Expected distributions from three-particle reactions. The dashed curves are the distributions expected for no interaction between the neutron and Be^8 . The solid curves graph the distributions in the case of an s-wave potential scattering of the neutron by Be^8 of strength measured by a scattering length of 2×10^{-12} cm.

If one assumes that there is no interaction between the alpha (or proton) and the other particles, but an s-wave potential scattering of the neutron by Be^8 , characterized by a scattering length $a = \pi/\alpha$, the distribution is expected to follow $dN/dp \sim p^2 q / (\alpha^2 + q^2)$. This expression is represented by the solid curves in Figure 7.13 drawn for $a = 2 \times 10^{-12}$ cm, which fits the (d, dn) data²⁸, and which represents a reasonable size for the scattering length of Be^8 . This suggests that the simple interaction chosen is insufficient. More complicated interactions are possible, but it seems unprofitable to introduce more parameters until more data pertinent to this problem are available. Therefore, in agreement with the conclusions of the authors of references 27 and 28 it is felt that, although a 1.8-Mev state is unlikely, it cannot be ruled out until a detailed fit of all the data can be obtained.

Recently, Kurath has published the result of intermediate coupling calculations in the $1p$ shell³⁸. If, as seems most likely, there is no state of Be^9 at 1.8 Mev, then the Be^9 level positions

are well fitted with a choice of the coupling parameter similar to that which applies to nearby nuclei. This conclusion would be strengthened if the 3.04-Mev state were assigned a spin of $1/2$ and negative parity. If this level decays primarily by neutron emission to the ground state of Be^8 , its reduced width can be computed simply³⁹ for various values of the orbital angular momentum of the emitted neutron, ℓ . The Wigner sum rule⁴⁰ places an upper limit to the reduced width. For an interaction radius of 3×10^{-13} cm, these considerations limit ℓ to 1, and thereby the spin of the 3.04-Mev level to $\leq 3/2$. However, since the level width of 280 kev used in this calculation is only a lower limit, a better measurement might limit the ℓ to 0 and the spin and parity to $1/2^+$.

XVII. INELASTIC SCATTERING FROM In, Cd, Sm, AND Tb

Inelastic proton scattering has been used as a spectroscopic tool to obtain information about several medium- and heavy-weight nuclei. Levels were observed in indium, cadmium, samarium, and terbium.

The absolute cross sections for inelastic proton scattering from these nuclei were determined as follows. The ratio of the cross sections of the inelastically to the elastically scattered particles was measured. The ratio of the elastic cross section to that predicted for Rutherford scattering was then determined by taking exposures with decreasing incident energy until the characteristic $1/E^2$ variation of the cross section was observed. The absolute cross sections were computed from the product of these two ratios, and from the Rutherford cross section.

A. Indium

In indium, four levels were observed at 1.982, 1.292, 1.135, and 1.078 Mev. The last three have not been previously reported. The angular variation of the absolute cross sections at 7.0 Mev were determined for these levels. Typical data for three of the angles of observation are shown in Figure 7.14. The measured ratios of inelastic to elastic cross sections determined at the various angles were related to each other by an experimental determination of the angular variation of the elastic cross section. The resultant angular distributions of the inelastic cross sections of the four levels observed are shown in Figure 7.15.

One or more of three mechanisms are expected to contribute to the inelastic scattering cross sections: Coulomb excitation, direct interaction, and compound nucleus formation. The experimental angular distributions do not agree with those expected from a Coulomb excitation process⁴¹, and the cross section for this process, as expected from the known electric quadrupole moment of indium⁴² is smaller than the measured cross section. It corresponds approximately to 0.02 millibarns per steradian at 90 degrees (see Fig. 7.15). It therefore appears that the levels are not primarily Coulomb excited.

Three of the distributions show a decided asymmetry about 90 degrees, which would indicate that compound nucleus formation is not the sole excitation process. The strong forward maxima

Figure 7.14

Data for angular distribution $\ln(p, p)$ - 7.04 Mev.

Figure 7.15

Experimental angular distributions inelastic proton scattering $E_{\text{in}} = 7.0$ Mev. Natural indium targets.

exhibited in these three distributions are indicative of a direct interaction process⁴³, and it is concluded that this is an important contributor to the cross sections of these levels at this energy.

B. Cadmium

The bombardment of targets of natural cadmium resulted in eight groups of inelastically scattered particles being observed, corresponding to levels in the region of excitation between 300 and 700 kilovolts. Two of them at 585 and 641 kev have not been previously reported (Figure 7.16). The absolute cross sections for the formation of these levels have been measured, and the variation of this cross section with incident energy (7.0 and 6.0 Mev), angle of observation (130 and 105 degrees), and type of bombarding particle (protons and deuterons) have been measured in order to obtain information about the nature of the excitation process (see Table 7.VIII). From the comparison of these variations with those expected from a Coulomb excitation process, it does not appear justifiable to conclude that this is the only significant mode of excitation in this range (see Table 7.IX).

TABLE 7.VIII

Cross-Section Measurements on Cadmium

Excitation energy (kev):			300	346	514	558	585	619	641	659
Assumed Isotope:			113	111	116	114	?	112	?	110
Exposure Conditions $E_{in}(Mev)$ θ Particle	$\sigma \times I$ σ		.017	.027	.033	.14	.024	.11	.046	.068
			.14	.21	.43	.49	-	.47	-	.54
7 130 protons	ϵ		26	22	20	10	19	10	21	12
	$\sigma \times I$		.027	.027	.058	.25	.040	.22	<.008	.079
7 130 deuterons	σ		.22	.21	.77	.86	-	.92	-	.64
	ϵ		17	16	10	10	12	10	--	10
6 130 protons	$\sigma \times I$		<.01	<.01	.028	.078	.014	.051	.013	.025
	σ		-	-	.37	.27	-	.21	-	.20
7 105 protons	ϵ		--	--	23	13	36	32	39	23
	$\sigma \times I$		-	-	.055	.18	.052	.12	.046	.083
	σ		-	-	.72	.61	-	.50	-	.67
	ϵ		--	--	21	10	19	10	19	11

σ = absolute cross section in millibarns per steradian

I = isotopic abundance of parent isotope of level

ϵ = estimated percentage error

Figure 7.16

Spectra of protons scattered from terbium, samarium, and cadmium targets.

TABLE 7.IX

Ratios of Cross Sections

Excitation (kev)	300	346	514	558	585	619	641	659
$\sigma(E_{in}, \theta, \text{and particle})$								
$\sigma(6-130-p)^*$	<1.4	<1.0	.87±.26	.57±.09	.60±.25	.47±.16	.25±.11	.39±.10
$\sigma(7-130-p)^{**}$	.83	.83	.79	.78	.78	.77	.77	.76
$\sigma(7-105-p)^*$	-	-	1.7 ±.5	1.2 ±.1	2.2 ±.6	1.1 ±.2	1.0 ±.3	1.2 ±.2
$\sigma(7-130-p)^{**}$	1.08	1.08	1.09	1.09	1.09	1.10	1.10	1.10
$\sigma(7-130-d)^*$	1.5 ±.5	1.0 ±.3	1.8 ±.4	1.7 ±.2	1.6 ±.4	1.9 ±.2	<0.3	1.2 ±.2
$\sigma(7-130-p)^{**}$	1.9	1.9	1.7	1.7	1.7	1.7	1.7	1.7

* measured

** calculated

In particular the ratios of the cross sections at 6 Mev to those at 7 Mev, $(\sigma_6 - 130-p)/(\sigma_7 - 130-p)$, except for one, are all lower than the predicted ones. A cross section, increasing with energy slightly faster than Coulomb excitation, would seem to indicate an additional process beginning to be important in this range. That the effects of this other process are not dominant even at 7.0 Mev is indicated by the fact that the ratios of the cross sections for inelastic deuteron scattering to those for inelastic proton scattering, $(\sigma_7 - 130-d)/(\sigma_7 - 130-p)$, are nearly as predicted for five of the levels. The 641-kev level does, in fact, disappear with deuteron bombardment and, therefore, appears to be excited almost completely by this other process.

Since the observed variations are not in serious disagreement with the predictions of Coulomb excitation theory for most of the levels at 7.0 Mev and also since Coulomb excitation is expected to become more dominant as the energy is decreased, the cross sections at 6.0 Mev are expected to result primarily from Coulomb excitation. The reduced electric quadrupole transition probabilities were therefore calculated for those levels of known isotopic parentage that were observed in the 6.0-Mev exposure. They are:

Excitation (kev)	514	558	619	659
$B_{E2}/e^2(10^{-48} \text{ cm}^4)$	.68	.52	.42	.42

B. Samarium and Terbium

In the rare earths, samarium and terbium, four previously known levels were studied. They are the 58- and 139-kev levels in Tb^{159} , the 80-kev level in Sm^{154} , and the 123-kev level in Sm^{152} .

The absolute cross sections for the formation of the terbium levels have been measured at 130 degrees and 5.0, 6.0, and 7.0 Mev. The cross section of the samarium levels has been measured at 7.0 Mev and 130 and 90 degrees. The reduced transition probabilities calculated, assuming electric quadrupole Coulomb excitation, are in agreement for the various levels at the different energies and angles of observation. It was therefore concluded that Coulomb excitation is the dominant process in the formation of these states in this energy range. The weighted averages for the transition probabilities determined from the various exposures are shown in Table 7.X. The expected precision of these measurements is approximately 10 percent.

TABLE 7.X

<u>Nucleus</u>	<u>Excitation in kev</u>	B_{E2}/e^2 <u>(10^{-48} cm^4)</u>
Tb ¹⁵⁹	58	3.5
Tb ¹⁵⁹	139	1.2
Sm ¹⁵⁴	80	3.2
Sm ¹⁵²	123	3.0

The lifetime of the 123-kev level has previously been measured by fast coincidence techniques, and the resulting transition probability $3.3 \times 10^{-48} \text{ cm}^4$ is in good agreement with these results⁴⁴. The measured ratio of the transition probabilities to the two states in the Tb¹⁵⁹ nucleus (2.8 ± 0.4) can be compared with the ratio predicted from the collective model of Bohr and Mottelson (1.8). This disagreement, although not too serious, is probably indicative of the inadequacy of the simple approximations upon which the model is based. (R. D. Sharp)

XVIII. EXCITED STATES OF F¹⁹ AND O¹⁶

Thin targets of barium fluoride have been bombarded with protons obtained from the MIT-ONR generator at various energies between 7.0 and 7.3 Mev. The protons and alpha particles scattered at angles of 60, 90, and 130 degrees were analyzed with the 90-degree magnetic spectrograph.

From the inelastically scattered proton groups the following levels in F¹⁹ were found: 0.111, 0.197, 1.350, 1.462, 1.558, 2.784, 3.912, 4.002, and 4.036 Mev. The scatter in the individual values obtained at different angles indicates that the random error is 1 kev.

From the alpha-particle groups, the Q-value for the reaction F¹⁹(p, α)O¹⁶ was found to be 8.110 Mev; and the following values were obtained for the energy levels of O¹⁶: 6.051, 6.131, 6.920, 7.120, 8.874, 9.852, 10.363, and 11.089 Mev. The random error in these values is 3 kev. (G. L. Squires)

XIX. THE $C^{12}(p, p')C^{12}$ REACTION

A recent calculation⁴⁵ on direct interaction inelastic proton scattering stimulated interest in a measurement of the angular distribution of protons inelastically scattered from C^{12} . The desire was to choose a nucleus and a bombarding energy such that only one level could be excited. The first level in C^{12} , lying at 4.431 Mev, is ideal because the next level is more than 2 Mev above it.

To hope to observe the direct interaction process, one should seek a bombarding energy such that compound nucleus formation is small. Thus, one should measure the yield of the inelastic proton group as a function of energy and then choose energies as far away from resonances as possible for the angular distributions.

Previous measurements^{46, 47, 48} of elastically scattered protons of gamma rays from inelastic scattering showed resonances at 4.8 Mev, 5.37 Mev, and 5.90 Mev, with an indication of another resonance around 7 Mev.

In the present work, the yield of protons leaving C^{12} in the 4.43-Mev level was measured at an angle of 45 degrees in the laboratory system for bombarding energies from 5.4 to 6.9 Mev. The protons were counted with the scintillation counter mounted in the broad-range spectrograph.

As shown in Figure 7.17, the resonances at 5.3 Mev and 5.9 Mev are observed with a smooth, gradually rising yield above the latter. This curve was taken with an input energy spread of about 0.1 percent and a target thickness of about 5 kev. The input energy was varied in steps of 30 kev, except in the region of the 5.90-Mev resonance, where 12-kev steps were used. As shown on the curve, the observed half-width of this resonance is 59 kev. Subtracting incident energy spread and target thickness leaves a width of about 55 kev, in agreement with previous measurements. The peak of the resonance lies at 5.891 Mev. Angular distributions were taken at energies of 6.13, 6.51, and 6.90 Mev. These energies are marked by arrows on the yield curve.

At each angle, an exposure was made at each of the three energies on one strip of a nuclear track plate. The spectrograph field was varied to separate the three groups. In view of the slow variation in the yield at these energies, the slight variations in input energy (± 0.1 percent) caused by this process of cycling the field of the input magnet introduced a negligible error.

The absolute cross section was determined by comparing the yield of the inelastic protons with the known yield of protons from the $C^{12}(d, p)$ reaction⁴⁹. The comparison was made at 90 degrees with an incident proton energy of 6.90 Mev and an incident deuteron energy of 3.29 Mev. The target was not moved between exposures. The (d, p) yield was measured before and after the (p, p') yield, the two runs agreeing to within 4 percent.

The angular distributions are shown in Figure 7.18, with the absolute differential cross section plotted against center-of-mass angle. Background from slit-edge scattering prevented observation at angles below 10 degrees.

Figure 7.17

Yield of inelastic protons from first excited state of C^{12} .

Figure 7.18

Angular distributions of inelastic protons from first excited state of C^{12} .

The curves bear little resemblance to those predicted for direct interaction. The direct interaction process leads to a forward maximum with a pronounced dip at about 70 degrees, rising again to around 0.6 of the forward yield at 150 degrees⁵⁰. The most serious discrepancy, however, is in the absolute cross section which is about 100 times the theoretical value for direct interaction.

Recent work of Schneider⁵¹ on the elastic scattering of protons from C¹² indicates the presence of other levels in this region that do not appear in the inelastic yield because of a high centrifugal barrier. It is to be noted that the present yield curve, while confirming resonances at 5.3 and 5.9 Mev, gives no indication of a level at 6.65 Mev. It is possible, however, that a broad level somewhere above 7.3 Mev overlapping the broad level reported by Schneider at 6.65 Mev could account for the observed yield. In any case, it seems that the number and width of levels in the region are sufficient to make compound nucleus formation the predominant effect overshadowing any direct interaction.

XX. THE O¹⁶(d, α)N¹⁴ REACTION

The measurements on the yield of the alpha particles leading to the ground state and first two excited states of N¹⁴, which were previously reported, have been extended. A stable oxygen target was provided by evaporating SiO₂ onto Formvar. The ground-state alpha group was recorded with a scintillation counter and nuclear emulsions, while the groups to the first excited state (isobaric-spin forbidden group) and to the second excited state were recorded on nuclear emulsions.

Typical plots of the observed alpha groups at several bombarding energies are shown in Figure 7.19. The ground-state group and the first and second excited-state groups are labeled (0), (1), and (2), respectively. Other groups come from the Si²⁸(d, α)Al²⁶ reaction.

The identification of the forbidden group was based on three factors: the agreement of the excitation in N¹⁴ with the known position of the first excited state; the constancy of the ratio of the intensity of this group to the intensity of the ground-state group for targets of MgO, LiOH, and SiO₂; and the constancy of the calculated excitation in N¹⁴ with changing bombarding energy and angle of observation. Typical data for the third method are shown in Table 7.XI. The significant point here is the constancy of the excitation, rather than the absolute number which is uncorrected for target thickness and, hence, is somewhat higher than the accepted value for the first N¹⁴ level.

The yields of the three alpha groups are plotted as a function of energy in Figure 7.20. The angle of observation was 30 degrees. The counter and plate data for the ground-state group are seen to agree closely.

Figure 7.21 shows an enlarged plot of the first excited-state group, emphasizing the resonance-like form of the yield curve.

The angular distributions of the ground state and first two excited-state groups are shown in Figure 7.22. The bombarding energy was 7.03 Mev. The data for the ground-state distribution

DEUTERONS ON SiO_2 TARGET

Figure 7.19

Five plots of alpha particles from SiO_2 targets at various bombarding energies.

TABLE 7.XI

Data for Identification of Forbidden Group

<u>Deuteron Energy</u>	<u>Angle</u>	<u>Target</u>	<u>Excitation in N^{14} (Mev)</u>
5.50	30°	SiO ₂ No. 1	2.321
6.00	"	" "	2.322
6.25	"	" "	2.320
6.50	"	" "	2.321
6.72	"	" "	2.323
7.01	"	" "	2.320
7.50	"	" "	2.321

7.03	15°	SiO ₂ No. 1	2.313
"	30°	" "	2.319
"	50°	" "	2.322
"	70°	" "	2.318
"	80°	" "	2.318

Figure 7.20

Yield of alpha groups leading to the ground state and first two excited states of N^{14} .

Figure 7.21

Yield of first excited-state group.

Figure 7.22

Preliminary data for angular distribution of ground state and first excited state of N^{14} .

were taken in three separate runs using the 70-degree point (laboratory system) for normalization. Target stability was checked by repeat measurements. Once the ground-state distribution was known, the two excited-state distributions were plotted from the intensity ratios as determined from the single exposures made at each angle. Errors arising from current integration or target nonuniformity should not affect the intensity ratios.

Figure 7.23 shows the region in the compound nucleus (F^{18}) involved in the present

Figure 7.23

Energy-level diagram of the compound nucleus F^{18} .

experiment, as well as the known levels extending to about 10.5 Mev. The solid lines between 13 and 14 Mev have been drawn to match the peaks in the ground-state alpha-group yield, while the dotted lines correspond to the maxima in the forbidden-group yield. This assumes that the

variations in yield are caused by the formation of levels in the compound state with $T = 0$ or $T = 1$. It is probable that groups of levels are involved rather than single levels. Where the group contains one or more $T = 1$ levels, the decay to the $T = 1$ state in N^{14} is enhanced, and the decay to the $T = 0$ levels is diminished.

It is to be noted that, in order to make any meaningful comparison of the allowed and forbidden intensities, observations over a range of energies and angles must be made. Estimates of the validity of the isotopic spin-selection rule based on a single observation depend on chance location of the energy with respect to resonances.

Both from the yield curve and the angular distributions, it is seen that the isobaric spin-selection rule has a strong effect on the yield of the first excited-state group, but the group is not completely inhibited.

While a yield curve at several angles would be necessary to determine the ratio of the total cross sections for the forbidden and allowed groups, an order of magnitude may be obtained from the present data. For the ratio of the forbidden group to the ground-state group, this ratio is a few percent. MacDonald⁵² has shown that an impurity of this magnitude might be expected in an energy state of O^{16} because of Coulomb forces in the nuclear core. Thus, the present results are explainable on the basis of Coulomb forces and do not indicate a violation of charge independence of nuclear forces.

It is interesting to note the approximate symmetry of the forbidden group angular distribution as opposed to the asymmetry of the allowed groups. This supports the hypothesis that a single $T = 1$ level in a group of $T = 0$ levels of F^{18} is responsible for the resonances in the forbidden group yield. (C. P. Browne)

XXI. THE $O^{16}(d, d)O^{16}$ REACTION

As part of the experiment on $O^{16}(d, \alpha)$ outlined in the preceding section, the absolute cross section for the $O^{16}(d, d)O^{16}$ reaction has been determined from 4.590 to 7.196 Mev deuteron energy (lab) at 135.54 degrees angle of observation in the center-of-mass system and from 4.570 to 7.006 Mev at 97.24 degrees (see Figure 7.24).

These results were obtained with a counter constructed for this and other similar experiments. The counter is a cesium-iodide scintillation counter mounted in the broad-range magnetic spectrograph. A relative pulse height calibration curve for this counter is shown in Figure 7.25. The counter consists of a polished CsI(Tl) crystal 0.8 mm thick cemented with Araldite directly to the face of a 6199 multiplier phototube. The tube is operated at -500 volts. The tube and crystal are mounted within a lead shield of about 3π geometry and 3 cm average thickness. This lead shield suppresses gamma background to the extent that no counting corrections were necessary for this experiment. The signal from the multiplier phototube is amplified by a standard Los Alamos

-144-

Figure 7.24

Yield of elastically scattered deuterons from O^{16} .

Model 100 preamplifier-amplifier combination, and the pulses are counted by two scale-of-64 counters that are adjusted as a single channel to count the desired particle group.

Figure 7.25

Relative response of CsI (Tl) crystal to protons, deuterons and alpha particles.

The 135.54-degree (C.M.) data consist of nine overlapping counter runs and the 97.24-degree (C.M.) data consist of three overlapping runs. The absolute cross section was determined at two points on the 135.54-degree (C.M.) deuteron yield curve by comparison with the yield of protons from $O^{16}(p, p)O^{16}$. The $O^{16}(p, p)O^{16}$ cross section is known from the work of Eppling⁵³. The yields of $O^{16}(d, d)O^{16}$ and $O^{16}(p, p)O^{16}$ were compared using nuclear track plates in the broad-range magnetic spectrograph.

The cross sections determined are:

$$\sigma_{CM} = 14.1 \text{ mb/steradian} \pm 5 \text{ percent at } 135.54^\circ \text{C.M., } E_d = 6.203 \text{ Mev (lab)}$$

$$\sigma_{CM} = 59.35 \text{ mb/steradian} \pm 5 \text{ percent at } 135.54^\circ \text{C.M., } E_d = 5.449 \text{ Mev (lab)}.$$

These are based on the following values for the $O^{16}(p, p)O^{16}$ cross section determined by Eppling.

$$\sigma_{CM} = 95 \text{ mb/steradian at } 122.25^\circ \text{C.M., } E_p = 2.999 \text{ Mev (lab)}$$

$$\sigma_{CM} = 93 \text{ mb/steradian at } 134.44^\circ \text{C.M., } E_p = 2.999 \text{ Mev (lab)}$$

At $E_d = 5.449 \text{ Mev}$, the deuteron yield at 97.24 degrees (C.M.) was measured relative to the yield at 135.54 degrees (C.M.) and is $0.178 \pm 4 \text{ percent}$ in the center-of-mass system.

The 135.54-degree curve displays eight maxima, which are summarized in Table 7.XII. These peaks are superimposed on a background that has the appearance of a broad resonance peaked

at $E_d = 5500$ kev with an estimated width of 750 kev. This effect is similar to the broad resonances in neutron cross sections calculated by Feshbach, Porter, and Weisskopf for the "Cloudy Crystal Ball Model".

TABLE 7.XII

Level	$B\rho$ Kg-cm.	<u>135.54°</u>	Excitation in F^{18} Mev	$B\rho$ Kg-cm.	<u>97.24°</u>	Excitation in F^{18} Mev
		E_d Mev ± 10 kev			E_d Mev ± 10 kev	
1	445.80	4.756	11.751	448.72	4.818	11.806
2	460.98	5.084	12.042	(463.17)	(5.133)	(12.086)
3	484.56	5.617*	12.516	-	-	-
4	491.15	5.771	12.653	491.88	5.788	12.668
5	504.49	6.088	12.934	505.59	6.115	12.958
6	517.29	6.401	13.212	-	-	-
7	523.95	6.566	13.359	-	-	-
8	530.64	6.735	13.509	(533.02)	(6.795)	(13.562)

* ± 20 kev

At $E_d = 5.491$ Mev, a sharp increase in yield was observed while using a target of 12-kev thickness and must be regarded as an unexplained counting anomaly, since it occurred on only one of the four runs over this point at 135.54 degrees (C.M.).

The cross section at 97.24 degrees is seen to vary about the Rutherford cross section. The maxima that appear above the Rutherford cross section are summarized in Table 7.XII adjacent to those maxima in the 135.54-degree cross section to which they appear to correspond. In each case the maxima shift to higher energy relative to the 135.54-degree data.

The fact that structure is observed in the cross sections clearly indicates compound nucleus effects. It is not, however, possible to analyze the apparent level structure at the present time without more data; specifically, a measure of the level widths and partial level widths.

(D. W. Berger and O. J. Loper)

XXII. THE $Si^{28}(d, \alpha)Al^{26}$ REACTION

In view of the results on the violation of the isobaric spin-selection rule in the $O^{16}(d, \alpha)N^{14}$ reaction (Section XX), it was decided to reinvestigate the $Si^{28}(d, \alpha)Al^{26}$ reaction. Previous measurements⁵⁴ at an observation angle of 90 degrees had shown five levels in Al^{26} up to 2.06-Mev excitation with the lowest at 0.418 Mev. A state at 0.23 Mev was known from gamma-ray measurements⁵⁵. Failure to observe an alpha group leading to this level indicated that this is the expected

$T = 1$ state.

Alpha groups have now been measured at 30 degrees with bombarding energies from 5.5 to 7.5 Mev and at angles from 15 to 130 degrees with 7.03-Mev bombarding energy. The broad-range spectrograph was used to separate the alpha groups, and both nuclear track plates and a scintillation counter were used to detect the particles.

A group corresponding to a state at 0.228 ± 0.005 Mev was observed in addition to the previously reported groups. Identification was based on energy shift, angle shift, and change of isotopic abundance. The yields of this state, the ground state, and the 0.418-Mev state were measured at 250-kev intervals at 30 degrees. Between 6.25 and 7.03 Mev, the ground-state yield was measured at 25-kev intervals. The results are shown in Figure 7.26. It is seen that strong resonances appear in spite of the fact that the excitation of the compound nucleus is 16 to 18 Mev. The forbidden group varies by a factor of 10 in intensity, and the ratio of this group to the ground-state group varied from 2 to 65 percent.

Figure 7.26

Yield curve from $\text{Si}^{28}(\text{d}, \alpha)\text{Al}^{26}$

At 7.03-Mev bombarding energy, the ratio decreases from 62 percent at 15 degrees to 12 percent at 60 degrees. The forbidden group is not seen at greater angles.

From the figure, it is evident that, in order to determine the degree to which the isobaric spin-selection rule holds, measurements must be made over a range of energies. In general, the forbidden group has a relatively low intensity, but at certain bombarding energies and angles of observation, its intensity becomes comparable to that of the allowed groups. As in the case of the $O^{16}(d, \alpha)N^{14}$ reaction, the appearance of the forbidden group is explainable solely on the basis of Coulomb forces. (C. P. Browne)

XXIII. APPARATUS DEVELOPMENT

While most of the effort of the group has been devoted to researches of the types in the preceding sections, there have been three developments in experimental techniques that have general applicability to work in this field.

1. Apparatus for measuring target thickness.

We have hitherto had no reliable way of measuring the thickness of thin targets, except by one or another cumbersome method involving at least one exposure with use of the spectrograph. Previously reported attempts⁵⁶ to measure thicknesses by placing the target between an alpha source and a scintillation counter, separated by almost the range of the particles in air, were not altogether successful. Far better results have now been obtained by using an end-window Geiger-Mueller counter instead of the scintillation counter.

The D.C. current through the Geiger counter is measured without any target between the source and the counter; the target is then brought into the beam of alpha particles, and the source is moved closer to the counter so that the current stays constant. The necessary displacement of the source is the air equivalent of the target. (H. Enge and M. Wahlig)

2. Gas target.

During this year, a gas-target assembly has been constructed and tested. Nickel foils are used for the entrance and exit windows. The assembly is mounted on a cover plate which is interchangeable with the lid of the target chamber of the broad-range spectrograph. In the present model, observations are possible only at angles near 90 degrees to the beam, but the design can be easily adapted for other angles. (F. J. Eppling and D. L. Helfer)

3. Rotating target mount.

Targets with low heat conductivity on Formvar backings have a tendency to break when exposed to beam currents in excess of a few hundredths of a microampere. The remedy heretofore has been to evaporate a thin layer of a heat-conducting heavy element (for example, gold) onto the Formvar backing before evaporating the actual target material onto it. Another possible remedy is to move the target continuously when exposed so that the heat is dissipated over a larger area. The number of undesirable elements present in the target and backing are hereby kept to a minimum.

Also, the surface contamination collected on the target at the spot where it is hit from the beam will be spread out over a larger area and will therefore be less bothersome.

We have acquired a rotating target holder in which the target on Formvar backing is supported by a ring-shaped frame of about an inch in diameter. The frame in turn is mounted in a ring gear resting on two smaller gears, one of which is driven and the other, free. The beam strikes the target about 7 to 8 mm from the center, so that, when the target rotates, the exposed area is a ring of mean radius 7 to 8 mm.

The gears are driven by an electric motor outside the target chamber with a magnetic coupling through the lid of the chamber and a flexible shaft inside. The target makes approximately one revolution per minute. (H. Enge)

REFERENCES

1. Almqvist, Clark, and Paul, Phys. Rev. 100, 1265 (A) (1955).
2. Paris, Buechner, and Endt, Phys. Rev. 100, 1317 (1955).
3. C. W. Li, Phys. Rev. 88, 1038 (1952).
4. Arthur, Allen, Bender, Hausman, and McDole, Phys. Rev. 88, 1291 (1952).
5. R. B. Day, International Conference at Geneva (1955).
6. P. M. Endt and J. C. Kluyver, Revs. Modern Phys. 26, 95 (1954).
7. E. Bleuler and H. Morinaga, Phys. Rev. 99, 658 (A) (1955).
8. Pieper, Stanford, and Von Herremann, Phys. Rev. 98, 1185 (A) (1955).
9. P. W. Davison, Phys. Rev. 75, 757 (1949).
10. Donahue, Jones, McEllistrem, and Richards, Phys. Rev. 89, 824 (1953).
11. A. G. W. Cameron, private communication and Bull. Am. Phys. Soc. 1, No. 4, 191 (1956).
12. Schwartz, Corbett, and Watson, Phys. Rev. 99, 655 (A) (1955).
13. USAEC, TID-5300, Nuclear Level Schemes (1955).
14. M. Deutsch and W. Wright, Phys. Rev. 77, 139 (1950).
15. G. A. Bartholomew and B. B. Kinsey, Phys. Rev. 89, 390 (1953).
16. P. H. Stelson and F. K. McGowan, Phys. Rev. 99, 112 (1955).
17. J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) A66, 565 (1953).
18. A. M. Demidov, private communication; see also Groshev, Adyasevich, and Demidov, International Conference on the Peaceful Uses of Atomic Energy, Geneva (1955).

19. B. J. Raz and J. B. French, Bull. Am. Phys. Soc., 1, No. 4, 232 (1956).
20. Fagg, Wolicki, Bondelid, Dunning, and Snyder, Phys. Rev. 98, 1538 (A) (1955).
21. H. A. Enge and A. Graue, Universitetet i Bergen, Aarbok 1955, No. 13.
22. F. L. Friedman and W. Tobocman, Phys. Rev. 92, 93 (1953).
23. Buechner, Mazari, and Sperduto, Phys. Rev. 101, 188 (1956).
24. H. A. Enge, Ph.D. Thesis, University of Bergen, October 1954.
25. Kinsey, Bartholomew, and Walker, Phys. Rev. 83, 519 (1951).
26. L. L. Lee, Jr. and D. R. Inglis, Phys. Rev. 99, 96 (1955).
27. Gossett, Phillips, Schiffer, and Windham, Phys. Rev. 100, 203 (1955).
28. Rasmussen, Sampson, Miller, and Gupta, Phys. Rev. 100, 851 (1955).
29. Moak, Good, and Kunz, Phys. Rev. 96, 1363 (1954).
30. Almqvist, Allen, and Bigham, Phys. Rev. 99, 631 (A) (1955).
31. Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. 81, 233 (1951).
32. Browne, Williamson, Craig, and Donahue, Phys. Rev. 83, 179 (1951).
33. R. C. Mobley and R. A. Laubenstein, Phys. Rev. 80, 309 (1950).
34. Noyes, Van Hoomisen, Miller, and Waldman, Phys. Rev. 95, 396 (1954).
35. Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).
36. R. Bender, private communication.
37. K. M. Watson, Phys. Rev. 88, 1163 (1952).
38. D. Kurath, Phys. Rev. 101, 216 (1956).
39. R. G. Thomas, Phys. Rev. 81, 148 (1951).
40. E. Wigner, Am. J. Phys. 17, 99 (1949).
41. K. Alder and A. Winther, Numerical Data on Electromagnetic Excitations, preprint, to be published.
42. J. E. Mack, Revs. Modern Phys. 22, 64 (1950).
43. Austern, Butler, and McManus, Phys. Rev. 92, 350 (1953).
44. As quoted by: G. Temmer and N. Heydenburg, Phys. Rev. 100, 150 (1955).
45. J. Lamarsh and H. Feshbach (to be published).
46. Martin, Schneider, and Semper, Helv. Phys. Acta 26, 595 (1953).
47. Maider, Martin, Muller, and Schneider, Helv. Phys. Acta 27, 167 (1954).

48. Reich, Phillips, Russell, and Henry, Bull. Am. Phys. Soc. 1, 96 (1956).
49. Holmgren, Blair, Simmons, Stratton, and Stuart, Phys. Rev. 95, 1544 (1954).
50. J. Lamarsh, private communication.
51. H. Schneider, Helv. Phys. Acta 29, 55 (1956).
52. W. M. MacDonald, Phys. Rev. 100, 51 (1955).
53. F. J. Eppling, Ph.D. Thesis, University of Wisconsin (1953); also private communication.
54. C. P. Browne, Phys. Rev. 95, 860 (1954).
55. F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).
56. Progress Report, Laboratory for Nuclear Science, M.I.T., November 30, (1952). p. 30.

W. W. Buechner

Radioactivity Group

I. INTRODUCTION

The Radioactivity Group during the past year has continued to be concerned primarily with studies of radioactive decay processes and investigations of the properties of positronium. A systematic program to investigate the properties of excited 0^+ states in medium-weight nuclei has been undertaken. The decay schemes of Al^{26} and Co^{57} have been studied and work is continuing on the resonance absorption of γ rays.

II. POSITRONIUM

During the past year our continuing experiments on the formation and quenching of positronium in gases have begun to give a coherent picture. It appears that the survey phase of this work is now nearly over, and that in the future we must be selective in order to avoid the accumulation of nearly meaningless data which has characterized much of the analogous work with electrons in gases.

Among the results obtained are the following:

1. In all of the gases investigated (with the possible exception of CO_2) the cross section for positronium formation at energies near threshold is large, of the order of 10^{-16} cm^2 . This is deduced from the observation that very small admixtures of these gases to argon (0.001 to 0.01 percent) increase the formation substantially. In the case of the noble gases this conclusion also follows from the enhancement of the production by electric fields.

2. In the noble gases a large fraction of the positronium is formed in the so-called Ore gap between the formation threshold and the first excitation potential. This conclusion is a corollary of 1. and is supported by the occurrence of a maximum in the curve of positronium formation vs. krypton pressure in argon-krypton mixtures. There is also some evidence for such maxima in other gas mixtures.

3. In argon, about one-third of the positrons are annihilated without either forming positronium or falling below the formation threshold. This is deduced from the fact that the enhancement of formation by an electric field saturates at a formation probability of about 0.7. An alternative explanation in terms of preferential formation of the singlet state is not excluded by the data, but seems implausible. Similar results hold for other noble gases.

4. In pure gases at pressures up to one atmosphere the formation probability is independent of gas pressure and of applied magnetic field.

5. The formation probabilities in several gases are:

"Pure" tank argon	0.27 $\pm$ 0.03
CO ₂	0.3
CF ₂ Cl ₂	0.38
C ₂ H ₄	0.46
C ₃ H ₆	0.46

6. The quenching of ortho-positronium by NO proceeds by reorientation of the spins; the positron is annihilated in free para-positronium following a collision. This follows from the observation that, in the presence of a small amount of NO, a magnetic field quenches more than one-third of the remaining triplet decay. Since the field only affects the state with $m = 0$, collisions with NO must re-orient the angular momentum from $m = \pm 1$ to $m = 0$. Quantitative evaluation shows this reorientation cross section to be equal to the quenching cross section. This is what would be expected from collisions which completely de-couple the spins.

7. The quenching by Cl₂ proceeds by annihilation of the positron with a bound electron, probably while bound to the molecule. This follows from the observation that the magnetic-quenching experiment shows no enhancement of the quenching by chlorine.

8. The quenching by O₂ proceeds at least in part as in NO. This result is based on the same type of experiment but with less precision.

9. The quenching rate for NO is $3.5 \times 10^9 \text{ sec}^{-1} \text{ atm}^{-1}$, corresponding to a cross section at thermal energies of $4 \times 10^{-17} \text{ cm}^2$. The apparent quenching rate increases somewhat with increasing NO pressure and decreasing argon pressure. All of the data can be made to agree with a constant cross section by assuming a reasonable variation of formation probability with NO concentration. The cross section seems independent of temperature.

10. The quenching rate for Cl₂ in argon at atmospheric pressure is nearly the same as for NO. The apparent quenching cross section is independent of chlorine pressure but decreases with increasing argon or freon pressure. This cannot reasonably be explained by a varying formation probability or by an energy-dependent cross section. A fairly consistent picture can be obtained by assuming that positronium forms a metastable compound with chlorine. The life-time of the positron in the compound should be about 10^{-9} sec and the compound can break up, with re-formation of positronium, by collisions with argon with a cross section of the order of 10^{-16} cm^2 . It is difficult to understand why such a process would not result in re-orientation of the spin (cf. 7 above).

11. The quenching rate for O₂ varies drastically with oxygen pressure. At partial pressures below 10^{-3} atm the apparent cross section is at least as large as that of NO. Above 10^{-2} atm it becomes at least one hundred times smaller. It is not even certain that complete quenching can be obtained at any oxygen pressure. This behavior can best be explained by assuming an energy-dependent, quenching cross section. Perhaps particles with energy exceeding that of the 1.6 eV triplet-singlet transition in oxygen are strongly quenched by ortho-para conversion, while those

with lower energies undergo a less likely process involving reorientation of the molecular angular momentum. The apparent cross section decreases with increasing argon or freon pressure. This could be due to energy loss by collisions, but quantitative agreement is not good with this hypothesis. It should also be noted that we had to invoke two different hypotheses to explain the pressure dependence of the apparent cross sections in NO and chlorine.

We have also studied the effect of a magnetic field on the decay rate of positrons in one solid, teflon, with the following results:

12. The long lifetime of positrons in teflon is due to the formation of a stable triplet state. This follows from the fact that the decay is affected by a magnetic field. This result has been obtained simultaneously by other workers with different methods.

13. The quenching of the three-photon decay in teflon occurs by annihilation with electrons of the solid ("pick-off") rather than by spin exchange or re-orientation. This follows from the fact that the decay of only one third of the long-lived component is affected by the field. The argument is analogous to that under 7.

14. The long-lived triplet structure must be quite similar to free positronium. This follows from the observation that the effect of the magnetic field is, within the experimental error of about ten percent, the same as calculated for free positronium. If we expand the wave-function of the system in eigenfunctions of free positronium, the 1S term must represent at least 90 percent of the total amplitude.

In the following we present selected items of the phenomenological theory used, of the experimental procedures, and of the results.

A. Theory of Formation in Gas Mixtures

As an example we discuss here the simplest case, that of a mixture of two noble gases, specifically of argon and krypton. Figure 8.1 shows the relevant energy levels of the two gases. The Ore gaps are indicated by cross-hatching. We make the simplifying assumption that all positronium formation occurs in these gaps. We use the following notation:

n_A : Formation probability in pure argon

$\sigma_f(A)$: Average formation cross-section in the argon Ore gap

p_A : Partial pressure of argon.

The analogous quantities for krypton are denoted by the index K, instead of A. Further, $\sigma_r = \sigma_a + 2 \times 10^{-4} \sigma_e$, where σ_a is the cross section for free annihilation and σ_e that for elastic scattering. σ_r is an effective cross section in argon for removing a positron from the energy range corresponding to the krypton Ore gap.

σ_x : Cross section for inelastic scattering by krypton, for positrons of energy corresponding to the argon Ore gap. Then, if n is the formation probability in the mixture:

$$n = \frac{\sigma_f(A)}{\sigma_f(A) + \sigma_x p_K / p_A} \times n_A + \frac{\sigma_f(K)}{\sigma_f(K) + \sigma_r p_A / p_K} \times n_K \quad (1)$$

Figure 8.1

Energy levels of argon and krypton atoms.

Figure 8.2

Formation of positronium in mixtures of argon and krypton.

Figure 8.3

Formation of positronium in mixtures of argon and freon.

The first term represents the reduction in formation by argon due to inelastic collisions with krypton and decreases with increasing krypton pressure. The second term, the production in krypton, increases with increasing krypton pressure. The rise in formation occurs in the pressure range $p_K/p_A = \sigma_T/\sigma_f(K)$, the decrease in the neighborhood of $p_K/p_A = \sigma_f(A)/\sigma_X$. If the first of these corresponds to a lower pressure than the second, then there will be a maximum in the curve of formation as a function of krypton pressure. Figure 8.2 shows such curves, obtained at two different magnetic fields. The occurrence of a maximum is established beyond experimental error, although the apparent discrepancy between the two curves indicates errors beyond the counting statistics.

A similar analysis can be applied to the addition of polyatomic gases to argon but the situation is complicated by the possibility of inelastic energy losses of various kinds. The analysis indicates that the addition of a gas with an ionization potential below that of argon should in general cause a rise in formation for very low partial pressures. The occurrence of a drop for higher partial pressures depends on the values of various cross sections. Figure 8.3 shows the monotonically rising curve for freon in argon. One series of measurements with ethylene and propylene in argon yielded curves similar to Figure 8.3. Another, under somewhat different conditions, seemed to indicate weak maxima near partial pressures of about 10^{-3} atm. The discrepancy is probably due to inadequate control of gas purity.

If we take Eq. (1) literally, we can deduce cross section ratios from Figure 8.1. The result is, to order of magnitude: $\sigma_f(K) = 5 \sigma_e(A)$; $\sigma_X(K) = 100 \sigma_f(A)$. It must be remembered that these cross sections are averages over energy regions in which they may be expected to vary considerably. In addition, the fundamental assumption that formation outside the Ore gap is negligible, is probably not correct. This will not change the qualitative aspects of the analysis, but it may change the numerical results considerably.

Figure 8.4

Observed three-photon annihilation rate in mixtures of argon and nitric oxide.

Maxima occur also in the three-photon yield when small amounts of NO, Cl₂ or O₂ are added to argon. In this case, the drop at higher partial pressures is, however, caused by the quenching action. A typical curve of this kind is shown in Fig. 8.4.

B. Effect of Collisions in a Magnetic Field

We use the following notation:

λ_S : Free annihilation rate of the singlet state,

λ_T : Annihilation rate of the triplet without magnetic field,

λ'_S : Annihilation rate of singlet in a magnetic field,

λ'_0 : Annihilation rate of the $m = 0$ state in a magnetic field.

We write $\lambda'_S = \lambda_S - \delta\lambda$; $\lambda'_0 = \lambda_T + \delta\lambda$; $\lambda_S = 1115 \lambda_T$; $\lambda_T = 7 \times 10^6 \text{ sec}^{-1}$

Also, with an accuracy sufficient for our discussion:

$$\delta\lambda = 2 \times 10^{-10} H^2 \lambda_S / (1 + 2 \times 10^{-10} H^2),$$

where H is the applied magnetic field.

We consider the rates of three kinds of collisions:

s_0 : Rate of "pick-off" quenching, i.e. annihilation with an electron other than that in the positronium,

s : Rate of conversion from triplet to singlet or vice versa,

s' : Rate of re-orientation, i.e. a change of the m -value of a triplet state,

$S = s + s_0$: Destruction rate of triplet.

The rates are related to the relevant cross sections by $s = N v \sigma$. We can write the differential equations for the number of positronium atoms in all four sub-states in terms of the above quantities. These can then be solved for the observed counting rate as a function of time, i.e. the result of a delayed-coincidence experiment. The result is of the form

$$n = n_1 e^{-\lambda_1 t} + n_2 e^{-\lambda_2 t} + n_3 e^{-\lambda_3 t} \quad (2)$$

Since our experiments are concerned primarily with the triplet state, we neglect the rapidly decaying third term and write approximate solutions for the first two. The accuracy of the approximation is ample for our purpose. It can be increased further by replacing s' in the subsequent formulas by $s' + s^2/\lambda_S$. We find:

$$\begin{aligned} \lambda_1 &= (1/2) (\kappa_1 + \kappa_2 + k) \\ \lambda_2 &= (1/2) (\kappa_1 + \kappa_2 + k) \end{aligned} \quad (3)$$

$$\begin{aligned} n_1 &= (n_0/8k) [(f_0 + 2f_1)(k + \delta\lambda - 3s') - 4f_1 \delta\lambda] \\ n_2 &= (n_0/8k) [(f_0 + 2f_1)(k - \delta\lambda + 3s') + 4f_1 \delta\lambda] \end{aligned} \quad (4)$$

$$\kappa_1 = \lambda_T + S + 2s' + \delta\lambda; \kappa_2 = \lambda_T + S + s'; k = [(\delta\lambda + s')^2 + 8s'^2]^{1/2}$$

f_0 and f_1 are the probabilities for detecting the decay in the $m = 0$ and $m = \pm 1$ states, respectively. If we detect two-quantum annihilation, then $f_0 = S + \delta\lambda$; $f_1 = S$; apart from numerical constants. If

we detect three-quantum annihilation, Drisko's angular distribution calculations can be used to determine f_0 and f_1 . n_0 is simply the total number of positronium atoms formed.

Alternatively, we can calculate the total number of three-photon annihilations observed, by integrating the solutions of our differential equations over time. The result is, with the same approximations and notation as Equations (3) and (4):

$$n_T = (n_0 \lambda_T / 4) [f_0 (\kappa_2 + 2s') + 2f_1 (\kappa_1 + s')] / (\kappa_1 \kappa_2 - 2s'^2) \quad (5)$$

We used Eq. (5) to analyze the quenching by NO, Cl₂ and O₂. Figure 8.5 illustrates some typical results. Instead of n_T we have plotted, for each value of H (and, hence $\delta\lambda$) the ratio of n_T to its value in pure argon, for which $S = s' = 0$. The curves drawn, for each gas, represent the best fit at low fields with $s' = 0$ and $s' = S$ respectively. There can be no doubt that re-orientation takes place in NO, but not significantly in Cl₂.

In analyzing the quenching in teflon, we have used Eqs. (3) and (4). We performed the usual delayed-coincidence measurement between the nuclear gamma ray of Na²² and the annihilation radiation. The source was placed between the pole pieces of an electromagnet and the delayed coincidence rates with and without field were compared. Figures 8.6 and 8.7 show some of the results.

Figure 8.7

Effect of magnetic field in teflon, medium field.

Cl₂ Quenching in a Magnetic Field

Figure 8.5

Ratio of three-quantum annihilation with quenching gas added to that in pure argon, as a function of magnetic field.

Figure 8.6

Ratio of the number of delayed coincidences in magnetic field to that without field in teflon, strong field.

results. Again, we have not plotted n but rather the ratio of n to its value with H (and hence $\delta\lambda$) equal to zero. The three curves in Fig. 8.6 were constructed with the assumption that $\delta\lambda$ has the value calculated for free positronium. It is clear that s' must be zero or at least quite small. The solid line in Fig. 8.7 is again drawn assuming $\delta\lambda$ to have the value for positronium. The dotted lines represent values of $\delta\lambda$ differing from this by about twenty percent. $\delta\lambda$ is proportional to the reciprocal of the square of wave function at the origin for an s -state, independent of the principal quantum number. It is also inversely proportional to the fourth power of any component amplitude with higher angular momentum.

Some of the results concerning gas mixtures have been reported in a Bachelor's thesis by P. M. Platzman and P. H. Levine. Others, as well as those on magnetic and collision quenching in gases were presented to the New York Meeting of the Physical Society. The results on teflon were reported informally at the Conference on Quantum Interactions of Free Electrons at the University of Maryland. More complete publications are in preparation. (B. Gittelman and M. Deutsch)

III. $0^+ - 0^+$ TRANSITIONS IN MEDIUM-WEIGHT NUCLEI

During the past year we have undertaken a systematic program to investigate the properties of excited 0^+ states. The literature contains a number of detailed studies of such states in very light nuclei, but very little is known about them in heavy nuclei.

The 0^+ state in Ge^{72} with an energy of 0.69 Mev has been known for some time. Attempts have been made to explain its occurrence and properties by characterizing it as a "pseudo-ground state" due to a $(g_{9/2})^2$ configuration as opposed to the $(p_{1/2})^2$ ground state configuration. We have studied the radioactive decay schemes of Ga^{72} and As^{72} . A detailed report on these experiments will be made shortly to the Physical Review. The main result obtained is the conclusion that levels which combine strongly with the excited 0^+ state do not combine strongly with the ground state either directly or indirectly. The level structure combining with the excited state does not show any striking analogies with that combining with the ground state.

A 0^+ excited state in Zr^{90} has been reported in the literature. It decays by the emission of internal conversion electrons and internal pairs. It is striking that the only two medium-weight nuclei exhibiting 0^+ first excited states contain a shell of 40 nucleons - neutrons for Ge^{72} , protons for Zr^{90} . We have undertaken to measure the lifetime of the state in Zr . This experiment is made difficult both by the short lifetime, expected to be in the millimicrosecond range, and the low abundance of the transition in the decay of the radioactive parent Y^{90} . We have obtained a value of 6 μsec for the half life of this state. The experimental arrangement used is illustrated in Figure 8.8. A Y^{90} source is sandwiched between two plastic scintillators, making counter A a 4π detector for the β rays of Y^{90} . The annihilation quanta due to the positrons from internal pair creation are detected in coincidence by counters B and C. Counter B is a plastic scintillator used for fast delayed coincidences with counter A, while counter C is a NaI detector used with good energy resolution in slow coincidence. Since the abundance of the internal pairs is only about 4×10^{-5} per disintegration,

the coincidence rates are very low even with the strongest sources that can be used without interfering with proper operation of counter A. The preliminary value of the mean life given above should be good to about ± 24 percent, provided no systematic errors are introduced by the rather extreme conditions of the experiment. A test involving the introduction of small amounts of Na^{22} into the Y source has shown no abnormal behavior and the result reported is probably correct. It is hoped to complete these experiments in the near future.

Figure 8.8

Experimental arrangement for measuring lifetime of 0^+ state in Zr^{90} .

A 0^+ state in Ge^{70} has been reported in the literature. It is reported to decay primarily by the consecutive emission of E2 photons of 0.17 and 1.1 Mev via a 2^+ state. We are now studying this decay scheme with a view to determining the $0^+ - 0^+$ transition probability.

It is planned to measure the lifetime of the 1.4-Mev $0^+ - 0^+$ transition reported to accompany the decay of RaC' . A system for collecting the active deposit from radon has been constructed and tested. Appropriate arrangements to introduce the source rapidly into the β -ray spectrometer for delayed coincidence experiments are in progress. (H. Kendall and M. Deutsch)

IV. RESONANCE ABSORPTION OF γ RAYS

If a photon encounters a nucleus in the ground state whose first excited level energy is very close to the energy of the photon, it can suffer a resonance absorption. The nucleus is raised to

its first excited state, and then a γ ray is re-emitted with the same energy. This is exactly analogous to the atomic case where, for example, if a beam of white light is shone through sodium vapor, the transmitted light exhibits the absorption lines characteristic of sodium. However, in the nuclear case, the probability of a γ ray undergoing resonance absorption is directly proportional to the energy width of the level. In contrast to the atomic case, this width is very small relative to the γ -ray energy; of the order of $10^{-3} - 10^{-4}$ ev for a 1-Mev γ ray. Consequently, the probability of absorption is quite small.

Measurement of the resonance absorption effect provides a direct measure of the level width of an excited state and an indirect estimate of the lifetime. If the angular distribution of the re-emitted γ rays is measured, the spin and parity of the excited state can often be found. Also, it is at least theoretically possible to measure the energy of electron capture transitions by resonance absorption experiments.

In most resonance absorption experiments a radioactive isotope is used as a source of γ rays. Stable nuclei of the same type as the daughter isotope are arranged as a scatterer and the re-emitted γ rays are observed. The γ rays have approximately the correct energy, but are a little too low in energy due to the fact that both the emitting and the absorbing nuclei take up a few electron volts of recoil energy. The cross section for resonance absorption is expressed by

$$\sigma = g \frac{\lambda^2}{8\pi} \frac{\Gamma^2}{(E - E_0)^2 + \frac{\Gamma^2}{4}}$$

where:

g = statistical factor characteristic of the nucleus,

λ = wave length of incident γ ray,

Γ = level width of excited level,

E = energy of incident γ ray,

E_0 = energy of the excited level.

It can be seen that with a level width of $10^{-3} - 10^{-4}$ ev, a value of a few electron volts for $E - E_0$ makes the cross section extremely small. In order to obtain an appreciable resonance absorption effect, the energy of a known portion of the γ rays must be raised to the exact energy of the excited level. If the radioactive nucleus emitting the γ ray is moving at the time of emission, there is a Doppler shift in the γ -ray energy. In previous resonance absorption experiments, this motion has been obtained by thermal motion at high temperatures, by spinning the source on the edge of a high speed rotor, or by utilizing the recoil motion from a previously emitted γ ray, β ray or neutrino. In this series of experiments the third method has been utilized.

The next difficulty is that the recoiling nucleus is travelling so fast that in a solid source it has many collisions with the surrounding atoms before emitting the γ ray and in this way loses most of its energy. It is necessary to have the source in a physical form where the recoiling nucleus is unlikely to have a collision before emitting the γ ray. A gaseous source is obviously most desirable

although resonance absorption measurements with liquid sources had been previously reported.

The first experiment was with sources of Au^{198} (411 kev) and scatterers containing Hg^{198} . This isotope was chosen to test the accuracy of liquid source methods, since it had been carefully measured by several other methods. A NaI(Tl) crystal mounted on a photomultiplier was used as a detector of the re-emitted γ rays. The crystal was shielded from the source by a cone of lead, which was later replaced by a cone of Mallory metal for better shielding. The pulses were amplified and passed through a differential discriminator. This enabled us to count only those γ rays which had the full energy and were therefore not Compton scattered. Other forms of elastic γ -ray scattering such as Rayleigh and nuclear Thomson scattering were eliminated by comparing scatterers of mercury and lead. The lead scatterer should give about the same amount of scattering for the other effects, but no resonance scattering.

The results of this experiment were of the right order of magnitude but incorrect by about a factor of three. This is interpreted as being caused by our lack of understanding of the slowing down process of heavy particles at this energy.

The second experiment was with a source of V^{48} (990 kev) with Ti^{48} as a scatterer. Gaseous sources are planned and from theory a large resonance absorption effect is expected. If the effect is large enough, a straight forward absorption curve can be measured and compared with the values found by methods involving assumptions concerning the microscopic behavior of the radioactive gas. The gaseous form of the source must be obtained by heating VOCl_3 until it is vaporized. The chemical preparation of this source has proved to be quite difficult but considerable progress has been made.

It is planned to measure the absolute cross section by several methods and also to measure the angular distribution of the re-emitted radiation. (R. C. McCall)

V. Co^{57} DECAY SCHEME

Preliminary experiments on the decay scheme of Co^{57} have been completed, and a more complete analysis is planned.

The recent literature on Co^{57} includes many conflicting reports. A group of three low-energy gamma rays is the only part upon which there is general agreement. Three other gamma rays are reported, although there is not general agreement on them. Also, some workers report a weak positron spectrum.

To clear up this situation, a search is to be made for low-energy positrons, using a 4π plastic scintillator. Also, the gamma spectrum will be studied in coincidence with conversion electrons and other gamma rays.

There is no satisfactory way of producing Co^{57} without also producing Co^{56} and/or Co^{58} .

Co^{57} has a half-period of about 270 days, while Co^{56} and Co^{58} each have half-periods of about 70 days. We will make our measurements with a 14-month old source. According to preliminary measurements, the contribution to the total activity of this source from Co^{56} and Co^{58} is about 0.1 percent. (J. M. Ferguson)

VI. Al^{26} DECAY SCHEME

It has been found that the short-lived positron activity previously thought to be the ground level decay of Al^{26} actually is an isomeric level. The true ground level has an extremely long half-period, and has only recently been observed.

The principal features of the ground level decay are now well established. It decays by positron emission to the 1.83 Mev first excited level in Mg^{26} . Thus, there is a 1.83-Mev gamma ray in coincidence with the positrons.

We have measured the end point of the positron spectrum as 1.14 ± 0.01 Mev, and have found a 1.84 ± 0.01 -Mev gamma ray in coincidence with the positrons. This gives an $\text{Al}^{26} - \text{Mg}^{26}$ mass difference of 4.00 ± 0.014 Mev. Our data agree with Endt's¹ value of 1.825 ± 0.005 Mev for the first excited state of Mg^{26} , and with Browne's² value of 4.01 ± 0.02 Mev for the $\text{Al}^{26} - \text{Mg}^{26}$ mass difference, obtained from reaction data.

A Kurie plot of the positron data indicates the spectrum is simple, and has a shape factor corresponding to a second forbidden transition. The spin of the Al^{26} ground level is predicted to be $5+$, by a King and Peaslee³ diagram, and the spin of the first excited state is expected to be $2+$, since it is the first excited state of an even-even nucleus. These spin assignments correspond to a unique second forbidden transition, and hence, agree with the experimental data.

There is evidence for the presence of other gamma rays in the spectrum. A group at Oak Ridge⁴ detected peaks in the gamma ray spectrum at 2.97 Mev and 0.72 Mev. The 2.97 Mev gamma ray corresponds to the 2.97 Mev second excited level in Mg^{26} , previously observed by analysis of the protons from an $\text{Mg}^{25}(\text{d}, \text{p})\text{Mg}^{26}$ reaction.¹ There should then also be a 1.1-Mev gamma ray present, corresponding to the transition from the 2.97-Mev to the 1.84-Mev level. We have observed the 1.1-Mev gamma ray both in the singles spectrum and in coincidence with the 1.83-Mev gamma ray.

The 0.72-Mev gamma ray reported by the Oak Ridge group is not accounted for by any previous level work on Mg^{26} . We have detected a peak in our singles spectrum at this energy, but more extensive experiments indicate that it is caused by the "adding" of the photopeak from one of the annihilation quanta and backscatter radiation from one of the other gamma rays. This peak can be completely eliminated by surrounding the crystal with 1/16" lead. This amount of lead would not appreciably attenuate a 0.7-Mev photon, but will absorb most of the backscatter radiation. Hence, our data indicate there is no 0.7-Mev gamma ray.

Figure 8.8 shows our proposed decay scheme. This scheme accounts for all data available on Al^{26} decay, and is consistent with the Mg^{26} level spectrum. It also agrees with the expected parities and angular momenta of the levels involved. (J. M. Ferguson)

VII. MEASUREMENT OF g-FACTOR OF LOW-LYING EXCITED STATES OF NUCLEI

The measurement of the gyromagnetic ratio of low-lying excited states of nuclei involves a precession-type experiment. In this particular experiment the nuclear state is coulomb excited and the resulting gamma-ray angular distribution is rotated through an angle $\theta = g\mu_N H_a \tau_N$ by an applied magnetic field H_a , where τ_N is the lifetime of the excited state.

Measurement of the 122-keV gamma-ray de-excitation angular distribution from solid $\text{Sm}^{152}_2\text{O}_3$ gives a value considerably smaller than that expected from semiclassical theory. These theoretical angular distributions are usually in good agreement with experiment. As a check on the equipment the 315-keV de-excitation gamma-ray angular distribution from $\text{Ag}^{107, 109}$ was measured. The results are in excellent agreement with those of other investigators.

The attenuation of the $\sim 2 \times 10^{-9}$ sec 122-keV state of Sm^{152} is not unexpected. The large quadrupole moment of this nucleus ($\sim 5 \times 10^{-24} \text{ cm}^2$) means that a strong coupling between the nucleus and the crystalline electric field gradient COULD attenuate the angular distribution. An arbitrarily strong static coupling will reduce the angular distribution to a minimum value. Our measurements show that the Sm^{152} angular distribution is not down to the minimum value.

To make possible a g-factor measurement, the attenuation must be removed. If the perturbation is the static $Q \frac{\partial^2 V}{\partial z^2}$ coupling, then a liquid environment will "restore" the correlation. Development of a liquid target is underway.

The actual magnetic field setup which involves shielded counters, magnet, scattering chamber is nearing completion. (R. P. Scharenberg, and G. Goldring)

REFERENCES

1. Endt, Haffner and Van Patter, Phys. Rev. 86, 518 (1952).
2. C. P. Browne, Phys. Rev. 98, 860 (1955).
3. R. W. King and D. C. Peaslee, Phys. Rev. 90, 1001 (1953).
4. T. H. Handley and W. S. Lyon, Phys. Rev. 99, 755 (1955).

R. D. Evans
M. Deutsch

Cyclotron Group

I. INTRODUCTION

The Cyclotron Group research activity during the past year has centered primarily on two phases of the general problems of nuclear physics; specifically, a study of the general properties of nuclear structure as determined by the measurement of elastic scattering angular distributions, and secondly, a study of the mechanisms of nuclear reactions.

In particular, we have been examining the elastic scattering of protons, deuterons, and alpha particles, hoping to interpret this data on the basis of the "cloudy crystal ball" nuclear model. We have also studied the inelastic alpha-particle reactions demonstrating the presence of a direct surface interaction.

Relative to the general problem of cyclotron instrumentation, we have been working towards a higher intensity machine so as to be able to use a system of magnetic analysis on the emergent beam and the reaction products.

II. MAINTENANCE AND IMPROVEMENT

To be able to successfully use a system of magnetic analysis on the reaction products in our scattering project, it was felt that it would be desirable to increase the available beam current. As a start on this project, we have reshimmed the cyclotron magnetic field, at the suggestion of K. Boyer of Los Alamos, using a field which is periodic in angle with an amplitude of $\pm (3 - 5 \text{ per cent})^1$. We have achieved this field by introducing the shims illustrated in Figure 9.1 into the shim

Figure 9.1

Top view of Thomas type wedge shim.

gaps on the cyclotron. With respect to this cyclotron, it has been found, empirically, that if the central circular region was less than 3 inches in radius or greater than 5-1/2 inches, there was no improvement in the internal beam of the cyclotron. To date we have only made measurements on the internal beam of the cyclotron using as criteria the beam currents at radii of 14 and 18 inches. This latter radius is just slightly less ($\sim 1/4$ inch) than the radius at which the beam is being extracted. In addition to the above mentioned shims, we are also using some, but not all of the "pyramid" shims which were in the machine to plate. The results of this reshimming process have been that the internal beam current at a radius of 18 inches has been increased by slightly more than a factor of two, while at the same time the loss of beam currents in going from 14 to 18 inches has been decreased from a 70 percent loss to about a 30 percent loss. This improvement in beam has resulted from the improved vertical focussing inherent in a periodic magnetic field. In the immediate future we will start a series of experiments to extract this higher beam current from the cyclotron. (F. Fay, N.S. Wall, and E. F. White)

III. ELASTIC DEUTERON SCATTERING

The angular distributions of 15 Mev deuterons elastically scattered from Al, Cu, and Au have been measured using a single crystal NaI spectrometer as the detector. To evaluate the contribution from protons arising from (d, p) reactions, we have made use of the fact that the (d, p) Q-values are positive, and therefore, we can estimate the proton contribution to the elastic deuteron peak from an energy spectrum of the particles surrounding the elastic group, and an appropriate graphical subtraction.

The differential cross section relative to that expected on the basis of point-charge Rutherford scattering has been determined by multiplying the observed differential cross section by $\sin^4 \frac{\theta}{2}$ and setting this equal to one at small angles, where this product is constant, to within experimental error. As yet, we only have preliminary results. All our results are in qualitative, but not quantitative agreement with those of Gove².

At present we shall complete the measurements on Al, Cu, and Au and also measure the angular distributions for an element with $A \sim 120$, since rather a complete series of measurements has recently been completed at Brookhaven National Laboratory by G. Igo and H. Wegner³. (C. W. Darden, III)

IV. ELASTIC PROTON SCATTERING

A. Elastic Proton Angular Distributions

We have completed the angular distribution measurements for 7.5-Mev protons scattered elastically from the elements Al, Ni, Cu, As, Cd, and In, atomic number $Z = 13, 28, 29, 34, 48$,

and 49 respectively. The results are shown in Figures 9.2 through 9.7. These distributions show essentially the same behavior as those for 10 Mev protons as observed by Hintz⁴. Calculations are at present underway at the Los Alamos Scientific Laboratory in an attempt to analyze the elastic scattering of charged particles by complex potential-well considerations. To date, however, no results have been received from that group.

We have developed a method by which we can make our cross section measurements with an accuracy nearly independent of the angle of observation. This eliminates large errors introduced by the slight amount of angular play ($\frac{1}{2}^\circ - 1^\circ$) in the beam direction when taking data at small angles, and makes unnecessary an exact knowledge of the zero angle. It makes use of the fact that the elastic scattering of 7.5-Mev protons from Au is Rutherford at all angles. (This has been demonstrated previously and was remeasured with great care in October.) We have taken our data and analyzed it as a ratio to the Rutherford cross section, not by multiplying the observed counting rate by $\sin^4 \frac{\theta}{2}$, but dividing by the counting rate from Au, measured at the same angle. Due to our method of monitoring with a counter looking directly at the targets, this gives the differential elastic scattering x-section relative to Rutherford in absolute measure, except for a small correction due to the center-of-mass effect, which is nearly constant at all angles, and target thickness. The value of this method is strikingly demonstrated by Figures 9.6 and 9.7 for Cd and In, done by the old method of multiplying by $\sin^4 \frac{\theta}{2}$, and showing a wide scattering of points, well outside of the expected statistical limits. These contrast sharply with the other curves, done with the new method, wherein the points lie well within the expected counting statistics of ± 3 percent. (N. S. Wall and W. F. Waldorf)

B. Elastic Proton Polarization Experiments

There has been some evidence in the optical model calculations and pertinent experiments of the presence of a spin-orbit term in the nuclear potential. This should manifest itself in the polarization of the scattered particles. Experiments are being undertaken to observe this polarization using the $\text{He}^4(p,p)\text{He}^4$ resonant scattering (from the ground and first excited states of Li^5) as a polarization analyzer. (C. W. Darden, III, and N. S. Wall)

V. FAST COINCIDENCES FROM CYCLOTRON REACTIONS

Measurements on the phase grouping of the M.I.T. cyclotron beam have been made. A preliminary investigation was made by displaying on an oscilloscope scintillation pulses from 7-Mev protons elastically scattered from gold. The scintillation pulses from a plastic scintillator of 10 μsec duration were amplified with a fast amplifier and fed directly to the deflection plates of a model 541 Tektronix scope. The scope was triggered externally with the same scintillation pulse and the linear sweep circuit of the scope utilized. The rf signal of the cyclotron was also used to sweep the scope. The photographed distribution of pulses, which shows three rf cycles, shows a very sharp grouping of particles in each rf cycle. The photograph indicates that the spread is

Figure 9.2

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 13$.

Figure 9.3

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 28$.

Figure 9.4

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 29$.

Figure 9.5

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 33$.

Figure 9.6

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 48$.

Figure 9.7

Differential cross section relative to Rutherford for 7.5-Mev protons on $Z = 49$.

$< 5 \mu\text{sec}$ out of a total rf period of $82 \mu\text{sec}$.

To get more detailed information about the phase distribution of the beam, a coincidence method was employed. Coincidences were taken between pulses produced by protons in the same rf cycle when one of the signals was delayed a fixed amount. The coincidence circuit is as indicated schematically in Figure 9.8.

Figure 9.8

Schematic drawing of coincidence circuit.

The fast pulses from the anodes of the scintillation counter photomultipliers are amplified with a fast amplifier, limited, delay line pulse shaped, and fed to the anode of a biased diode which constitutes the fast coincidence circuit. The resolving time of this circuit may be made as short as $2 - 3 \times 10^{-9}$ sec by using a plastic phosphor. Pulse-height analysis of the scintillation pulses is accomplished by taking a signal from the nest to last dynode, amplifying, and analyzing it with a single-channel, pulse-height analyzer. The two pulse-height analyzers are gated with the signal from the cathode of the fast coincidence diode and a double coincidence is taken between the two signals from the pulse-height analyzers. Fixed delays were inserted in either of the two arms of the circuit indicated in Figure 9.8. A negative delay in one arm corresponds to a positive delay in the other.

The beam of the cyclotron was allowed to strike a gold target, and coincidences were taken between scattered particles in a single rf cycle. A plot of the coincidence counting rate as a function

of the inserted delay is shown in Figure 9.9. From this curve one must subtract the prompt coincidence curve of the circuit which was obtained by using the annihilation quanta from the decay of Na^{22} as a prompt source. The prompt coincidence curve is also shown in Figure 9.9. The difference between the delayed curve and the prompt curve represents twice the actual phase spread of the beam. This shows the beam to be very sharply bunched around the maximum of the rf cycle. The curves show the width of the proton group to be about $1 \mu\text{sec}$ at 10^{-3} , and its maximum height. The rf period of the cyclotron is $82 \mu\text{sec}$, thus the beam occupies only about 1 percent of the total rf period.

Figure 9.9

Time resolution curve of the cyclotron beam as compared to prompt resolution curve of the electronic equipment.

Utilizing a sharply peaked beam of this nature to excite isomeric levels of nuclei, one may use the delayed coincidence method to determine the half-periods of these excited states. For delays greater than $1 \mu\text{sec}$, there will be no problem with chance coincidences. Such experiments are anticipated. (L. W. Swenson)

VI. INSTRUMENTATION

A. External Beam Magnetic Analysis Design

The magnet system described in the progress report for February 1956 is still under consideration. Before going ahead with its construction, it is felt that the beam current in the present scattering chamber should be increased by about a factor of three. To this end the work described in the first section of this report was undertaken. It is felt that any further increase in the scattering chamber current will most profitably come from a rebuilding of the external beam focussing system using strong-focussing lenses. (N. S. Wall)

B. Particle Identification Scheme

We have been investigating the possibility of improving the response of the particle-selective system. It was determined that a thin (~ 10 mg/cm² of argon) gas counter to measure dE/dA , rather than a thin plastic scintillator⁵, was not feasible because simple considerations of the fluctuations in energy loss indicate that, to be able to resolve 15-Mev protons from 15-Mev deuterons, it is necessary to absorb about 1 Mev of proton energy. A gas counter of sufficient thickness to absorb this much energy (~ 60 mg/cm²) is not practical to install in our present scattering chamber. However, we do have the setup Aschenbrenner⁵ used with a thin plastic scintillator, and it is convenient to replace that crystal by a CsI (Tl) or NaI (Tl) crystal about 0.015 inch thick, which will give adequate light output, as well as the necessary amount of energy loss so that the over-all peak width should be of the order of 20 percent full width of the energy separation between the protons and deuterons. (C. E. Hunting)

REFERENCES

1. Also see L. H. Thomas, Phys. Rev. 54, 580 (1938).
2. H. Gove, L.N.S.E. Progress Report, July (1950). p. 145.
3. G. Igo, private communication.
4. N. Hintz, private communication.
5. F. A. Aschenbrenner, Phys. Rev. 98, 657 (1955).

M. S. Livingston

Synchrotron Group

I. SYNCHROTRON OPERATION

A. Routine Operation and Maintenance

Over the past year the synchrotron has been run on a continuous schedule (7-day week, 24-hour day).. We estimate that the beam "on time" has been about 70%, with 30% spent on maintenance, repair, and turn-offs for the purpose of changing experiments. It is worthwhile at this time to attempt an evaluation of such a schedule as opposed to a discontinuous one. From an economic view it has been very successful. The extra cost consists of power, parts failure proportional to running time, and the wages of one operator. The failure of parts is difficult to determine, but in many cases it is as much determined by shut-downs than by running time so that continuous operation could even prove less expensive. We have been fortunate in being able to use undergraduate students as night operators; they have proved to be satisfactory. In addition, the use of undergraduate operators has stimulated the interest of the undergraduate physicist in the experimental program. We obtain an additional gain by avoiding the tuning problem which inevitably occurs after a prolonged shut-down.

We have installed a circuit to stabilize the magnet voltage. There is a thyatron ignited when the condenser back recharges to the correct voltage, measured by a discriminator. This ignitron bleeds off the current supplied to the condenser bank from the rectifiers, and acts to keep the voltage constant during the wait for a 60 cycle phasing signal which triggers the main ignitrons. If the rectifier current should vary (e. g. from a line voltage change) there is then a relatively large change in bleeder current principally because the condenser voltage discriminator fires earlier with respect to the 60 cycle phasing pulse. We now use this current to control the current limiter filament voltage and thereby change the rectifier current. This circuit allows long term stability in condenser voltage and thereby in beam energy. This in turn gives greater intensity stability.

B. Van de Graaff Injector

We have obtained and tested a 1-Mev Van de Graaff generator to be installed as an injector into the synchrotron. We expect the increased charge per unit solid angle to give an increased beam intensity. Simultaneously with this we are installing a new ceramic doughnut with larger cross-section. Following are the various components and their stage of development.

- (1) Doughnut - assembly and vacuum testing.
- (2) R. F. Oscillator - assembly and testing.
- (3) Inflector - assembly.
- (4) R. F. Cavity - testing
- (5) Van de Graaff pulsing circuit - tested.

(6) Beam contractor - assembled.

We are in the process of testing various cathodes to obtain a higher peak current than the cathode which is available in the present Van de Graaff generator. The two most promising cathodes are the Raytheon TL-4 and a thoriated tungsten wire which give about 50 ma pulses collected on a Faraday cup. (R. Schluter, L. S. Osborne, D. M. Ritson, G. S. Janes, C. Strumski, W. Lobar)

II. PHOTOPRODUCTION OF π^+ MESON FROM HYDROGEN AT 265-MEV GAMMA-RAY ENERGY

In this experiment the γ -ray beam of the M.I.T. synchrotron was incident on a thin-walled, liquid-hydrogen target. The synchrotron was operated so as to give a short γ -ray beam of about 2 μ sec duration during which time the counter phototubes and the electronics were gated off. Mesons produced in the target were stopped in the center tank of a counter, which essentially consisted of two concentric cylinders, where they were detected by their μ - e decays after the γ -ray beam had ended¹. The γ -ray energy was determined by generating the synchrotron at peak energies of 285 and 260 Mev and subtracting the results. A different thickness of carbon absorber was placed in front of the counter at each angle so that mesons from 265 Mev γ -rays would stop in the same position, thus keeping the geometrical efficiency of the counter a constant.

Figure 10.1

π^+ Photoproduction from hydrogen at 265-Mev gamma-ray energy.

In Figure 10.1 our results, corrected for multiple scattering, absorption in the carbon, and decay in flight, are plotted together with the results of Cal. Tech.², Cornell³, and the theoretical

curve of Chew⁴. This experiment did not measure an absolute cross-section. The normalization of our relative measurement was adjusted to give the best fit of our data between 45° and 160° to the Cornell and Cal. Tech. points.

The most interesting feature of the results is the dip and rise in the angular distribution at forward angles. This dip may be understood on a simple picture as an interference between direct production from the meson cloud, and the S-wave production, yielding a term with an angular distribution of the form $-\beta^3 \sin^2 \theta / (1 - \beta \cos \theta)^2$.

There appears to be some disagreement between this experiment and the predictions of Chew. The dip in the forward direction appears to be more pronounced than predicted by Chew.
(B. Richter, L. S. Osborne)

III. π^0 PHOTOPRODUCTION FROM VARIOUS ELEMENTS

A π^0 detector was built consisting of two, three-counter systems designed to detect the π^0 decay gamma rays in time coincidence. The coincidence circuit consisted of a four-fold Garwin circuit and a two-fold 6BN6 circuit; the over-all resolving time being about 10^{-8} secs. The fast time resolution allowed measurements to be taken at forward angles. No anticoincidence counter was used in front of the lead radiation; instead, the photon yields were measured by taking the difference in counting rates with the radiators in front and then in back of the two front counters. The counting efficiencies of the telescopes were measured as a function of energy by taking a series of runs in the synchrotron beam and varying the maximum electron energy from 175 Mev to 90 Mev.

This method of detection defines the π^0 meson energy by favoring those energies where the angular separation of the two counters corresponds to the angular separation of the two gamma rays emitted at 90° in the π^0 center-of-mass system. The intrinsic energy resolution of our system corresponded to a gamma-ray energy of 250 ± 15 Mev. The system also favors those π^0 's emitted along the bisector of the angle between counters; however, higher energy π^0 's will emit photons with the same total angular separation as lower energy ones but their line of flight is off the bisector. This angular resolution is computed to be $\pm 15^\circ$, full width.

Yields of π^0 's were measured for hydrogen and deuterium in the liquid-hydrogen target. In the case of deuterium the counter separation angle was set to correspond to elastic production kinematics. The results are plotted in Figure 10.2. It is difficult to obtain an absolute measurement by this method involving, as it does, the product of two counter efficiencies. We have, therefore, normalized the 90° hydrogen point to previous measurements.⁵ The cross-section from protons can be written

$$\frac{d\sigma}{d\Omega} = (12.0 \pm 1.2) - (3 \pm .8) \cos \theta - (4 \pm 1.5) \cos^2 \theta$$

Figure 10.2

π^0 photoproduction from hydrogen and deuterium.

Figure 10.3

π^0 differential cross section near 0° divided by $A^{4/3}$.

Figure 10.4

Variation of potential well calculation with absorption.

The cross-section for deuterium involves both elastic and inelastic production. The effect of the coherence between neutron and proton π^0 waves is such as to peak the cross-section toward forward angles. A disturbing and unexplained feature of this cross-section is the large drop from 60° to 0° . Specific calculations of the coherent production⁶ show relatively little change in cross-section in this region. We have made a rough calculation using the impulse approximation to include the effects of inelastic production; this is, by no means, sufficient to explain this rise.

The yields of π^0 's from heavier elements were measured from 0° to 90° . In general, these showed the general characteristic of a peak in the yield toward forward angles. This result suggests the coherent production of π^0 in all nuclei but not from all the nucleons in the nucleus because of the strong absorption of meson in nuclear matter. If the "skin" of the nucleus is radiating coherently, one would expect a yield proportional to the square of the number of emitters, i.e. $\sigma \propto A^{4/3}$. A check of this rough idea is shown in Figure 10.3. The yield of π^0 mesons in the forward direction (where the nuclear form factor is nearly unity) is plotted again by A. It appears that this coherent model is roughly correct.

A more detailed description has been calculated using the following model. The wave equation is solved for meson emission from a spherical source with a complex potential and a spherical source term giving rise to P-waves retarded by the photon phase factor. The results of this calculation for Cu are shown in Figure 10.4, assuming the nuclear radius, $1.2 \times 10^{-13} A^{1/3}$ cm., and the imaginary potentials $V_i = 30$ Mev and 100 Mev. Our poor angular resolution might explain the fact that the measured 0° cross-section does not go to 0 as expected. The disagreement at 90° can come from production of inelastic π^0 's. It is gratifying to note that the data show a mild minimum at the prescribed angle, 40° . It appears that our data are relatively consistent with our calculations but more careful experiments would be required to check this out in detail.

(R. Barringer, R. Meunier, L. S. Osborne)

IV. THE MOMENTUM OF NUCLEONS IN VARIOUS NUCLEI FROM THE HIGH ENERGY PHOTOEFFECT

The previously reported studies of the high energy photo-ejection of neutrons and protons showed the basic validity of the "quasi-deuteron" model (L. N. S. Annual Progress Report, 1955). One observes that the kinematics of the "quasi-deuteron" disintegration are modified from those of the photo disintegration of a free deuteron at rest due to the initial motion of the neutron and protons in a complex nucleus. The modification of the kinematics was measured for Li, C, O, Al and Cu in an attempt to compare the momentum of the nucleons in these nuclei.

The data were analyzed somewhat naively as reported previously (L. N. S. Annual Progress Report, 1955). Since then a re-analysis of the theory has been made. The data were corrected for the finite resolution of the detecting equipment. A small relativistic correction was applied. A more exact theoretical expression was employed. A correction of about 10% was also made for

refraction at the nuclear surface. With these corrections, it was found that E_g , the 1/e energy of the gaussian momentum distribution, became for Li, $E_g = 8 \pm 1$ Mev; for C, $E_g = 18.4 \pm 1.5$ Mev; for O, $E_g = 18.4 \pm 2.5$ Mev. (A. Wattenberg, A. C. Odian, P. C. Stein, B. T. Feld, and R. Weinstein)

V. STUDY OF PHOTOMESON PRODUCTION FROM COMPLEX NUCLEI

It is planned to study the neutrons in coincidence with π^+ mesons from complex nuclei when bombarded by the bremsstrahlung beam of the M.I.T. synchrotron. By measurement of the distribution of neutron angles in the laboratory for fixed meson angles and energy, it is hoped to obtain some information on the momentum distribution of protons in light nuclei.

π^+ mesons with an energy of 80 Mev produced by 255 Mev X-rays will be selected by a two-counter range telescope. The counters are liquid scintillators; the second one is surrounded by an annular outer tank designed to detect the decay electrons emitted by the mesons which stop in that counter. A separate liquid scintillation detector will be used to detect the neutrons. The energy of the neutrons will be determined by their time of flight. The time of flight coincidence circuit consists of a chronotron capable of detecting time differences down to about 5 m μ sec.

The detectors and all electronics have been completed and set up for the experiment; the determination of operating biases and approximate detector efficiencies has been completed. It is expected that data for the experiment itself will be taken shortly. (W. D. Rankin, A. Wattenberg, B. T. Feld, P. C. Stein)

VI. PHOTOMESON PRODUCTION FROM DEUTERIUM

An attempt is being made to determine the contributions of spin-flip and non-spin-flip processes in photo-meson production from deuterium.

The measurement consists of measuring the energy spectrum of neutrons in coincidence with positive π photomesons. The meson detector consists of a two-counter telescope; a dE/dx counter and a counter in which the meson stops is surrounded by an annular cylindrical counter which detects the decay electron from the meson. The neutron detector consists of a 12" diameter scintillation counter. The neutron energies are measured by a time-of-flight technique, utilizing a "chronotron" built at this laboratory. The time interval between the arrival of the meson and the arrival of the neutron is measured.

The equipment has been built and tested, and data is now being taken. (B. T. Feld, P. C. Stein, W. Rankin, A. Wattenberg, and R. Weinstein)

VII. THE ELECTRIC-DIPOLE "GIANT RESONANCE" IN PHOTONUCLEAR REACTIONS FROM A MICROSCOPIC POINT OF VIEW

From the success of the quasi-deuteron model at high energies, it appeared that it might be valuable to look upon the giant Goldhaber-Teller "resonance" from a microscopic point of view. Perhaps ironically one of the consequences is that it isn't a resonance. The advantage to the point of view is that it would provide an explanation of the following:

- (1) the fine structure observed by L. Katz et al⁷ and A. S. Penfold et al⁸;
- (2) the large number of directly ejected protons;
- (3) the large values for the (γ, np) cross section;
- (4) the proximity of the maximum in the cross section to the (γ, np) threshold.

As of the present time the calculations are crude ones, based on a momentum distribution. The purpose of this write-up is heuristic.

Barton and Smith at Illinois, and a group of us at M.I.T., have established the validity of the two-body model of the high energy photoeffect (J. S. Levinger's quasi-deuteron model⁹). We employed this effect to measure the momentum distribution of nucleons in Li, C, and O. In interpreting the data, it was convenient to perform a separation into the relative momentum of a neutron and proton and the momentum of the center-of-mass of the neutron and proton in a complex nucleus.

P. Morrison has pointed out that an electric dipole matrix element is essentially a weighted average of the momentum distribution. A crude calculation of the electric dipole transition probability was carried out employing the relative momentum distribution used in interpreting the high energy data, (a gaussian for Li, C, and O). On this model no correlation is assumed in the motion of nucleons in a nucleus; the relative momentum of a neutron and proton is assumed to be that arising from random motion of nucleons in a nucleus.

From this calculation one obtains for the photoeffect a broad peak with an exponential fall-off. The exponential fall-off results from the choice of a gaussian. One of the difficulties in the calculation concerns how to put in conservation of energy. In this calculation plane waves were employed for final states. Obviously this is wrong, especially as not all final states are available in the nucleus due to the Pauli principle. An attempt to correct this consisted of a subtraction from the matrix element of the states already occupied. The previously obtained broad peak became narrower, and the shape of the rise was seen to be dependent on the assumption of the density of states available to the nucleons.

The relationship of the average kinetic energy of nucleons in a nucleus to the peak of the "giant resonance" is pointed out in Blatt and Weisskopf. Detailed calculation based on the momentum of nucleons have been performed by Morrison and Winslow (unpublished) according to J. S. Levinger¹⁰. The author is certain that he is indebted to a great extent to Morrison for the momentum point of view. The above crude calculation indicates the momentum distribution is the

determining factor on the high energy side, and on the low energy side the availability of energy states plays the important role.

The above considerations are now combined with a microscopic view of the interaction of radiation with a nucleon system. The n-p pair would seem to be the system that has the dominant interaction. Transitions for the p-p and n-n systems have a zero matrix element for electric dipole, and are forbidden for all magnetic multipoles due to the allowed states of two identical Fermions being 1S 3P 1D 3F etc.

If one assumes the interaction of photons with the n-p system to be the dominant one, the data of Katz and Penfold and their coworkers can be understood as follows. Consider a light nucleus in which there is not a great number of levels. Immediately above the (γ, n) threshold, the cross section should rise due to the density of states factor for the continuum. The proton initially associated with the neutron is left behind in the ground state of the residual nucleus. As the energy increases, one reaches the first excited state for the residual nucleus. This may make available another state for the associated proton. If this is the case, there should be an enhancement in the cross section for the (γ, n) process; namely the ground state and free neutrons continue to have an increasing cross section and to this process is added the process where the proton is in an excited state and the free neutron associated with that state starts an increasing cross section. Such a picture is an extreme one. It fits Katz's data on Li^7 . The energy difference between the threshold [for the (γ, n) reaction in Li^7] and the first four breaks he observes correspond within 100 keV to the excited levels of Li^6 (the residual nucleus). On this model one would naively predict a break at about 11.7 MeV which does not appear in Katz's data.

Perhaps one should not be surprised to see such a simple picture fit Li^7 .

In more complex nuclei the situation cannot be interpreted quite so simply. Levels should also occur which initially correspond to bound states for both the neutron and proton (or any electric dipole transition). These states thus decay via some complex mode (the regular compound nucleus model). However, such states corresponding to two initial bound nucleons will not have the continuous rise in cross section that is associated with the continuum states. They should have widths like other compound nuclear states. This picture might explain the anomalous behavior of the widths above 21 MeV observed by Penfold in O^{16} .

In light nuclei due to the low density of levels the (γ, np) process is somewhat inhibited until one is above the (γ, np) threshold where a continuum of states is available to both nucleons. Thus, if the momentum spectrum predicts a maximum below the (γ, np) threshold, the maximum will not appear. Instead, the maximum will appear slightly above the (γ, np) threshold. Katz and co-workers show a large number of maxima in the vicinity of the (γ, np) threshold, (R. Montalbetti, L. Katz, and J. Goldenberg¹¹). Where the maximum is below the (γ, np) threshold, it is the author's opinion that it is probably due to the momentum distribution. In such a case, the curve of the giant resonance should be broader at the top than for those cases where the (γ, np) threshold determines the maximum. Those responsible for the original data

are better able to judge how seriously to take the shapes of their curves.

In heavy nuclei, the density of bound states is probably sufficiently great so that these considerations of the (γ, np) threshold have little validity in regard to the maximum.

The large number of high energy fast protons observed would be explained from the microscopic point of view as being due to those disintegrations that occur at the surface of a nucleus and eject the protons away from the surface. For monoenergetic photons, the ratio of this surface process to the total effect should be roughly as $\frac{1}{3A^{1/3}}$ before correcting for the coulomb barrier. This ratio is for a sphere. For shapes which have larger surface-to-volume ratios the surface effect (high energy protons) will be larger.

The (γ, np) reaction can be pictured as arising from an equatorial belt where both nucleons have a high probability of escape. This could explain why the (γ, np) process is larger in some nuclei than the (γ, nn) .

The above has been an extreme model as if the interaction is solely with the neutron-proton pairs. This is not a fundamental part of the picture except for providing the lowest continuum of states. There is some evidence that there are interactions with other subunits. Specifically, a large number of deuterons are observed which can be pictured as arising from a three-body interaction. (The smallest four-body system in an S state is an alpha particle and the electric dipole matrix element for d-d is zero.) However, some deuterons can arise from "internal pick-up" at the surface as has been shown by Bransden at higher energies.

The motivation for the point of view taken is to try to change the photodisintegration studies from a set of "self-consistent" phenomena, to data that may be able to answer questions of general interest to nuclear physics.

Specifically, if this model were correct, studies of high energy (surface) protons might be able to prove or disprove Johnson and Teller's picture of heavy nuclei with the protons inside a shell of neutrons.

Also other techniques for studying momentum distributions are difficult to apply to other than light nuclei. There is some indication in L. W. Jones and K. M. Terwilliger's data¹² that the high energy side of the "resonance" drops more rapidly for heavy elements than light elements. If this is a true representation of the cross section, this would show that the momentum distribution of heavy elements has less spread than the momentum distribution of light elements. The exponential obtained in my calculation came from assuming a Gaussian momentum distribution. If a Fermi momentum distribution had been used for a box, there would have been a sharp high energy cutoff.

The interpretation of the low energy side requires more quantitative relationships. If the straightforward analytical methods do not seem amenable to handling this problem, there is now the hope of machine calculation such as that performed by K. G. Dedrick¹³ with the quasi-deuteron model at 100 Mev.

The relationship of this model to that of others is a lengthy subject. Levinger and Bethe's sum rules should apply independent of the model. It is to be noted that the number of neutron-proton pairs in a nucleus is $\frac{N Z}{A}$.

Two words of caution are perhaps in order. One is that the agreement of experimental data with such a model does not necessarily have anything to do with the assumption of no correlation amongst the nucleons. Specifically, an extreme correlation model (namely the neutron and protons as fixed frequency oscillators always traveling in pairs) would give a high energy dependence on the momentum of the pairs. In this extreme correlation case, the momentum comes in because of the Doppler broadening of the frequencies.

The second word of warning is that the electric matrix element cannot be simply interpreted in terms of the momentum distribution at energies where an individual nucleon has an electromagnetic polarizability. From the scattering experiments of Frisch and co-workers, this seems to be set in above 80 Mev. (A. Wattenberg)

VIII. γ -RAY SCATTERING

The experiments on the nuclear scattering of γ -rays have been completed, and the data have been analyzed. Experiments were done with H, D, Li, Be, C, Cu, and Sn. Data were taken at three angles, 45° , 90° , and 135° , and scattered γ -rays were recorded in the energy range from 50 Mev to 134 Mev, which was the peak energy of the beam. All important results of the work will be reported in an article for the Physical Review which is being prepared for publication. The experiment itself will be described in full in Mr. Gomez' Ph.D. thesis (M.I.T. Physics Department, June 1956).

Scattered γ -rays from a target placed in the bremsstrahlung beam of the M.I.T.-O.N.R. synchrotron were detected using the large energy-sensitive liquid scintillator previously reported. After correcting for the response of the counter, we obtained the ratio between scattered γ -rays per steradian in each energy interval, and the number of γ -rays in the incident beam in the corresponding energy interval (allowing for Compton degradation of the scattered γ -range energy). In the case of hydrogen and deuterium this ratio was normalized to σ_{KN} , which is the cross section one could expect on the basis of Klein-Nishina scattering by a particle of proton mass (a recoil correction had to be made for deuterium). The resulting data are plotted in Figure 10.5. The statistics on the deuterium are too poor to be useful in any discussion of theory. The statistics on hydrogen, although still poor, seem to indicate that in the energy range above 80 Mev there is a reduction in scattering at 45° and perhaps an increase in scattering at 135° . This is as we would expect from our work on other elements. Presumably this asymmetry results from the interference between magnetic dipole scattering (associated with the magnetic dipole resonance in meson production) and the normal Thomson electric dipole scattering. The large increase in counting rate

Figure 10.5

Gamma-ray scattering data on hydrogen and deuterium.

Figure 10.6

Gamma-ray scattering data in complex nuclei,

at low energies observed at 45° is evidently not elastic scattering. A reduction in peak beam energy reduced the yield at lower energies. We believe these events result from γ -rays which are produced simultaneously with pair production, when one electron of the pair radiates in the field of the same nucleus in which it was produced.

In the case of scattering by complex nuclei we have plotted (Figure 10.6) the ratio between scattered and incident γ -rays as a ratio to

$$Z^2 \sigma_T = Z^2 \left(\frac{e^4}{M_p^2 C^4} \right) (1 + \cos^2 \theta)$$

which is what would be expected if there were Thomson scattering by Z protons in a point nucleus. Because of the finite nuclear size this elastic scattering would be multiplied by the form factor $f^2 \leq 1$. As an aid in evaluating the data this quantity f^2 for a square nuclear charge distribution of radius $1.2 A^{1/3} \times 10^{-13} \text{cm}$ has been plotted as the light line in each graph. One would expect the scattering to be increased slightly by inelastic scattering. Roughly speaking, the inelastic scattering can be estimated as $(1 - f^2) Z \sigma_{KN}$. The total expected scattering then, given by $Z^2 f^2 \sigma_T + (1 - f^2) Z \sigma_{KN}$, is plotted as the heavy line in each graph.

Again at low energies the 45° data show the excess yield which we blame on internal bremsstrahlung during pair production: $\gamma + Z \rightarrow Z + \beta^- + \beta^+ + \gamma'$. This excess yield was investigated as a function of angle and found to be proportional to $\sim \theta^{-4}$, which is as expected for this type of process. It is also roughly proportional to Z^2 , which is correct for a bremsstrahlung associated process.

However, on complex elements there is also an excess low energy yield at 90° and 135° . This is blamed on resonance or dispersive scattering associated with nuclear resonances. Since these are mostly of the electric dipole type, one would expect their contribution to have the same angular distribution as Thomson scattering. At 90° and 135° where the effect can be observed, this seems to be the case.

At high energies (above 80 Mev) we observe the now familiar decrease of cross section at 45° and an increase in cross section at 135° caused, as for free nucleons, by the polarizability of the nucleons themselves.

We have assumed that most of our anomalous effects at high energy result from dispersive scattering associated with virtual meson production, and that these effects are not primarily due to scattering from the anomalous magnetic moment of the proton treated as a rigid object. Powell¹⁴ has calculated the scattering by a free proton with a fixed anomalous (Pauli) magnetic moment. The ratio of his cross section to Klein-Nishina is plotted as an extra curve on the hydrogen data.

One of the authors, Richard Gomez, has now completed a similar calculation for protons in a complex nucleus. The result indicates that because the protons (and neutrons) in a nucleus tend

to line up with anti parallel spins and magnetic moments their effects cancel out almost completely, and the coherent scattering should be almost exclusively of the Thomson type.

In summary, we see that, to our present accuracy, the scattering of 40 to 130 Mev γ -rays by protons, and complex nuclei is what is to be expected from other experiments on 1) resonance scattering in nuclei at lower energies, and 2) the excited $S = 3/2$ state of the proton-meson system studied at higher energies. It is interesting that this agreement with other data follows only if two conditions are met: a) The available virtual antiproton states of a proton which has absorbed a gamma inside a complex nucleus must be approximately those of a free antiproton, not distorted much in energy by the antiproton nuclear forces¹⁵; and b) The $S = 3/2$ state is excited approximately as easily for a nucleon inside complex nuclei as for a free nucleon. (D. H. Frisch, R. Gomez, G. S. Janes, G. E. Pugh)

IX. PULSE-HEIGHT TELESCOPE

A fast coincidence-anticoincidence telescope for ionizing particles using two of the 14-stage R.C.A. 6810 photomultipliers is presently being tested at the M.I.T. synchrotron. Each photomultiplier views a 4-inch crystal and feeds the pulses on to the grids of three 6BN6 tubes. It is planned to set the biases on the grids independently, and the outputs of the 6BN6 will be fed into a slow coincidence-anticoincidence arrangement. An event is to be accepted if the pulses from the two multipliers fall within prescribed limits. (D. H. Frisch, L. G. Hyman, R. J. Olness, W. B. Marks, W. S. Helly)

X. HIGH-ENERGY γ -RAY DETECTOR

A counter utilizing lead glass chips and a liquid scintillator with matching index of refraction is being considered for use in measuring the energy of γ -rays in the > 20 Mev region. The shower would be developed primarily in the lead glass chips and the charged particles created produce light in the scintillator material.

Preliminary calculations indicate the scheme is feasible with liquids and glass with reasonable attenuation coefficient having indices of refraction within $\Delta n = .1$ of each other. High density lead phosphate glass and α -methyl naphthalene is the most promising combination. (D. H. Frisch, L. G. Hyman, R. J. Olness, W. B. Marks, W. S. Helly)

REFERENCES

1. A. Winston, Ph.D. Thesis, M.I.T., June 1954.
2. Walker, Teasdale, Peterson, and Vette, Phys. Rev. 99, 210 (1955).
3. Jenkins, Luckey, Palfrey, and Wilson, Phys. Rev. 95, 179 (1954).
4. G. F. Chew, Phys. Rev. 95, 1669 (1954).
5. Goldschmidt-Clermont, Osborne, and Scott, Phys. Rev. 97, 188 (1955).
6. John Chappellear, Phys. Rev. 99, 254 (1955).
7. L. Katz et al., Phys. Rev. 95, 464 - 471 (1954).
8. A. S. Penfold et al., Phys. Rev. 100, 1375 - 1377 (1955).
9. J. S. Levinger, Phys. Rev. 84, 43 (1951).
10. J. S. Levinger, Rev. Ann. Nucl. Sci. 4, 13 (1954).
11. Montalbetti, Katz and Goldenberg, Phys. Rev. 91, 659 (1953).
12. L. W. Jones and K. M. Terwilliger, Phys. Rev. 91, 699 (1953).
13. K. G. Dedrick, Phys. Rev. 100, 58 (1955).
14. J. L. Powell, Phys. Rev. 75, 32 (1949).
15. H. P. Duerr and E. Teller, Phys. Rev. 101, (1956), p. 494.

L. S. Osborne

Theoretical Group

I. INTRODUCTION

The work of the Theoretical Group has spanned a wide gamut, ranging from low-energy nuclear physics, going on through meson phenomena, high-energy nucleon scattering, and strange particles. In the low-energy nuclear field, a great deal of emphasis has been put on the Bohr-Mottelson model, which still suffers from some logical difficulties. In particular, the question of what the moment of inertia is, the behavior of the quadrupole moments, and the relation of the unified model to a more fundamental nuclear Hamiltonian are still not understood. Discussions of these matters are made by Weisskopf, Gottfried, and Villars. The recent successes of the Chew-Low theory have prompted further meson calculations. In particular, the Chew-Low theory does not give a discussion of s-wave phenomena, and in the papers by Zachariasen, Friedman, Bincer, and Drell, a phenomenological s-wave theory is proposed and compared with experiment. Two-meson phenomena in which p-wave mesons are involved are explored via the Chew-Low theory by Rodberg. The connection of p-wave meson effects and the spin-orbit forces in nuclei is also being explored. Finally, the model for nucleon-nucleon scattering has been developed which explains qualitative features of that scattering and gives a qualitative fit to the data running from 0 to 275 Mev.

II. THE CLOUDY CRYSTAL BALL MODEL

Calculations of the total cross section, shape elastic angular distribution, and cross section for the formation of the compound nucleus have been calculated by the Whirlwind Computer for the potential

$$V = -V_0(1 + i\xi) \frac{1}{2} \left[1 - \tanh \frac{r - R}{d} \right]$$

A set of parameters was chosen so as to give the correct 0 energy behavior and the above calculations were made for all nuclei for neutron energy up to 4 Mev. An effective range description of low-energy data has also been investigated. (H. Feshbach, C. E. Porter, V. F. Weisskopf)

III. INVESTIGATIONS REGARDING THE OPTICAL MODEL POTENTIAL

We have re-examined the significance of the real and imaginary part of the optical potential. If one starts out with the assumption that all magnitudes in the nucleus should depend only on the

nuclear density, one necessarily comes to the following conclusions. The potential energy cannot be solely due to normal attractive forces. Exchange terms are necessary. The effect of these exchange terms necessarily must have the consequence that the potential well depth is momentum-dependent. This dependence is necessarily such that the well depth increases with increasing momentum. More quantitative evaluations are underway.

In this connection, further studies were made as to the discrepancy between the nuclear radius as measured by the charge distribution, and as measured by the potential energy extension. This discrepancy has been resolved by the following argument. The larger extension of the potential radius is explained along the lines of the ideas of S. Drell, in which the attractive forces have a longer range than the repulsive forces in the nucleus. The fact that the mass density in a potential well has a smaller radius than the potential well can be explained by the sloping walls of the potential, which keep the particles with lower kinetic energy nearer to the center of the nucleus.
(C. Schwartz and V. F. Weisskopf)

IV. INVESTIGATIONS REGARDING THE BOHR-MOTTELSON MODEL

The attempt was made to understand the measured values of the nuclear moments of inertia by applying the idea due to Bohr and Mottelson that the interaction between the nucleons decreases the moment of inertia. The wave functions employed were those developed by K. Gottfried.

Further investigations were made to explain the preponderance of positive quadrupole moments. We came to the conclusion that no explanation of this preponderance exists at present. All theories give roughly the same probability for large negative quadrupole moments. Deformed nuclei have states with large positive and negative quadrupole moments with very small energy differences between them. Thus, the theory at present can only explain the large absolute values of those moments. Further studies in this direction are in progress. (K. Gottfried and V. F. Weisskopf)

V. INVESTIGATIONS REGARDING THE NATURE OF THE SPIN-ORBIT COUPLING

A critical study of the Feingold-Keillson theory of the spin-orbit coupling was made. These authors maintain that the spin-orbit coupling results from the tensor force interaction between a nuclear particle and the nuclear core. We found that this effect does exist but that it has the wrong sign. This is in contrast to the results of the previous authors. We are planning to look for other explanations of the spin-orbit coupling. A suggestion of David Frisch is under investigation, in which the spin-orbit coupling is connected with the isomeric state in the meson-nucleon system.
(D. H. Frisch and V. F. Weisskopf)

VI. DIRECT INTERACTION IN INELASTIC NEUTRON SCATTERING

The inelastic scattering of neutrons can occur via the compound nucleus, through excitation of rotational level of the target nucleus, and finally by direct knock-on collision with an incident nucleon of the target nucleus. The last would proceed via the residual forces existing inside the nucleus after the cooperative effects responsible for the shell model potential are subtracted. It would be presumably of short range. The method of distorted waves is then used, assuming that the potential responsible for the inelastic scattering is of the form of a delta-function, to compute the angular distribution and total inelastic cross section. The results have been evaluated for carbon in which the transition is from a $0+$ to a $2+$ first excited state. The cross section is found to be of the order of a few millibarns and should be observable between resonances. (J. LaMarsh and H. Feshbach)

VII. NUCLEON-NUCLEON SCATTERING

Nucleon-nucleon scattering data from 0 to 274 Mev are discussed by means of a boundary condition approximation. For internucleon distances greater than the core radius, which may depend on the state under discussion, the nucleon-nucleon interaction is assumed to vanish, while at the core radius the logarithmic derivative of the wave function or the reaction matrix satisfies a boundary condition. Assuming charge independence, it has been found possible to fit most of the experimental data with all but one energy-independent boundary condition. The core radius for the 1S_0 state is assumed to decrease with increasing energy. We find that p-p scattering is composed mostly of scattering in the 1S_0 and 3P_0 states, both of which give isotropic distributions. The scattering from the 3P_0 state is close to the scattering by a repulsive sphere of radius 1.32×10^{-13} cm. The scattering in the isotopic singlet state below 100 Mev, assuming that the n-p angular distribution is symmetric about 90° , is entirely determined by the low energy fit to triplet ($^3S_1 + ^3D_1$) n-p scattering. Above 100 Mev the ($^3S_1 + ^3D_1$) states make the major contribution to the isotopic singlet scattering. The predicted cross sections fail significantly in only one detail in that they are not sufficiently large for n-p scattering near 180° . Regardless of the validity of this particular fit, the boundary condition approximation is found to provide a comparatively simple method for the broad correlation and understanding of the experimental results. (H. Feshbach and E. L. Lomon)

VIII. PHOTODISINTEGRATION OF THE DEUTERON

The phase shifts and wave functions obtained by Lomon and Feshbach were used to estimate the cross section for photodisintegration of the deuteron in the intermediate energy range (less than γ -rays of 100-Mev energy). Inclusion of the interaction in final states does help reduce the

discrepancy between theory and experiment, but a very sizable discrepancy still remains. The effect of quadrupole and higher order transitions is being investigated. A related problem of some interest is the bremsstrahlung on proton-proton scattering. This would involve transitions which form a rather small part of the photodisintegration process and, therefore, would give a sensitive test for any wave functions describing the p-p system. (J. Bernstein and H. Feshbach)

IX. THE BOHR-MOTTelson MODEL

In this investigation we attempted to derive the energy operator of the Bohr-Mottelson unified nuclear model from the Hamiltonian of a system of interacting nucleons, by means of a canonical transformation. After a "pilot" calculation, using a two-dimensional space only, had been completed, the actual problem was solved, again using the method of "redundant" variables. (This method was introduced independently, also by Lipkin, de-Shalit and Talmi¹). The result is an operator, which has exactly the structure of the operator of the unified model. There is one difference, however. As a result of the introduction of collective variables along with the particle coordinates (or "intrinsic" variables), the wave function of the system must satisfy a set of subsidiary conditions. No such condition is considered in the original formulation of the unified model. In the transformed energy operator a certain coupling between collective and intrinsic motion survives. Its physical meaning is that of an inertial force term on the intrinsic motion in a frame of reference following the collective flow. In principle, this residual coupling can be removed by either perturbation theory or by additional canonical transformations. The difficulty of doing this arises from the fact that the coupling energy does not commute with the subsidiary condition. If one disregards the subsidiary condition altogether, the problem becomes relatively easy and has been discussed². We are now in the process of finding a formulation of the problem with the subsidiary condition included. (F. Villars)

X. NUCLEAR SATURATION

An attempt is underway to generalize the Brueckner theory of nuclear saturation to finite size nuclei. The essential quantity of the theory, the coherent scattering amplitude t_c for an infinite nuclear medium, is replaced by an amplitude t'_c for a finite nucleus. t'_c and t_c are related by a simple integral equation. As a preliminary to the solution of this equation, models for t_c have been constructed. (F. Villars)

XI. RELATIVISTIC WAVE MECHANICS

A report is being written, in which we try to give a unified presentation of the relativistic wave mechanics of spin 0, spin 1/2 and spin 1 particles. The interpretation of the wave function

will be discussed, and the connection with the quantum-field theoretical description will be established. The discussion will be elementary throughout, and we hope this report will be useful to experimenters having to deal with relativistic particles. (F. Villars and H. Feshbach)

XII. STRANGE PARTICLES

An analysis is being made as to whether the properties of hyperons and K-mesons may be understood in terms of simple coupling schemes. To start with, a "strong" coupling between K-mesons and pions, of type

$$\sum_{\alpha=1}^3 \phi_{\alpha} (\chi_s^{*\tau} \chi_p + \chi_p^{*\tau} \chi_s)$$

(where ϕ_{α} are the three pion amplitudes, $\chi_{s,p}$ the scalar and pseudoscalar K-meson amplitudes), has been looked at. In this scheme, the hyperons are considered as "molecules", made of a nucleon and a K-meson, bound by the common pion field (in close analogy to Goldhaber's³ assumption). This scheme leads to associated production and to a hyperon isotopic triplet state (Σ) of higher mass than the singlet (Λ) state. A difficulty arises from the fact that the K-mesons and their antiparticles couple with equal strength to the nucleon, giving rise to a doubly charged Σ and a singly charged Λ . This difficulty and other schemes are presently being investigated. (F. Villars)

XIII. THEORY OF S-WAVE MESON SCATTERING AND PHOTOPRODUCTION

This work, reported in preceding quarterly progress reports, is now finished and prepared for publication.

A fixed source analysis of the s-wave pion nucleon interaction is constructed along the lines of the Chew-Low-Wick formalism. A bilinear s-wave interaction of the form

$$\lambda_0 \vec{\varphi} \cdot \vec{\varphi} + \lambda \vec{\tau} \cdot \vec{\varphi} \times \vec{\pi}$$

is added to the usual p-wave coupling $\sqrt{4\pi} f/\mu \vec{\sigma} \cdot \vec{\nabla} \vec{\tau} \cdot \vec{\varphi}$. Scattering equations are developed and solved in the one-meson approximation. Values for the renormalized coupling parameters λ_0 and λ are determined which give reasonable agreement with the s-wave phase shifts up to ~100-Mev pion kinetic energy. This s-wave interaction with the parameters fixed by the scattering analysis is then applied to the discussion of the π^+ and π^0 photoproduction cross sections. A Kroll-Ruderman theorem is proved for the above non-local interaction, and it is shown that the contributions to s-wave neutral and charged photoproduction are consistent with experiment. (S. D. Drell, F. L. Friedman, and F. Zachariasen)

XIV. TWO S-WAVE MESON PHENOMENA

The theory developed above can be confronted with two additional cross sections involving low-energy s-wave pions. These are the magnetic dipole photoproduction of two s-wave pions and the inelastic scattering of an incident p-wave into two s-wave pions. Comparison with measured cross sections for these processes near threshold will help define the possible role of a pion-pion interaction.

Cross sections of these two processes have been calculated by extensions of the methods in the preceding work. Numbers are now being computed. (A. M. Bincer)

XV. PROTON POLARIZABILITY

In analyses of the scattering of high-energy electrons and protons the electric charge and magnetic moment distributions of the proton are treated as if rigid. This ignores effects on the scattering from the electron-induced polarization of this charge and current cloud. This polarization is responsible for the nuclear Compton effect, but it contributes only $\left\{\frac{1}{137}\right\}^2$ corrections to the main $\left\{\frac{1}{137}\right\}$ term of the electron-proton scattering amplitude. On the other hand, the proton polarizability can be anomalously large near those frequencies ("resonance") for which photomeson production is big, i.e. for $\hbar\omega$ from 200 to 400 Mev. These are also the significant electromagnetic field frequencies felt by the proton in small impact parameter, large-angle electron scattering which are sensitive to the charge and current distributions of the proton. We have calculated these polarizability effects and found them to contribute corrections of less than 1% for electron energies ~ 400 Mev. The reason for the smallness of this correction is found to be the phase cancellation in contributions above and below "resonance" from the virtual photon spectrum of the scattered electron.

This work was started at Brookhaven last summer and completed this year in collaboration with Professor M. Ruderman of the University of California, Berkeley, California. (S. D. Drell)

XVI. NUCLEAR SATURATION

The boundary conditions model of the nucleon-nucleon interactions as formulated by E. Lomon and H. Feshbach has been applied to the problem of the saturated nucleus by the method of Brueckner et al. To obtain a solution with the boundary condition model, modifications have been made in Brueckner's self-consistent method. Calculations of the binding energy and radius of the saturated nucleons have been completed and give too little binding at too low a density. (K. Cuff)

XVII. A HIGH-ENERGY APPROXIMATION FOR RELATIVISTIC SCATTERING CROSS SECTIONS

The short wavelength approximation of Moliere⁴ has been extended to take account of both relativistic and spin effects. The approximation is best at small angles, but still gives good agreement with exact calculations at 90°, even for large values of Z , both for Coulomb scattering and for scattering by an extended nucleus. The method should be particularly useful for calculating variations of the scattering cross section, when the form factor of the extended nucleus is varied. A report on this work was presented at the Washington meeting of the American Physical Society, April 26, 1956. (L. R. B. Elton)

XVIII. THE INELASTIC SCATTERING OF 30-MEV PROTONS BY HEAVY NUCLEI

A theory has been developed to account for the experimental results on the inelastic scattering of 30-Mev protons by Sn.⁵ The results show a strong forward peaking, which clearly indicates that the process cannot take place via compound nucleus formation and decay. It was first shown that the fair agreement with experiment obtained previously⁶ on the assumption of knock-on collisions taking place throughout the nucleus was fortuitous, and due to an unjustifiable approximation. In fact, this process yields less than 10% of the experimental values. The unjustifiable approximation referred to was the neglect of total internal reflection at the boundary of the nuclear potential. At the energy concerned, this is by far the most effective way by which nucleons are trapped in the nucleus. This is true even for knock-on collisions taking place in the diffuse rim of the nucleus.

It was then proposed that the scattering is due to the interaction between the incident proton and a target nucleon, which, because of quantum-mechanical effects, is temporarily unbound. This allowed two parameters with which to fit the experimental results:

- (a) The maximum kinetic energy $E_{\max}$ of the unbound nucleons.
- (b) The number N of such nucleons present at any moment.

Of these parameters, only the first affects the shape of the angular distributions; the second merely affects the absolute cross sections.

Surprisingly good agreement with experiment was obtained by taking the very reasonable values $E_{\max} \sim 6$ Mev, $N \sim 3$. (L. R. B. Elton, and L. C. Gomes)

XIX. PION PRODUCTION IN PION-NUCLEON COLLISIONS

The Chew-Low formalism is being applied to the problem of pion production in pion-nucleon collisions through a linear coupling. The equation for the T-matrix element appropriate to this problem has been found, analogous to the Chew-Low equation for meson scattering. In the

one-intermediate-meson approximation, this equation gives a set of coupled linear integral equations. These serve to give the cross section for this process in terms of the cross section for meson scattering. By assuming that this scattering proceeds only through the $J = \frac{3}{2}$, $T = \frac{3}{2}$ state, the equations can be solved. At present, numerical values are being obtained. Future work will involve the computation of the total cross section, the angular distribution, and an investigation of the validity of the method. (L. S. Rodberg)

REFERENCES

1. Lipkin, de-Shalit and Talmi, Nuovo Cimento X, Vol. 2, p. 773 (1955).
2. A. Kerman, Kgl. Danske Videnskab. Selskab, 30, No. 15 (1956).
3. M. Goldhaber, Phys. Rev. 101, 433 (1956).
4. G. Molière, Z. Naturforsch. 2A, 133 (1947).
5. R. M. Eisberg and G. Igo, Phys. Rev. 93, 1039 (1954).
6. Hayakawa, Kawai, and Kikuchi, Prog. Theo. Phys. 13, 415 (1955).

V. F. Weisskopf

CAMBRIDGE ACCELERATOR PROJECT GROUP
(Harvard-M.I.T. Strong Focusing Synchrotron)

I. INTRODUCTION

The Massachusetts Institute of Technology and Harvard University are cooperating in the design, construction and operation of a 6-Bev electron accelerator to be located in Cambridge, Mass., on Harvard University grounds. Funds for the support of this machine are to be provided by the U.S. Atomic Energy Commission as part of their program in support of research in high energy physics in the universities. Preliminary design studies have been supported for the past two years by a joint program of the Office of Naval Research and the Atomic Energy Commission, using the part-time services of about twenty-four scientists and engineers from Harvard and M.I.T.

Cost of construction, including all buildings and personnel salaries, is estimated to be \$6,500,000. The time required to complete construction will be about 4 years. Detailed designing will start by July 1, 1956, and the construction of some of the buildings should be underway by late fall. The responsibility for the construction contract with the Atomic Energy Commission will be assumed by Harvard University. However, a joint management committee of scientists and administrators from both schools will supervise the construction and operation of the accelerator as a research facility. Although the initial authorization provides funds to power the accelerator to 6.0 Bev, the orbit radius has been chosen large enough to allow higher ultimate energy. Future expansion of the power supply is planned to reach 7.5 Bev.

II. GENERAL DESCRIPTION

The accelerator will be an electron synchrotron, formed of a ring of 48 strong-focusing magnets utilizing the alternating-gradient principle. Magnet sectors will be spaced by 48 field-free straight sections, each 4 feet long. The magnet circle radius is to be 118 feet and the orbit radius within magnet sectors is 86 feet. The flux density required for 6.0-Bev electrons is 7.6 kilogauss; for 7.5 Bev it will be 9.5 kilogauss. This relatively large orbit radius and low magnetic field is deliberately chosen to reduce the problem of radiation by the orbiting electrons to manageable proportions. Since flux densities are well below the saturation region, the design of the magnet is considerably simplified and corrections are minimized.

The AG magnet sectors will be arranged in a sequence described by the code-word "fodod" (focusing-zero-focusing-defocusing-zero-defocusing), in which the straight sections (zero) are placed in the centers of the gradient sectors. This location involves minimum effect on oscillation amplitudes by straight sections, and simplifies construction. The gradients, or n -values, will be designed to provide 5.4 free oscillation wavelengths per turn, for both radial and vertical free

oscillations. We choose to avoid orbital resonances, of the integral, half-integral and sum types, but we use the results of the Brookhaven electron analogue to justify operation on a difference resonance. In this location within the stability "diamond" a variation of $\pm 2.5\%$ in average n -value is allowable. Quadrupole lenses in the straight sections will be time-scheduled to provide corrections of the average gradient due to changing magnetic properties, so as to maintain operation within the stability diamond during acceleration.

Each magnet sector will be constructed of laminated iron, as for a transformer, bonded into solid segments about 4 inches thick for rigidity, and assembled into a rigid structural unit 11 feet long, having the orbit radius of curvature. Present plans call for die-stamping the laminations as complete units, with the designed pole-face profile. Half of each sector will have a "positive" gradient and half a "negative" gradient. Excitation windings formed in layers to slip between pole tips will enclose the entire sector, formed of water-cooled bus bars and insulated with glass-fibre tape and a polyester resin.

The magnet will be excited by a resonant power supply at 30 cycles per second, with a dc bias to give uni-directional pulsing. Parallel resonant circuits for each magnet sector will use capacitors to store energy and transfer it to air-gap chokes during the low-field part of the magnetic cycle. The peak-stored energy in the magnetic field (for all 48 sectors) will be about 800,000 joules, and the power required to excite the magnet, including conductor heating and magnetic losses, will be about 400 kw at 6-Bev excitation or 650 kw at 7.5 Bev. Injection will occur near 25 gauss, at a phase of the cycle when the rate of field increase, dB/dt , is low, which minimizes eddy current distortion of the field. The interval for acceleration, during which the field rises to maximum, is 15 milliseconds, and the electrons will reach maximum energy in about 20,000 turns.

Radiofrequency accelerating cavities will be located in 16 of the straight sections, driven in phase at a constant frequency of about 500 megacycles, which is a high harmonic (about the 350th) of the orbital frequency. This use of high harmonic order reduces the dimensions of the cavities and so lowers the circulating electrical energy and rf losses. It also reduces synchronous oscillation amplitude. The maximum rate of acceleration, at half-excitation, is 0.4 Mev per turn.

Energy loss due to radiation by the beam increases with the fourth power of particle energy, reaching 4.4 Mev per turn per electron at 6 Bev and 10.7 Mev per turn at 7.5 Bev. These peak values occur at the end of the acceleration cycle and set the volts-per-turn requirement. For perspective it might be pointed out that the 16 cavities represent a spaced linear accelerator of about 40 feet total length; an output energy of 10.7 Mev in a 40-foot linear accelerator is well within current practice.

Each cavity will be a drift-tube-loaded resonant system, with 2 (or possibly 3) accelerating gaps between drift tubes depending on choice of frequency, and will look like a short section of a linear accelerator, about 2.5 feet long and 18 inches in diameter. An outer vacuum tank will enclose the copper cavity, which will be water-cooled for thermal stability. For such a resonant cavity we estimate an electrical efficiency Q of 30,000 and a shunt impedance of 10 megohms.

The peak voltage requirement per cavity, of about 1 million volts sets the peak power requirement for the radiofrequency amplifiers. A more demanding requirement is the average power, to supply cavity losses and beam load during the long (nearly 50%) rf duty cycle. Beam load will represent about half of the total power. Present plans call for klystron amplifiers delivering a peak power of 25 kva and an average power of 5 kw per cavity at 6 Bev, or a peak of 75 kva and an average of 12 kw per cavity at 7.5 Bev. The total dc power needed to supply the klystrons will be about 750 kw at 7.5 Bev.

Electrons will be accelerated initially to about 20 Mev in a linear accelerator, operating at a frequency which is preferably an integral multiple of the synchrotron rf frequency. At this energy the velocity defect will shift the equilibrium orbit inward only 0.4 inches. The angular spread of the linear beam, estimated as $\pm 1 \times 10^{-3}$ radians, will cause betatron amplitudes in the AG magnet field of about ± 0.4 inches. However, the energy spread of ± 0.5 Mev will produce a radial spread in equilibrium orbits up to ± 1.5 inches. We anticipate some loss in beam due to this energy spread, and hope to develop an energy-bunching system to reduce it.

An electrostatic inflecting field in one straight section will direct the linear beam into the central orbit, with the pulse timed to match the magnetic field for injection. This inflecting field will be pulsed off in a time short compared with the 0.75 microsecond orbital period, filling essentially one turn. We estimate that with a pulse current of 0.25 amperes from the linear accelerator, about 1×10^{12} electrons will be injected into the orbit. Orbit acceptance in the 5-inch $\times$ 1.5-inch vacuum chamber, and phase acceptance into synchronous orbits will reduce the number captured to about 2×10^{11} per pulse, which should then be accelerated to high energy.

The anticipated output beam intensity, at 30 pulses per second, is 6×10^{12} electrons per second, a time-average current of 1 microampere. At 6 Bev energy this represents a beam power of 6 kilowatts, which can be compared with about 16 kilowatts radiated during acceleration.

We will now discuss some of the special features which have been analyzed during design, and present some preliminary results from magnet model studies.

III. PHASE-MODULATED INJECTION

The intensities described above represent expected values from a free-running linear injector, and suffer losses due to the phase acceptance limitation of the synchrotron. We propose to increase the intensity of electrons captured in synchronous orbits by phase-modulating the injector. For example, if the linear accelerator is designed to operate at a frequency which is an integral multiple of the synchronous radiofrequency, such as 1000 Mc ($\times 2$) or 3000 Mc ($\times 6$), the output beam of the linear machine will be pre-bunched in phase, with a phase spread which is narrow compared with the phase acceptance of the synchrotron. Furthermore, if the input to the linear accelerator (at the electron gun) is modulated at the synchronous frequency, a single pulse of electrons will

be accelerated for each synchrotron cycle. The modulated output of the linear machine can have much higher peak current, for the same power input, increasing intensity of the useful beam injected into the synchrotron by a factor of 2 or more. Another useful result is the reduction of initial synchronous radial oscillations associated with energy oscillations in the synchrotron.

To accomplish this result the linear accelerator will be driven at a harmonic of the synchrotron frequency, from a common master oscillator, with relative phasing controls to determine the phase of pulse injection. The type of modulation required for the linear machine will be determined after suitable power tubes and frequencies are chosen. Beam loading of the rf cavities for such increased intensities exceeds the capacity of the designed rf power supply. Higher intensity will require an increase in rf power, which sets the intensity limit for this type of accelerator.

Phase modulation represents an attempt to match the properties of the injector to those of the accelerator. It has a more general application than just to this electron machine, and might be considered to advantage for other accelerator systems.

IV. MAGNET ALIGNMENT

We have conceived a technique for magnet alignment using the electron beam called "one-turn alignment", which should relax mechanical alignment requirements and also provide a method of correcting deviations from alignment during operation. This is based on a theoretical study of oscillation amplitudes due to misalignments and a conclusion that the maximum deviation Δx in one turn in our AG magnet system will grow to no more than about $2 \Delta x$ in a large number of turns.

We propose to inject a sequence of extremely short pulses of electrons from the linear beam, with a steady inflecting field and a steady magnetic field, and to explore the particle trajectory in the first turn. Available high quality surveying techniques should be sufficient to keep the beam within the chamber during one turn, although possibly with large amplitude deviations. We propose to study the effect on beam trajectory of all types of magnet misalignments, in sufficient detail to be able to recognize and identify the consequences of any single type. With this information it should be possible to correct all major deviations by observing the trajectory, and through a series of corrections to reduce amplitudes below the desired Δx .

The technical features required are a set of 48 pairs of "sensing" electrodes in the straight sections, each of which will provide a differential pulse signal when the electron pulse passes to show the radial (or vertical) deviation. A cathode-ray tube presentation of these signals will show beam location and oscillation amplitudes around the orbit. Suitable controls on magnet alignment screws (possibly motor driven) should make it possible to perform the indicated adjustments, with the effects observable on the C.R.T. With such techniques we believe the magnets can be brought into alignment with a reasonably small effort. Eddy current and other effects due to dynamic pulsing will of course have to be corrected separately.

V. RADIATION-INDUCED OSCILLATIONS

During the design study a new and fundamental problem of an AG machine has been recognized and analyzed. This is the growth of oscillations due to the difference in radiation energy loss on the inside and outside of the equilibrium orbit location. The electron radiation has a purely classical energy distribution, extending up to a characteristic energy of about 30 kilovolts. Emission of quanta of these energies exerts a small but finite effect on the amplitude of electron oscillations. Consider an orbit with a residual betatron oscillation. When radiation occurs, the location of the equilibrium orbit jumps instantaneously inward. The electron will radiate more where it has a small radius of curvature, i.e., on the outside of the equilibrium orbit, and less when inside the equilibrium position. This results in a net increase in the amplitude of the betatron oscillation, an anti-damping effect. We estimate that some beam loss due to amplitudes exceeding the uniform field region would start at about 5 Bev and might become serious at 6 Bev.

Several techniques are available to provide positive damping sufficient to overcome the amplitude build-up at high energies. For example, a radial gradient in the accelerating electric field might be provided by slanting the faces of the rf gaps in some of the accelerating cavities; this could add energy at a different rate for particles inside and outside the equilibrium orbit, providing damping for betatron oscillations. Another method might be to provide special correcting magnets in straight sections which would induce greater radiation for particles on the inside of the orbit and so compensate for the anti-damping effect. Such a magnet would have equal-length sections of opposed field, to give zero angular deviation, but with both sections formed with a negative gradient so the local orbit curvature is greatest at small radii. Other techniques are possible such as coupling radial and vertical betatron oscillations which would cancel the anti-damping effect.

In addition to the classical effect described above, another source of induced oscillations at high energy comes from the quantum nature of the radiation. Emission of quanta of these energies will produce a statistical build-up of oscillation amplitudes, both betatron and synchronous. For our conditions, this is computed to lead to a radial amplitude of several inches by the time the particles reach 6 Bev energy, if no damping were provided. The damping systems described above are sufficient to limit this increase to a few millimeters while also compensating for the classical build-up effect. The phase amplitude of the synchronous oscillations due to the quantum effect is a more serious limitation. Phase oscillations would grow to about 25° (rms) in phase by 6 Bev, requiring a smaller synchronous phase angle and higher peak rf voltage.

VI. MAGNET MODEL STUDIES

A full-scale section of the magnet has been constructed, using the chosen 2-inch gap at the central orbit, with 1 foot of positive gradient and 1 foot of negative gradient. Excitation coils have the approximate shape planned for the final magnet. It was formed of 0.025-inch Electrical Grade

silicon steel; each lamination was coated with insulation; the laminations were bonded by adhesive into solid blocks 4 inches thick. Pole faces were precisely machined to a hyperbolic shape with a constant, $K = 7.95 \text{ in.}^2$, designed to give an n -value of 100 at the chosen orbit radius. (Present plans would increase this to about 116 and would use larger orbit radius.) The central 6-inch width of the 7-inch pole face follows the hyperbolic curve, with a 1/2 inch round at the nose and a 1/2 inch flat at the wide side of the gap for edge corrections.

Measurements made to date include only dc field plots and excitation studies. An ac power supply for dynamic tests is under construction. A variety of instruments have been used, with a relative precision of 0.5 % and an absolute calibration of 1 to 2 %. Further details are available in a laboratory report.

Radial plots across the field on the median plane show a wider region of uniform-gradient than anticipated. Over the entire excitation range between 500 gauss and 9.5 kilogauss the uniform ($\pm 0.5\%$) region was over 4-1/2 inches wide. At injection field (25 gauss) it was 5-1/2 inches wide. In order to utilize the full effective width we have displaced the two parts of the magnet radially by 1 inch, so the equilibrium orbit is near the center of the uniform-gradient region in both sectors.

Gradients measured in the radial plots are the same as the computed values, within the accuracy of the measurements, for both types of sector. Slight differences between sectors have been noted which may prove to be significant with better precision, and which may be a consequence of the back-leg asymmetry. Extension of the radial plots to higher excitation (maximum 11.4 kilogauss) shows a decrease below the computed gradients of about 3%. We have not powered the magnet to saturation and find that the required excitation (ampere-turns per gauss) is only 3% larger at 9.5 kilogauss than at low fields.

The remanent field at the central orbit following full uni-directional excitation is measured to be 19 gauss in both sectors. (This might be reduced by using iron with a higher silicon content.) Radial plots of the remanent field show the same width of uniform-gradient region as at injection field, and with only slightly higher n -values. We are greatly encouraged by observing this uniform-gradient remanent field, and believe that remanent field effects will not distort the radial field distribution.

Extension of fields into the straight sections at sector ends has been studied with some care. The location of the "magnetic face" of the magnet (the position dividing the fringing field into equal areas on a B vs z plot) varies considerably with excitation. At injection field the magnetic face on the central orbit is close to the physical face; at 1500 gauss it is 1.3 inches outside the physical face; at 9.5 kilogauss it has withdrawn to 1.0 inches. Other plots at different radii and off the median plane show the shape of the end fringing field. We intend to use these plots to determine the amount of non-uniform gradient at different radii, and so to predict the change in location of the working point within the stability diamond. The location of the magnetic face at full excitation will be used to determine basic AG magnet parameters; deviations at lower fields can

be corrected by using the quadrupole lenses in the straight sections.

A preliminary conclusion from these dc measurements is that the radial field patterns are sufficiently uniform to maintain operation within the stability diamond by using only quadrupole lenses for corrections of average gradient. Dynamic measurements may show the need for some time-scheduled variation of radial field. If so, we plan to use pole face windings cemented to the poles.

VII. BUILDING PLANS AND SHIELDING ARRANGEMENTS

We plan to place the accelerator in a covered trench, with the beam 10 feet below ground level. The tunnel roof will be covered by 4 feet of earth, increased to 8 feet over the target area where radiation intensities will be greatest. Our calculations of the expected intensity of secondary radiations show that the chief component coming through the tunnel roof will be relatively low energy (< 200 Mev) neutrons. The shielding thickness is estimated to keep external intensities well below tolerance levels for all normal operations.

A large experimental area will be provided on one side of the orbit, behind a 10-foot shielding wall. Beams of gamma rays and other radiations from 3 or 4 alternative target locations will be brought through channels in this wall. Magnetic analysis in the target area inside the wall can be used to separate beams of charged particles, and focusing magnets can be located in this region. The experimental area behind the wall will be about 60 ft. $\times$ 200 ft., large enough to allow the permanent installation of 10 or more major research installations, and with a beam run over 100 ft. in length in some directions.

The shielding wall will be graded in density, with a 1-ft. layer of steel plate at beam level. The sharply-directional electron gamma-ray showers and the high-energy nuclear components of the radiation will be contained within this central steel band. Above and below the steel plates will be iron-loaded concrete blocks; at still wider angles normal concrete blocks will be used. Nuclear components making wider angles with the beam will be of lower energy than those in the forward direction, so less density is required. The widest-angle component is neutrons, for which normal concrete is best. Attenuation calculations show the wall will be sufficient to reduce intensity levels below tolerance with all holes plugged. However, when beam channels are opened, the intensity in the experimental area will exceed tolerance and local shielding will be required, strongly dependent on the type of experimental target. If necessary, personnel will be vacated to remote observing stations in the laboratory building.

VIII. RESEARCH PROGRAM

The scientific justification of this accelerator is primarily to explore a region of energy of the order of six times higher than will have been reached with beams of electrons or X-rays. Despite

the relative weakness (by a factor of about 100) of the electromagnetic interactions relative to nuclear interactions, there are excellent reasons for using electrons. As described earlier, electrons can be obtained in high intensity with relative ease and accelerated at constant frequency and at high repetition rates. The effective beam current will be hundreds of times that of a proton machine of equal energy but higher cost. The large fractional on-time makes electronic detection and coincidence experiments easier. Furthermore, the most readily available radiation will be the sharply-collimated beam of X-rays emerging from a target, with a half-angle of only 10^{-3} radians. The high flux density in this beam allows efficient shielding and compact target arrangements, giving large solid angles and low backgrounds in experiments. The opportunity of using small targets may be of great importance in searching for new particles with short half-lives.

We anticipate programs of research in the following general areas:

(a) Production and study of proton-antiproton pairs. The threshold for this production reaction with X-rays is at 3.8 Bev; our surplus above threshold should result in considerably higher intensities than are available with existing machines.

(b) Production of strange new mesons and hyperons and their antiparticles. Our plans for 7.5 Bev are based in part on the desire to exceed the threshold (6.35 Bev) of the reaction producing pairs of "shower particles", the heaviest of all known strange particles in the cosmic radiation.

(c) Photoproduction studies of pions, muons and nucleons at higher energies. Extension of data on interaction cross sections to higher energy will give new information about the relation of mesons to nucleonic and nuclear structure. Furthermore, high intensity beams of much higher energy mesons will become available.

(d) Electron structure. The electron or X-ray wavelength in electron-electron or electron-nucleon impacts is short relative to electron or nuclear radii, permitting exploration of charge distribution and structure with considerably better resolution than from existing accelerators. The limits of validity of the laws of relativistic electrodynamics may be tested to these higher energies.

M. Stanley Livingston (Director Cambridge
Accelerator Project)

P. T. Demos

F. J. Eppling

B. T. Feld

D. H. Frisch

G. S. Janes

W. L. Kraushaar

L. S. Osborne

A. Pevsner

I. A. Pless

D. M. Ritson

R. A. Schluter

A. Wattenberg

R. W. Williams

PERSONNEL LISTING BY PROJECTS

A. ADMINISTRATION

Steering Committee

Zacharias, Prof. J. R. (Chairman)
Harrison, G. R., Dean of School of
Science
Benedict, Prof. Manson
Cope, Prof. A. C.
Frank, Prof. N. H.

Cecconi, W. E.
Crepeau, W. J.
Griffith, E. W.
Karasik, H.
Lewis, R. M.
Mersereau, T. O.
Robbins, E. H.
Sherry, F.
Stanowicz, J. T.

Headquarters

Zacharias, Prof. J. R., Director
Demos, Dr. P. T., Assistant Director
Eppling, Dr. F. J.
Thompson, D. C.
Bulfer, Charlotte A.
Caldwell, Rita C.
Gazan, Margaret M.
Rajner, Lucille C.

General Service

Scrima, V. J.
Baker, D. W.
Dillon, J. L.
Tardivo, S. A.
Roxborough, J.

Purchasing

Sargeant, J. L.
D'Andrea, T.
Libertini, A. J.
Nickerson, Patricia*
Sedergran, Dorothy M.
Tricomi, R. J.

RESEARCH GROUPS

Chemistry of the Fission Elements Group

Staff

Hume, Prof. D. N. (on leave)
Lee, Dr. J. K.
Rogers, Prof. L. B.
Leussing, Dr. D. L.*
Whiteker, Dr. R. A.

Electronics Shop

DeAgazio, E.
Parker, E.
Purington, A. T.
Zufelt, H. C.
Mangan, E. J.
Riseman, John H.

Graduate Students

Breese, R. F.
Burns, E. A.*
DeGeiso, R. C.
Forman, E. J.
Hanselman, R. B.
Heintz, E. A.
Keily, H. J.*
Krebaum, L. J.† (now with Biology
Dept., M.I.T.)
Loder, E. R.*
Morrison, C. F.
Hercules, D. M.
Newman, L.*
Ohnesorge, W. E.
Przybylowicz, E. P.
Purdy, W. C.*
Reinmuth, W. H.
Rosenberg, N.*

Drafting

Tourtellotte, C. W.
Peinert, C. H.
Rowe, Grace W.
Saia, N. A.

Machine Shop

Gustavson, R. H.
Burke, P. A.

* Terminated

† Transferred

Personnel

Non-Staff

Bowen, Katherine

Nuclear Chemistry (Inorganic) Group

Staff

Coryell, Prof. C. D.
Irvine, Prof. J. W., Jr.
Cotton, Dr. F. A.
Herber, Dr. D. H.*
Horne, Dr. R. A.
Schindewolf, Dr. U. L.

Graduate Students

Alexander, J. M.
Dietz, R. J., Jr.
Fix, R. C.
Freeman, D. H.
Gleit, C. E.
Holm, R. H.
Poskanzer, A. M.
Rudзитis, E.
Winchester, J. W.*

Visitors

Schonken, Dr. Paul* (F.S.S.P., Centre
d'Etudes pour les Applications de
l'Energie Nucleaire, Brussels,
Belgium)
Tuck, Dr. Dennis* (F.S.S.P., United
Kingdom Atomic Energy Authority,
Windscale Works, Cumberland,
England)
Brubaker, Prof. C. H.* (Michigan State
College, East Lansing, Michigan)
Dostrovsky, Dr. Israel (Weizmann Inst.,
Rehovoth, Israel)
Shiokawa, Prof. Takanobu* (Department
of Radiochemistry, Shizuoka Univer-
sity, Shizuoka, Japan)

Non-Staff

Poole, W.
Vanelli, Charleen

Nuclear Chemistry (Organic) Group

Staff

Sheehan, Prof. J. C.
Swain, Prof. C. G.
Greene, Dr. F. D., II

Halmann, Dr. M. M.*
Kresge, Dr. A. J.
Yang, Ding-Djung

Graduate Students

Allen, Malvina
Bader, R.*
Griffin, R. N.
Holland, G. F.*
MacLachlan, A.
Pegues, Betty E.
Reuwer, J. F., Jr.
Schaad, L. J.
Stivers, E. C.*
Wiles, R. A.
Zale, V.
Zanet, P. M.

Visitors

Thompson, G. A.
Balliol College, Oxford University
Oxford, England

Cosmic Ray Group

Staff

Rossi, Prof. B. B.
Blumenfeld, Dr. H.
Bridge, Dr. H. S.
Caldwell, Dr. D. O.
Clark, Prof. G. W.
DeStaebler, Dr. H., Jr.*
Kraushaar, Prof. W. L.
Linsley, Dr. J.
Olbert, Dr. S.
Pevsner, Dr. A.
Smith, W. B.
Williams, Prof. R. W.

Graduate Students

Altman, Leonilda*
Boldt, E. A.
Brenner, A.*
D'Arcy, R.
Earl, J. A.
Fournet, Diane*
Morency, A. J.*
Pal, Y.
Sandri, G.
Scherb, F.
Stora, R.
Strickland, J. S.

* Terminated

Visitors

Jauneau, Dr. L.
Ecole Polytechnique
Paris, France
Oda, Dr. M.*
Osaka City University
Japan
Palmeira, R.*
Centro di Pesquisas Fisicas
Rio de Janeiro, Brazil
Sreekantan, Dr. B. V.*
Tata Institute of Fundamental Research
Bombay, India

Non-Staff

Aruda, Gloria M.
Fernald, C. M.
Forte, C.
Hewitt, R. A.
Mudge, R. H.
Weiner, S. J.

Elementary Particle Scattering GroupStaff

Feld, Prof. B. T.
Demos, Dr. P. T.
Ritson, Dr. D. M.
Frisch, Prof. D. H.
Pugh, Dr. G. E.*
Sargent, Dr. C. P.
Schluter, Dr. R. A.
Strumski, C. J.
Wattenberg, Dr. A.

Graduate Students

Bertozzi, W.
Paolini, F. R.
Wachter, M. H.

Non-Staff

Greene, H. W.

Rockefeller Generator GroupStaff

Goodman, Prof. C. (Absent)
Mark, Hans*
Salomaa, M. K.

*Terminated

Graduate Students

Collins, S. A.*
Paulissen, G.

Undergraduate Students

Alexander, Peter*

Visitors

Goldring, Dr. Gvirol
The Weizmann Institute
Rehovoth, Israel
Guernsey, Dr. Janet B.
Wellesley College
Wellesley, Mass.

Non-Staff

Iacono, Carmen D.

ONR Generator GroupStaff

Buechner, Prof. W. W.
Van de Graaff, Prof. R. J.
Bockelman, Dr. C. K.*
Browne, Dr. C. P.
Enge, Dr. H. A.
Eppling, Dr. F. J.
Sperduto, Dr. A.

Graduate Students

Angleman, C. C., Lt. USN
Berger, D. W., Lt. USN
Cobb, W. C., Lt. USN*
Douglass, D. H., Jr.
Green, J. W., Lt. USN
Guthe, D. B., Lt. USN*
Helfer, D. L.
Jarrell, D. L., Lt. USN
Loper, O. J., Lt. USN
Sharp, R. D.
Smith, A. J., Lt. USN
Wahlig, M. A.
Zimmerman, S. F., Jr.*

Undergraduate Students

Copps, E. M., Jr.*
Maier, Roe J., Jr.*

Visitors

Elbeck, Bent*
Universitetets Inst. for Teoretisk
Fysik, Copenhagen, Denmark

Personnel

Paris, Dr. C. H.
University of Utrecht
Utrecht, Holland
Squires, Dr. G. L.
Cavendish Laboratory
University of Cambridge
Cambridge, England
Alba, Fernando*
University of Mexico
Mexico, D.F.

Non-Staff

Darrow, Sylvia G.
Freedman, Estelle
Nickerson, E. W.
Recupero, Anna E.*
Tripp, W. A.
Vaudo, A. A.
White, Mary E.

Radioactivity and Cyclotron Group

Staff

Evans, Prof. R. D.
Deutsch, Prof. M.
Livingston, Prof. M. S.
Bulkley, J. B.
Backofen, Elizabeth W.
Brownell, Dr. G. L.
Frazer, J. B.
Helmick, Marie
Hine, Dr. G. J.
Kendall, Dr. H. W.
Kuchta, Dorothy
Maletskos, Dr. C. J.
Marshall, Dr. J. H.*
Salter, L. P.*
Scharenberg, Dr. R. P.
Tavola, Maria
Wall, Dr. N. S.
White, E. F.
White, Virginia
Williams, J. B.*

Graduate Students

Bear, J. L.
Beique, R. A.
Darden, C. W.
Farley, T. A.
Ferguson, J. M.
Gittelman, B.*
Greenberg, J. S.*
Hunting, C. E.
Kraner, H. W.

McCall, R. C.
Rasmussen, N. C.
Swenson, L. W.
Watters, H. J.*
Waldorf, W. F.

Undergraduate Students

Alston, W. J., III
Vinsonhaler, N. R.

Visitors

Ljunggren, K.*
The Royal Institute of Technology
Stockholm, Sweden
Looney, Dr. W. B.
Natl. Institutes of Health
Bethesda, Maryland

Non-Staff

Fay, F. J.
Nummela, A. R.
Rhodes, R.

Synchrotron Group

Staff

Osborne, Dr. L. S.
Feld, Prof. B. T.
Frisch, Prof. D. H.
Wattenberg, Dr. A.
Janes, Dr. G. S.
Lobar, W.
Pless, I. A.
Pugh, Dr. G. E.
Ritson, Dr. D. M.
Rosengren, Prof. J. W.*
Schluter, Dr. R. A.
Strumski, C. J.
Weinstein, Dr. R. W.

Graduate Students

Baron, N.*
Barringer, R.
Christie, E., Lt. USN*
Davidson, G.
Fournet, Diane M.
Fung, Dr. S.-C.*
Gomez, R.
Helly, W. S.
Hyman, L.
Land, R.
Maglich, B.
O dian, A. C.*

* Terminated

Personnel

Ozaki, S.
Rankin, D. W.
Richter, B.
Russell, J., Jr.
Stein, P. C.
Wilson, H. H., Lt. USN*

Undergraduate Students

Barrett, M. J., Jr.
Bjorken, J. D.
Marks, W. B.
Markowitz, D.
Quinn, G. L.

Visitors

Meunier, Dr. R.
Commissariat a L'Energie Atomique
Paris, France
Mohler, Prof. Nora
Dept. of Physics, Smith College
Northampton, Mass.
Manaresi, Dr. Elena
Istituto di Fisica
Rome, Italy
Robouch, B.
Beirut University
Beirut, Lebanon

Non-Staff

Gagliardi, D.
Hayes, Patricia
Kallmes, Therese
Lane, A.*
Lanza, Mariantonia*
Pal, Nirmal
Pastan, Barbara*
Warren, Catherine
Zlochiver, P.

Theoretical Group

Staff

Weisskopf, Prof. V. F.
Feshbach, Prof. H.
Drell, Prof. S. D.*
Elton, Dr. L. R. B.
Eyges, L.*
Friedman, Prof. F. L. (On Leave)
Friedman, Prof. M. H.
Huang, Dr. K.*
Lane, Dr. A. M.*
Villars, Prof. F. M. H.

Wandel, C.*
Zachariasen, F.

Graduate Students

Bincer, A. M.
Gottfried, K.*

Visitors

Beck, Dr. F.*
Fritz Haber Institut der Max Planck
Gesellschaft, Berlin-Dahlem,
Germany
Lanza, Dr. G.*
Istituto Nazionale Fisica Nucleare
Padua, Italy
Verlet, L.
Ecole Normale Supérieure
Paris, France
Zemach, Dr. C.
Harvard University
Cambridge, Mass.

Non-Staff

Berringer, Norma

* Terminated

APPENDIX B

PUBLICATIONS - JUNE 1, 1955 to MAY 31, 1956

Chemistry of the Fission Elements Group

- C. A. Lermond and L. B. Rogers, "Differential Measurements of Reflectance", *Anal. Chem.* 27, 340, (1955).
- H. J. Keily and L. B. Rogers, "Instrumental Variability of a Model 7 Coleman Photonephelometer", *Anal. Chem.* 27, 459, (1955).
- H. J. Keily and L. B. Rogers, "Nephelometric Determination of Sulfate Impurity in Certain Reagent Grade Salts", *Anal. Chem.* 27, 759, (1955).
- J. W. Collat and L. B. Rogers, "Fluorimetric Determination of Aluminum and Gallium in Mixtures of their Oxinates", *Anal. Chem.* 27, 961, (1955).
- C. A. Lermond and L. B. Rogers, "Use of a Reflectance Attachment to Obtain Excitation Spectra", *Anal. Chim. Acta*, 13, 387 (1955).
- R. M. Rush and L. B. Rogers, "Effect of the Substrate Upon Two Catalytic Spot Tests for Copper", *Mikrochemica Acta*, 4, 821 (1955).
- L. B. Rogers, "Electrodeposition Studies Involving Dilute Solutions", *Record of Chemical Progress*, Vol. 16, No. 3 (1955).
- W. C. Purdy, E. A. Burns, and L. B. Rogers, "Sensitivity of Bromine-Bromide Potentiometric End Point", *Anal. Chem.* 27, 1988 (1955).
- D. L. Leussing and Leonard Newman, "Spectrophotometric Study of the Bleaching of Ferric Thio-glycolate", *J. Am. Chem. Soc.*, 78, 552 (1956).
- R. C. DeGeiso and D. N. Hume, "The Basicity of the Silver Bromide Complex Ion", *J. Phys. Chem.*, 60, 255 (1956).
- L. B. Rogers, "Analysis - The Key to Chemistry", *The Science Counselor*, 19, (1) 2 (1956).
- D. N. Hume, "Polarographic Theory, Instrumentation and Methodology", *Anal. Chem.*, 28, 625 (1956).
- E. P. Przybylowicz and L. B. Rogers, "Coulometric Titrations with Electrolytically Generated Mercury (I and II). Chloride, Bromide and Iodide", *Anal. Chem.*, 28, 799 (1956).
- E. G. Peattie and L. B. Rogers, "Analytical Studies of the Fluorescence of Samarium in Calcium Tungstate", *Spectrochimica Acta*, 7, 321 (1956).
- H. J. Keily and L. B. Rogers, "Measurements in the Ultra-Violet Region of Apparent Absorption by Barium Sulfate Sols", *Anal. Chem. Acta*, 14, 356 (1956).

Nuclear Chemistry (Inorganic) Group

- R. H. Herber and J. W. Irvine, Jr., "Anion Exchange Studies. III. Ni(II) in Aqueous HCl and Lithium Chloride", *J. Am. Chem. Soc.* 78, 905 (1956).

- U. Schindewolf, "Review of Recent Applications of Ion Exchangers in Analytical Chemistry", Laboratory for Nuclear Science Technical Report No. 68, December 15, 1955.
- R. H. Herber, K. Tonguc, J. W. Irvine, Jr., "Anion Exchange Studies. II. The Effect of Cross-Linkage on the Elution of Several Transition Elements", J. Am. Chem. Soc. 77, 5840 (1955).
- C. J. Maletskos and J. W. Irvine, Jr., "Quantitative Electrodeposition of Radiocobalt Zinc and Iron", Nucleonics, 14, No. 4, 84 (1956).
- R. C. Sangster and J. W. Irvine, Jr., "Study of Organic Scintillators", J. Chem. Phys., 24, No. 4, 670 (1956).

Nuclear Chemistry (Organic) Group

- C. G. Swain, V. P. Kreiter and William A. Sheppard, "A Procedure for Routine Assay of Tritium in Water", Anal. Chem. 27, 1157 (1955).

Cosmic Ray Group

- R. W. Williams, "High-Energy Cross Sections. I. The Size of the Nucleus", Phys. Rev. 98, 1387 (1955).
- R. W. Williams, "High-Energy Cross Sections. II. Nucleon-Nucleon Cross Sections at Cosmic-Ray Energies", Phys. Rev. 98, 1393 (1955).
- W. L. Kraushaar, "High Latitude Impact Zones for Solar Cosmic Rays", Progress in Theoretical Physics, 14, No. 1 July 1955.
- W. L. Kraushaar, "The Magnetic Field in the Vicinity of the Solar System", Progress in Theoretical Physics, 14, No. 1 July 1955.
- D. O. Caldwell, "Masses of the New Particles and the Range-Energy Relation", Letter to the Editor of Nuovo Cimento 2, 183 (1955).
- D. O. Caldwell, "The Range-Energy Relation and Masses of the New Particles", Phys. Rev. 100, 291 (1955).
- F. Harris and I. Escobar V., "East-West Asymmetry of Positive and Negative Mesons at the Geomagnetic Equator", Phys. Rev. 100, 255 (October 1, 1955).
- R. Armenteros, B. Gregory, A. Hendel, A. Lagarrigue, L. Leprince-Ringuet, F. Muller, and C. Peyrou, Ecole Polytechnique; H. S. Bridge, H. C. DeStaebler, Jr., B. Rossi, and B. V. Sreekantan, M.I.T., "Mass Values of the $K_{\mu 2}$ - and $K_{\pi 2}$ -Meson" (submitted to Nuovo Cimento, June 1955).
- G. Sandri, "Influence of 'New Unstable Particles' on the Electromagnetic Properties of Nucleons", Letter to the Editor of Phys. Rev. 101, 1616 (March 1, 1956).
- H. S. Bridge, D. O. Caldwell, Y. Pal, and B. Rossi, "Further Analysis of the Massachusetts Institute of Technology Anti-Proton Event", Phys. Rev. 102, 930-931 (May 1, 1956).

Publications

Elementary Particle Scattering Group

- B. T. Feld, A. Odian, D. M. Ritson and A. Wattenberg, "The Spin of the τ^+ Meson", Phys. Rev. 100, 1539 (1955).
- E. L. Iloff, W. W. Chupp, G. Goldhaber, S. Goldhaber, A. Pevsner and D. M. Ritson, "Mean Lifetime of Positive K Mesons", Phys. Rev. 99, 1617 (1955).
- R. Hill, E. O. Salant, M. Widgoff, L. S. Osborne, A. Pevsner, D. M. Ritson, J. Crussard and W. D. Walker, "Disintegrations Produced in Nuclear Emulsions by 1.5-Bev Pions", Phys. Rev. (in press).
- S. C. Fung, A. Pevsner, D. M. Ritson, M. Widgoff, G. T. Zorn, G. Goldhaber and S. Goldhaber, "Characteristics of K^+ Particles", Phys. Rev. 101, 1085 (1956).
- S. C. Fung, N. Mohler, A. Pevsner and D. M. Ritson, " $K^+ - \tau^+$ Mass Difference", Phys. Rev. 101, (1956).
- L. S. Osborne, "Interpretation of K^+ Scattering in Nuclear Emulsions", Phys. Rev. (in press).

Neutron Physics Group

- H. Mark, C. McClelland, and C. Goodman, "Electric Excitation of Certain Medium-Weight Nuclei by Protons", Phys. Rev. 98, 1245 (1955).
- J. B. Guernsey and C. Goodman, "Neutron Cross Sections for Zirconium", Phys. Rev. 101, 294 (1956).
- H. Mark and G. Paulissen, "Electric Excitation of Certain Rare-Earth Nuclei by Protons", Phys. Rev. 100, 813 (1955).
- H. Mark and C. Goodman, "Angular Distribution of Neutrons from $O^{18}(p, n)F^{18}$ ", Phys. Rev. 101, No. 2, 768 (January 15, 1956).
- J. B. Guernsey and C. Goodman, "Neutron Cross Sections for Zirconium", Phys. Rev. 101, No. 1, (January 1, 1956).
- G. Goldring and G. T. Paulissen, "Ratios of Transition Probabilities between Rotational States in Odd-A Nuclei" (in press).

ONR Generator Group

- C. H. Paris, W. W. Buechner, and P. M. Endt, "Energy Levels of S^{33} , S^{35} , Cl^{36} , Cl^{38} , and Ba^{139} ", Phys. Rev. 100, 1317 (1955).
- W. W. Buechner, C. M. Braams, and A. Sperduto, "Inelastic Proton Scattering from Vanadium", Phys. Rev. 100, 1387 (1955).
- W. W. Buechner, M. M. Mazari, and A. Sperduto, "Magnetic Spectrograph Measurements on the $Al^{27}(d, p)Al^{28}$ Reaction", Phys. Rev. 101, 188 (1956).
- P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, "Nuclear Levels in S^{32} , S^{34} , Cl^{35} , and Cl^{37} ", (submitted to Phys. Rev., April 1956).
- W. W. Buechner, "The Determination of Nuclear Reaction Energies by Deflection Measurements", Progress in Nuclear Physics, 5, Edited by O. R. Frisch, Pergamon Press, London (1956).

Radioactivity and Cyclotron Group

- M. Deutsch and H. W. Kendall, "Annihilation of Positrons in Flight", Phys. Rev., Second Series 101, No. 1, 20-26 (January 1956).
- M. Deutsch and J. S. Greenberg, "Positrons from the Decay of P^{32} and Y^{90} ", Phys. Rev. 102, 415-421 (April 15, 1956).

Synchrotron Group

- Goldhaber Group, Berkeley; A. Pevsner and D. M. Ritson, M.I.T., " K^+ Lifetimes", (submitted to the Physical Review).
- E. Christie, B. T. Feld, A. C. Odian, P. C. Stein, and A. Wattenberg, "High-Energy Neutron Detectors Employing Liquid Scintillators", Review of Scientific Instruments (in press).
- B. T. Feld, A. C. Odian, D. M. Ritson, and A. Wattenberg, "Spin of the τ^+ -Meson", Letter to the Editor, The Physical Review, 27, No. 3, 137-131, (March 1956).
- R. M. Weinstein, A. Odian, P. C. Stein, and A. Wattenberg, "Photoproton-Proton Coincidences from Various Nuclei", Phys. Rev. 99, 1621-1622, (September 1, 1955).
- D. M. Fournet and M. Widgoff, "Interactions of K^- Mesons in Nuclear Emulsion" (submitted as letter to the editor, Phys. Rev.).
- J. E. Lannutti, W. W. Chupp, G. Goldhaber, S. Goldhaber, E. Helmy, E. L. Iloff, A. Pevsner, and D. M. Ritson, "Interactions of Positive K Mesons", Letter to the Editor, Phys. Rev. 101, 1617 (1956).
- L. S. Osborne, "Interpretation of K^+ Scattering in Nuclear Emulsion", Phys. Rev. 102, 296 (1956).
- D. M. Ritson, A. Pevsner, S. C. Fung, M. Widgoff, G. T. Zorn, S. Goldhaber and G. Goldhaber, "Characteristics of K^+ Particles", Phys. Rev. 101, 1085 (1956).
- D. H. Frisch, "Possible Origin of π Forces in Nuclei", Letter to the Editor, Phys. Rev. 101, 1833 (1956).

Theoretical Group

- A. E. Glassgold, "Scattering of High-Energy Electrons by Nuclei", Phys. Rev. 98, No. 5, 1360, (June 1, 1955).
- A. M. Lane and C. F. Wandel, "Evaluation of the Imaginary Part of the Nuclear Complex Potential" Phys. Rev. 98, No. 5, 1524 (June 1, 1955).
- F. Beck, "Stability of a Phase Boundary Inside a Superconductor", Phys. Rev. 98, No. 4, 852, (May 15, 1955).
- H. Feshbach and S. I. Rubinow, "Equivalent Two-Body Method for the Triton", Phys. Rev. 98, No. 1, 188 (April 1, 1955).
- S. D. Drell and Kerson Huang, "Proton Bremsstrahlung", Phys. Rev. 99, No. 3, 686, (August 1, 1955).
- S. D. Drell and L. Verlet, "Multiple Scattering Corrections in π^+ -Deuteron Scattering", Phys. Rev. 99, No. 3, 849 (August 1, 1955).

Publications

- V. F. Weisskopf, "Enrico Fermi", *Die Naturwissenschaften* 12, 353-354 (1955).
- D. A. Geffen, "Simple Nonrelativistic Model for Single Meson Production", *Phys. Rev.* 99, 1534-1541 (September 1, 1955).
- S. D. Drell, "Nuclear Radius and Nuclear Forces", *Phys. Rev.* 100, 97 (October 1, 1955).
- F. L. Friedman and V. F. Weisskopf, "The Compound Nucleus", Niels Bohr and the Development of Physics, Pergamon Press, London (1955).
- V. F. Weisskopf, "A Model of the Nucleus", Scientific American (December 1955).
- V. F. Weisskopf, "George Placzek, Theoretical Physicist", *Science* 123, No. 3193, 409 (March 9, 1956).
- F. Zachariasen, "Proton Charge Density", *Phys. Rev.* 102, 295 (April 1956).

APPENDIX C

ADDRESSES - JUNE 1, 1955 to MAY 31, 1956

Chemistry of the Fission Elements Group

- L. B. Rogers, "Recent Developments in Potentiometric Measurements", Analytical Group of the East Tennessee Section of the American Chemical Society, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 9, 1955.
- L. B. Rogers, "Principles of Chemical Separations", Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 8, 1955.
- L. B. Rogers, "Neglected Aspects of Spectrophotometry", Society for Analytical Chemists of Pittsburgh, A.C.S., Pittsburgh Section, Pittsburgh, Penna., May 13, 1955.
- L. B. Rogers, "Electrodeposition Studies Involving Dilute Solutions", Lecture Series on 'Frontiers in Chemistry', Kresge-Hooker Scientific Library, Wayne University, Detroit, Michigan, April 18, 1955.
- D. N. Hume, "Photometric Titrations", University of Connecticut, Storrs, Conn., April 3, 1956.
- D. N. Hume, "Photometric Titrations", University of Massachusetts, Amherst, Mass., April 18, 1956.

Nuclear Chemistry (Inorganic) Group

- C. D. Coryell, "Atomic Energy and National Affairs", Wheaton College Science Club, Norton, Mass., February 28, 1956.
- C. D. Coryell, "Education and Science in the Middle East", Boston Technion Society, January 9, 1956.
- C. D. Coryell, "Basic Science and Engineering of Radioactive Decay. I. Uninuclear Reactions", Westinghouse Atomic Power Division, Bettis Station, Pittsburgh, Penna., January 25, 1956.
- C. D. Coryell, "Basic Science and Engineering of Cation-Anion Resins in Nuclear Science", Westinghouse Atomic Power Division, Bettis Station, Pittsburgh, Pennsylvania, January 27, 1956.
- C. D. Coryell, "Neutron and Proton Shell Numbers in the Cosmic Abundance of the Elements", Harvard-M.I.T. Physics Seminar, Harvard University, February 16, 1956.
- C. D. Coryell, "The Chemistry of Creation", Talk before special joint meeting of the Tufts Chemical Society and Seminar in Chemistry, Tufts University, Medford, March 13, 1956.
- C. D. Coryell, "Proton and Neutron Magic Numbers in the Cosmic Abundance of the Elements", Cornell Section of the American Chemical Society, Ithaca, New York, March 21, 1956.
- C. H. Brubaker, Jr., "Distribution of Tellurium(IV) between Aqueous Hydrochloric Acid Solutions and Isopropyl and β, β' -Dichloroethyl Ethers", Talk to be presented before the Division of Physical and Inorganic Chemistry of the American Chemical Society, Dallas, Texas, April 13, 1956.
- R. H. Herber and J. W. Irvine, Jr., "Anion Exchange Studies. III. Ni(II) in Aqueous Hydrochloric Acid and Lithium Chloride", paper presented before the Division of Physical and Inorganic Chemistry, 128th National Meeting of the American Chemical Society, Minneapolis, Minn., September 13, 1955.

Addresses

- J. W. Irvine, Jr., "Measurement of Radionuclides", Raritan Valley Subsection of the New Jersey Section of the American Chemical Society, Rutgers University, New Brunswick, New Jersey, September 27, 1955.
- P. Schonken, "Hydrogenation Kinetics", Department of Chemistry, Iowa State College, Ames, Iowa, October 7, 1955.
- C. D. Coryell, "Radiochemical Studies of Shell Effects in Fission", Dedication Ceremonies of the U.S. Naval Radiological Defense Laboratory, San Francisco, Calif., October 15, 1955.
- C. D. Coryell, "Nuclear Chemistry", Boston University Chemical Society, November 1, 1955.
- C. D. Coryell, "Identification of Inorganic Complexes by Anion Exchange Studies", Department of Chemistry, University of Washington, Seattle, November 9, 1955.
- C. D. Coryell, "Chemistry in the Atomic Energy Industry", Puget Sound Section of the American Chemical Society, Seattle, Washington, November 9, 1955.
- F. A. Cotton, "Organometallic Compounds and Carbonyl Hydrides", Department of Chemistry, Tufts College, Medford, November 16, 1955.
- C. D. Coryell, Series of Lectures on Nuclear Chemistry, 2nd Chemistry Institute High School Teachers Conference, Syracuse University, Syracuse, New York, July 18-22, 1955.
- A. C. Pappas, "The Distribution of Nuclear Charge in Low Energy Fission", UN International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, August 1955.
- C. D. Coryell, "Chemistry of the Creation of the Cosmos", Brandeis University, Waltham, April 12, 1956; Wheaton College, Norton, May 2, 1956; Clark University, Worcester, May 3, 1956.
- C. D. Coryell, "Nucleon Shell Numbers in the Chemistry of the Creation", General Electric Company, Schenectady, New York, April 20, 1956.
- J. W. Irvine, Jr., "Solvent Extraction of Metal Chlorides", Army Chemical Center, Maryland, April 16, 1956.

Nuclear Chemistry (Organic) Group

- C. Gardner Swain, "Detection of Transient Ion Pair Intermediates in Chemical Reactions", several talks at colleges of the University of London, England, February - June, 1955.

Cosmic Ray Group

- B. B. Rossi, "Lecture Notes on the Origin of Cosmic Rays", Colloquium of College Physicists, Iowa, June 17-18, 1955.
- B. B. Rossi, "Lecture Notes on Fundamental Particles", Colloquium of College Physicists, Iowa, June 17-18, 1955.
- B. B. Rossi, "Present State of the Problem of Cosmic Rays", Conference of the International Union of Pure and Applied Physics, Guanajuato, Mexico, September 6, 1955.
- G. W. Clark, "General Description and Preliminary Results of a Large Air Shower Experiment", Conference of the International Union of Pure and Applied Physics, Guanajuato, Mexico, September 7, 1955.

- S. Olbert, "Deduction of Primary Spectrum from Large Air Showers and Underground Measurements", Conference of the International Union of Pure and Applied Physics, Guanajuato, Mexico, September 7, 1955.
- R. W. Williams, "The Absolute Intensity of Cosmic-Ray Primaries Above 10^{16} ev", Conference of the International Union of Pure and Applied Physics, Guanajuato, Mexico, September 7, 1955.
- R. W. Williams, "Air Shower Experiment in the Southern Hemisphere", Conference of the International Union of Pure and Applied Physics, Guanajuato, Mexico, September 9, 1955.
- H. S. Bridge, "Charged K Mesons", American Physical Society Meeting, Mexico City, Mexico, August 31, 1955.
- D. O. Caldwell and Y. Pal, "Photometric Mass Determination in a Multiplate Cloud Chamber", American Physical Society Meeting, University of Southern California, December 30, 1955.
- G. W. Clark, "Arrival Directions of Air Showers", Washington Meetings of the American Physical Society, April 28, 1956.
- J. Linsley, W. L. Kraushaar, G. W. Clark, B. B. Rossi, J. A. Earl, and F. Scherb, "An Investigation of Large Cosmic-Ray Showers", Washington Meetings of the American Physical Society, April 28, 1956.
- W. L. Kraushaar, "Massachusetts Institute of Technology Air Shower Experiment", Oxford Cosmic Ray Conference, April 14, 1956.

Elementary Particle Scattering Group

- A. Wattenberg, "An Attempt to Measure the Spin of the τ^+ Meson", University of Kanazawa, Japan.
- A. Wattenberg, "Some Problems in Understanding the Decays of Heavy Mesons", University of Tokyo, Japan.
- A. Wattenberg, "Current Status of the Atomic Energy Program", The Harvard Club of Tokyo.
- A. Wattenberg, "Research Reactors", Tokyo Physicists invited by the Yomuri Shimbun.
- A. Wattenberg, "Applications of Atomic Energy", Scientists from the Japanese Ministry of Agriculture and Forestry.
- A. Wattenberg, "Applications of Atomic Energy", Staff Members of the Foreign Office of the Japanese Government.
- B. T. Feld, "Effects of Angular Momentum on τ -Meson Schemes", Chicago Meeting of the American Physical Society, November 26, 1955.
- D. Fournet, A. Pevsner and D. M. Ritson, " K^- Interactions", Chicago Meeting of the American Physical Society, November 26, 1955.
- D. M. Ritson, "Recent Work in K-Mesic Physics", Brookhaven National Laboratory Colloquium, October 11, 1955.
- D. M. Ritson, "Properties of Strange Particles", Harvard University Colloquium, October 26, 1955.
- A. Pevsner, "Meson Interactions", Brookhaven National Laboratory Colloquium, November 4, 1955.

Addresses

- D. M. Ritson, "Masses and Frequencies of K-Mesons", Columbia University Particle Symposium, December 1955.
- D. M. Ritson, "Properties of K-Particles", New York American Physical Society Meeting, January 1956.
- D. M. Ritson, D. Fournet, and A. Pevsner, Abstract "K⁻ Interactions", New York American Physical Society Meeting, January 1956.
- N. S. Wall and W. F. Waldorf, "The Elastic Scattering of 7.5-Mev Protons", American Physical Society Meeting, Washington, D. C., April 27, 1956.

Neutron Physics Group

- Janet B. Guernsey, "Neutron Cross Sections for Zirconium", New England Section A.P.S., Brown University, April 2, 1955.
- H. Mark and G. Paulissen, "Cascade Transitions between Rotational Levels of Odd-A Nuclei", Toronto Meeting A.P.S., June 22-24, 1955.
- A. Rubin, F. Ajzenberg and H. Mark, "Energy Levels of Si²⁸", Mexico Meeting A.P.S., August 29-31, 1955.

ONR Generator Group

Addresses (with Abstract References)

- A. Sperduto and W. W. Buechner, "(p, p') and (p, α) Reactions of Potassium", Phys. Rev. 100, 961 (1955). Given at University of Mexico.
- C. P. Browne, "Isotopic Spin-Selection Rule Violation in O¹⁶(d, α)N¹⁴", Bull. Amer. Phys. Soc. 30, No. 7, 26 (1955); Chicago Physical Society Meeting, November 25, 1955.
- W. W. Buechner and A. Sperduto, "Inelastic Proton Scattering from Iron", Bull. Am. Phys. Soc. 1, No. 1, 39 (1956); New York Meeting of American Physical Society, January 31, 1956.
- H. A. Enge, W. W. Buechner, A. Sperduto, and M. M. Mazari, "Al²⁷(d, p)Al²⁸ Stripping Analysis", Bull. Am. Phys. Soc. 1, No. 4, 212 (1956); Washington Meeting of American Physical Society, April 26, 1956.
- A. Sperduto and W. W. Buechner, "(d, p) Reactions of the Iron Isotopes", Bull. Am. Phys. Soc. 1, No. 4, 223 (1956); Washington Meeting of the American Physical Society, April 26, 1956.
- P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, "Excited States of S³², S³⁴, Cl³⁵, and Cl³⁷", Bull. Am. Phys. Soc. 1, No. 4, 223 (1956); Washington Meeting of the American Physical Society, April 26, 1956.
- C. P. Browne, "Isotopic Spin-Selection Rule Violation in Si²⁸(d, α)Al²⁶", Bull. Am. Phys. Soc. 1, No. 4, 212 (1956); Washington Meeting of the American Physical Society, April 26, 1956.

Invited Papers

- C. P. Browne, "Experiments on Isobaric Spin-Selection Rules", Seminar at Indiana University, July 26, 1955.

- W. W. Buechner, "Nuclear Energy Levels Observed from Inelastic Proton Scattering Experiments", University of Mexico, Mexico City, August 29, 1955.
- C. P. Browne, "Experiments on Isobaric Spin-Selection Rules", The Case Institute, November 1955.
- C. P. Browne, "Violation of Isobaric Spin-Selection Rules in Nuclear Reactions", Yale University, February 1956.
- C. P. Browne, "Isobaric Spin-Selection Rules in Nuclear Reactions", University of Notre Dame, April 1956.
- C. P. Browne, "Isobaric Spin-Selection Rules in Nuclear Reactions", Duke University, April 1956.

Radioactivity and Cyclotron Group

- M. Deutsch, E. P. Dulit, and B. Gittelman, "Formation of Positronium in Gases", American Physical Society Meeting, February 3, 1956.
- M. Deutsch, E. P. Dulit, and B. Gittelman, "Quenching of Orthopositronium in Gases", American Physical Society Meeting, February 3, 1956.
- H. J. Watters, "Elastic and Inelastic Scattering of 31.5-Mev Particles", American Physical Society Meeting, January 31, 1956.
- N. S. Wall and W. F. Waldorf, "The Elastic Scattering of 7.5-Mev Protons", Washington Meeting of the American Physical Society, April 26, 1956.

Synchrotron Group

- D. Ritson, S.-C. Fung, A. Pevsner, M.I.T.; M. Widgoff, Harvard University; G. Zorn, Brookhaven; S. and G. Goldhaber, University of California at Berkeley, "The Characteristics of K-Particle Decay", Proceedings of the Pisa Conference, June 1955.
- S.-C. Fung, N. Mohler, A. Pevsner and D. M. Ritson, " $K^+ - \tau^+$ Mass Difference", Proceedings of the Pisa Conference, June 1955.
- A. Pevsner and D. Ritson, M.I.T.; M. Widgoff, Harvard University; " K^- Interactions at Rest", Proceedings of the Pisa Conference, June 1955.
- A. Pevsner and D. Ritson, M.I.T.; M. Widgoff, Harvard University; " K^- Interactions and Decays in Flight", Proceedings of the Pisa Conference, June 1955.
- A. Pevsner and D. Ritson, M.I.T.; S. and G. Goldhaber, University of California at Berkeley; " K^+ Interactions and Decays in Flight", Proceedings of the Pisa Conference, June 1955.
- A. Pevsner, "Photoplate Studies in the K-Meson Family", Mexico City Meeting of the American Physical Society, September 4, 1955 (invited talk).
- R. Gomez, "Gamma-Ray Scattering by Complex Nuclei", Chicago Meeting of the American Physical Society, November 25, 1955.
- G. S. Janes, "Gamma-Ray Scattering by Hydrogen", Chicago Meeting of the American Physical Society, November 25, 1955.

Addresses

- G. Pugh, "Nuclear Gamma-Ray Scattering Techniques", Chicago Meeting of the American Physical Society, November 25, 1955.
- B. T. Feld, A. C. Odian, W. Rankin, P. C. Stein, A. Wattenberg and R. Weinstein, "High Energy Photoneutron-Proton Pair Ejection from Nuclei", Chicago Meeting of the American Physical Society, November 26, 1955.
- A. M. Shapiro, M. Widgoff, D. Fournet, A. Pevsner, D. M. Ritson, R. A. Schluter, V. Henri, and V. Fitch, "Composition of a Beam of Scattered K^+ -Mesons", Washington Meeting of the American Physical Society, April 1956.
- R. Barringer, L. S. Osborne, and R. Meunier, " π^0 -Meson Production in Complex Nuclei at Forward Angles", Washington Meeting of the American Physical Society, April 1956.
- R. Meunier, L. S. Osborne, and R. Barringer, " π^0 -Meson Photoproduction from Hydrogen and Deuterium", Washington Meeting of the American Physical Society, April 1956.
- A. Wattenberg, A. Odian, P. C. Stein, and R. Weinstein, "Momentum of Nucleons in Various Nuclei", Washington Meeting of the American Physical Society, April 1956.
- G. E. Pugh, "Scattering of 40- to 130-Mev Photons by Protons and Other Nuclei", New York Meeting of the American Physical Society, January 1956.

Theoretical Group

- S. D. Drell, Brookhaven National Laboratory, "Nuclear Radius and Nuclear Forces", July 5, 1955.
- L. R. B. Elton, "A High-Energy Approximation for Relativistic Scattering Cross Sections", Washington Meeting of the American Physical Society, April 1956.
- S. D. Drell, M. H. Friedman, and F. Zachariasen, "Chew-Low Treatment of S-Wave Mesons", Washington Meeting of the American Physical Society, April 1956.

APPENDIX D

THESES - June 1, 1955 to May 31, 1956

Bachelor of Science

- R. Smith and W. Sooy, "Cross Section for the $\text{Cu}^{63}(\beta, n)\text{Cu}^{62}$ Reaction", in the Department of Physics, Physics, June 1956.
- S. Silverstein, "The Calibration of a Positron Counter for Cu^{62} Beta Decay", in the Department of General Sciences, June 1956.
- P. Alexander, "An Examination of: Absolute NaI - Tl Crystal Efficiency for 100-500 K.E.V. Gammas and the As Decay Scheme", in the Department of Physics, June 1956.
- H. W. Kraner, "A Study of Internal Bremsstrahlung in Manganese 54 and Iron 55", in the Department of Physics, May 1955.

Master of Science

- A. J. Morency, "The Mean Free Path for Nuclear Interactions of High-Energy Protons with Iron", in the Department of Physics, September 1955.
- G. T. Paulissen, "Transition Probabilities for Low-Lying Levels in Odd-A Nuclei", in the Department of Physics, May 1956.
- S. F. Zimmerman, Jr., "Focusing Properties of a High-Resolution, Magnetic Spectrograph", in the Department of Physics, August 1955.
- Lt. J. W. Green and Lt. A. J. Smith, "Nuclear Energy Levels in Mn^{56} ", in the Department of Physics, May 1956.
- Lt. D. W. Berger and Lt. O. J. Loper, "Yield of Elastically Scattered Deuterons from O^{16} ", in the Department of Chemistry, May 1956.
- J. B. Williams, "Scintillation Counting of Thin Alpha Sources", in the Department of Chemistry, August 1955.

Doctor of Philosophy

- L. Newman, "Mixed Ligand Complexes", in the Department of Chemistry, April 1956.
- E. A. Burns, "Analytical Chemistry of Indium", in the Department of Chemistry, May 1956.
- H. J. Kelly, "Titrations in Glacial Acetic Acid", in the Department of Chemistry, May 1956.
- W. C. Purdy, "The Determination of Trace Manganese by Colorimetry and Activation Analysis", in the Department of Chemistry, July 1955.
- J. W. Winchester, "A Study of Fission Products in the Region of Mass Numbers 103 to 131", in the Department of Chemistry, August 1955.
- E. C. Stivers, "The Tritium Isotope Effect in the Enolization of Alpha-Phenyl Phenylisocaprophenone", in the Department of Chemistry, May 1956.

Theses

- L. Altman, "The Mean Free Path of High Energy Nucleons in the Atmosphere", in the Department of Physics, December 1955.
- R. D. Sharp, "Inelastic Scattering in Medium- and Heavy-Weight Nuclei", in the Department of Physics, May 1956.
- J. S. Greenberg, "Internal Pair Creation Accompanying Beta-Decay", in the Department of Physics, May 1955.
- N. C. Rasmussen, "Standardization of Electron Capture Isotopes", in the Department of Physics, January 1956.
- H. J. Watters, "Angular Distributions of Alpha Particles Scattered by Light Nuclei", in the Department of Physics, January 1956.
- R. Barringer, "Coherent Photoproduction of Uncharged π Mesons in Complex Nuclei", in the Department of Physics, June 1956.
- R. Gomez, "Scattering of γ -Rays by Hydrogen and Other Light Nuclei in the Range from 50 to 135 Mev", in the Department of Physics, June 1956.

APPENDIX E

TECHNICAL REPORTS - JUNE 1, 1955 to May 31, 1956

Frank B. Harris, Jr., "East-West Asymmetry of Positive and Negative Mesons", Technical Report No. 67, December 15, 1955.

I-XVI AND
1- 223

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK