FINAL PROJECT REPORT FOR CONTRACT DE-AC02-76ER00535 BETWEEN THE UNIVERSITY OF
COLORADO AND THE U.S. DEPARTMENT OF ENERGY.

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I. ABSTRACT

This report is a summary of the research accomplished under contract DE-AC02-76ER-00535 between the University of Colorado and the USAEC, (ERDA), (DOE) from June 1, 1957 until January 31, 1981. The program is currently continued under contracts DE-AC-81-ER-40014, 40015 and 40016.

Sections II, III, IV and V will present some of the highlights of this research and some of the important implications of the work. Many of the research results combine coherently advances in all aspects of our program and are not easily separated into the tasks A, B, C, or D of our contract. The divisions used for this report must be considered to have highly permeable boundaries. Annual progress reports and timely publications are not able to discuss the influence of work first performed at Colorado, and this report attempts to indicate some of the effects of our work. Lists of publications, research associates, and Ph.D. theses are in Appendices A, B, and C.

II. FACILITY AND INSTRUMENTATION

A. Introduction

The University of Colorado 52-inch cyclotron was conceived in the fall of 1956. A preliminary contract was awarded June 1, 1957 by the Atomic Energy Commission for research studies and investigations leading to design of the cyclotron. This contract was later expanded and modified to include engineering, construction, and operation of the cyclotron. By 1976 the AEC had amortized the cyclotron to zero value, and title was transferred from the Federal government to the university.

On January 4, 1960, the project moved into the new Nuclear Physics Laboratory provided by the University of Colorado. The building was enlarged in 1964 with matching funds from the National Science Foundation and the university. First beam from the incomplete cyclotron was achieved at 3 a.m. on April 7, 1962. Use of the extracted beam from the accelerator for experiments started in May, 1963. Dr. Glenn Seaborg, Chairman of the AEC, officiated at the dedication of the cyclotron on June 28, 1963.

Operation of this facility has continued until the present. A new contract was negotiated with the DOE and took effect February 1, 1981.

B. Cyclotron Design, Engineering and Construction

In 1957, when the contract was initiated, the objective was the design, engineering and construction of a 30-MeV variable energy cyclotron accelerating protons, deuterons, ^3He and ^4He projectiles for nuclear structure studies. Design studies on the relatively new application of alternating gradient focussing to cyclotron operation were completed. A 4-sector spiral shim design with windings around the individual shims was

selected. The magnetic field configurations were conservative in design so that ^3He energies of 45 and ^4He energies of 36 MeV have been achieved.

The radiofrequency system is driven from a stable oscillator and has a tuning range of 3:1 so harmonic acceleration is possible. Beam energies from as low as 200 keV to over 45 MeV have been achieved with the cyclotron. In addition to a remarkable reliability and absence of malfunction it has a fine record for minimal maintenance. Many critical components have operated for 18 years without replacements.

A special characteristic of this cyclotron is the high stability of the beam tuning. Once a suitable beam is delivered on target, the cyclotron will run without attention from an operator for days at a time. From the beginning no professional operators have been employed. There are few, if any, comparable cyclotrons which have a better performance record. We feel that this performance was due in part to the intimate involvement of the laboratory scientific staff in the design and construction of most of the components. Thus critical matters were of direct concern to the ultimate users.

C. Operation

Over a period of 17 years and 9 months of recorded operation, the cyclotron has been in use for experiments 55% of the time, for a total of 84,876 hours of running time. It was out of commission for maintenance and repairs, both scheduled and unscheduled, or unusable because of major construction or improvements, for 17,512 hours or 11% of the time.

Over the years, not counting casual drop-ins or personal acquaintances, approximately 17,000 people in 380 groups have toured the laboratory. Elementary, high school, and college teachers from a several-state area

bring their classes back every year. Several teachers have remarked that the cyclotron and laboratory are of a size which, while impressive, are comprehensible to students.

D. Negative Hydrogen Ion Acceleration

On April 13, 1962, just six days after the first internal beam was achieved, the University of Colorado cyclotron became the first cyclotron to in the world to produce a useful beam of negative hydrogen ions. The circulating beam passed through a foil which stripped away both electrons, leaving a proton beam which simply curved out of the magnetic field. In addition to the attractive possibilities of nearly 100% beam extraction efficiency and easily variable energy, it was pointed out that a conventionally extracted negative ion beam would have a number of other interesting possibilities, including post acceleration in a tandem electrostatic accelerator.¹

It is now possible to look back and see that many of these possibilities have indeed been realized. The University of Manitoba added axial injection of H^- ions to its high field cyclotron, and successfully achieved 100% extraction efficiency and a variable energy capability from 20 MeV to 50 MeV.²

The Tri-Universities Nuclear Laboratory (TUNL), for example, employed a commercially produced, fixed energy, negative ion cyclotron (Cyclotron Corporation, Berkeley, California) to inject 15 MeV H^- or 7.5 MeV D^- ions into an electrostatic tandem accelerator. This combination, called a cyclo-graaff, provided a very flexible nuclear physics research facility.³ A similar arrangement, employing a 26-MeV negative ion, sector-focussed cyclotron (Cyclotron Corporation, Model CN30) injecting into an electrostatic

tandem accelerator (High Voltage Engineering Corporation, Model EN) has been completed at the Australian National University in Canberra.⁴

Certainly the most ambitious project to take advantage of the H^- cyclotron technology originated here is TRIUMF, a meson physics facility located in Vancouver, Canada. The TRIUMF accelerator was especially designed to have excellent vacuum and low magnetic field to reduce the probability of stripping the weakly bound (0.7 eV) second electron from the H^- ion. As a reward, they have achieved a variable energy proton machine with unique capabilities.

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- ¹ Rickey ME, Smythe R. The Acceleration and Extraction of Negative Hydrogen Ions in the CU Cyclotron. Nucl. Inst. & Meth. 1962; 18,19: 66-69.
 - ² Batten RA, Bruckshaw J, Gusdal I, Knote G, Mc Ilwain A, McKee JSC, Oh S. Axial Injection of H^- Ions Into the University of Manitoba Variable Energy Cyclotron. Nucl. Inst. & Meth. 1976; 136: 15-17.
 - ³ Newson HW, Blipuch EG, Purser FO, Boyce JR. An Operational Review of the TUNL Cyclo-Graaff. Nucl. Inst. & Meth. 1974; 122: 99-113.
 - ⁴ Ophel TR. The ANU 26-MeV Cyclotron Injector. Nucl. Inst. & Meth. 1974; 122: 115-118.

E. The Beam Swinger

By late 1970 it was apparent that modern experiments needed resolution superior to that obtained with solid state detectors. A design for a novel magnetic spectrometer system was reached by early 1971 and construction of the major magnets was begun in 1971. This design involved rotation of the incident beam about the target. We thus vary $\vec{q} = \vec{K}_i - \vec{K}_f$ by changing $\vec{K}_i$, not $\vec{K}_f$ in the usual fashion. This beam swinger operates in two modes. The first mode, for neutron time-of-flight runs, is fully isochronous, producing no observable broadening of the time resolution of the incident beam, indicating a time resolution due to the swinger of no worse than a few hundred picoseconds. The neutron detectors are fixed in well-shielded locations, providing an angular range of 0 to 140 degrees.

In the second mode, the beam swinger system places a beam with high momentum-position correlation on the target, suitable for a dispersion matched or energy-loss spectrometer system. The change in magnification needed to analyze products from a variety of reactions is provided by a stack of four quadrupole lenses between the target and the reaction analyzing magnet. A careful field mapping of the four magnets comprising this zoom lens found essentially perfect quadrupole fields. The final momentum analysis is accomplished by a 90 degree bending magnet. Focal plane localization is accomplished with a variety of helical cathode detectors. With the energy-loss system, a final resolution as good as 8 keV is obtained even though the beam on the target may be spread over 100 keV. No aberrations have been noted in studies of the best resolution, determined

by the size of the entrance aperture only, although in practice target thickness effects place a limit on the final peak width.

Particle identification is redundantly provided by simultaneous determinations of momentum, total energy (in a backing scintillator), energy loss in the anode gas, time-of-flight (modulo the cyclotron RF cycle) and transverse deflection by an electric field. Very rare events can be separated from background in this fashion. A system of baffles is included in the analysis magnets, using ray tracing in the measured fields, such that only the desired trajectories are transmitted. This has provided a very clean system for small angle cross section measurements. In many cases we take data exactly at zero degrees. With the energy-loss principle, we can utilize the full extracted cyclotron current, as much as 10 μ A on target.

The rotating beam system, first used in Boulder, has also been applied at MSU and Hammersmith Hospital (London). The excellent resolution, count rate, particle identification and momentum filter properties of this system have provided excellent data for many studies for over eight years so far. All the design and engineering were completed at the NPL, as were many of the components and all installation, field mapping and calibrations. A series of six publications in Nuclear Instruments and Methods documents this instrument.

F. Detector Development

Measurement of the energies, momenta, flight times and species of reaction products is as important as is the provision of the cyclotron beam. The NPL has been in the forefront in developing and testing a wide range of detectors.

When Si(Li) counters provided most of the information on charged reaction products these were constructed in the laboratory. Almost all needs were met by this in-house manufacture from 1967 to 1977, with depletion depths of up to 10 mm. Ge(Li) gamma-ray detectors were also manufactured, at the state of the art from 1966 to 1970, and continuing until 1977. Commercial sources of both types had so improved by 1977 that in-house manufacture was ended.

Particle detectors made from high purity, intrinsic Ge were needed for higher energy beams encountered at the Indiana University Cyclotron Facility, and a 2 x 14 mm telescope was constructed. Several small gamma-ray counters were also made. More recently, the properties of solid state counters made from CdTe or HgI₂ have been investigated.

Particle localization in the focal plane of the spectrometer is accomplished by a variety of helical cathode detectors. When the first of these was built in 1973 it was the longest one in operation anywhere. Replacements and new varieties of these detectors are now made routinely.

A large effort has been made to build large volume neutron detectors with good time resolution and good discrimination against gamma-ray events. Designs suited to a range of neutron energies (1 to 50 MeV) have been built. Many other laboratories using the neutron time-of-flight method have since followed these designs. Pulsing of the cyclotron beam has been accomplished by a gated ion source and by an external radio-frequency beam deflector.

A double-focussing beta spectrometer, an on-line transport system for conversion electrons and a curved Ge crystal diffraction spectrometer were designed and built for the study of electron and photon spectra.

Prior to construction of the beam swinger, a quadrupole spectrometer was

used for a momentum filter. The quadrupole spectrometer design has been followed elsewhere, for instance at Munich and at Livermore, where neutron induced charged particle reactions are studied. Two versions of a time-of-flight, time-loss spectrometer have been designed, for charged particles and for neutrons.

G. Plasma Physics of Ion Source

A one-quarter scale model of the main cyclotron magnet was made for field mapping and orbit design studies around 1960. More recently, this system has been reconnected as a test bed for basic studies of the plasma physics of arc ion sources. A sophisticated optical diagnostic system is now installed and providing important new information that may lead to more intense sources from cyclotrons and other accelerators.

H. Computing

A PDP-9 was installed in 1968 for off-line analysis and some on-line data acquisition. This was replaced by a PDP-11/34 in 1978, with most of the off-line analysis now performed with a PDP-11/60 installed in 1980. The 11/34 is dedicated to on-line data acquisition. The analysis package SPECTR has proven to be a versatile and simple tool for manipulation of spectra. This package has been exported to a number of laboratories. A data acquisition routine KAOS has been developed for the 11/34, and has been in common use since 1978.

III. EXPERIMENTAL HIGHLIGHTS

A. Reaction Mechanism Studies

A sizeable fraction of the effort at the Nuclear Physics Laboratory over the years has been directed towards a better understanding of the nuclear reaction mechanisms in various light ion reactions. In many ways this interest was stimulated both by the capabilities of the facilities and the expertise offered by the faculty members at the laboratory interested in theoretical nuclear physics. Because of the energy of the charged particle beams available, the direct reaction mechanism is the process of interest with particular emphasis on the distorted wave Born approximation (DWBA) method. Some of the highlights of the studies that have been completed in the last twenty years are listed:

1. A study of inelastic proton scattering on ^{90}Zr with the first analysis (with G. R. Satchler) of such data by the use of microscopic interactions, i.e. shell model wave functions and an assumed proton-nucleus potential. Since then, this has become a standard method of analysis for inelastic and charge exchange reactions, most clearly successful at the IUCF.

2. A series of two-neutron pickup reactions (p,t) were studied which, when coupled with a DWBA analysis, yielded important information on the dependencies of the results on the assumed optical model potentials for the proton and triton, the shell model configuration involved, the potential for the bound neutrons and other details of the calculations. Experimental tests were made to ascertain the reliability of the L-value assignments and the enhancement factors extracted from the data. This work was important to the analysis of pairing vibrations.

More recently the energy dependence of the reaction mechanism has been investigated using data taken here at 26 MeV, data taken at 80 MeV at the Indiana University Cyclotron Facility, and several studies done by others. This was the first such investigation where both zero-range and exact finite-range calculations could be compared with the data. Studies of nucleon transfer induced by heavy ion reactions now rely on these methods.

3. The role of two-step or sequential processes in reactions such as the (p,d) and (p,t) have been extensively investigated here. In the case of the (p,d) reaction $(p,p')(p',d)$ sequences explained in a very reassuring way the population of core coupled states which are forbidden for the one-step process. In the (p,t) reaction the populations of unnatural parity states in ^{58}Ni and ^{60}Ni were completely accounted for by a combination of $(p,p')(p',t)$ and $(p,d)(d,t)$ processes.

4. Various features of the $(^3\text{He},t)$ reaction have been brought to light by a combination of theoretical and experimental studies carried out here in the last 15 years. Included in this category are the importance of the tensor part of the interaction for excitation of unnatural parity states, the role of two-step processes in the excitation of states in odd-odd nuclei, the dependence on the optical model parameters for the ^3He and tritons, as well as the energy dependence of the reactions. More recently, detailed comparisons of $(^3\text{He},t)$ and scattering data have revealed very simple isospin relations to compare to inelastic pion scattering.

B. Isobaric Analog States and the Lane Model

Isobaric analog states (IAS) were discovered in the (p,n) reaction at direct reaction energies by Anderson and co-workers at Livermore. The Lane Model offered a unification of proton elastic scattering, neutron elastic

scattering and the quasi-elastic (p,n) transition to the IAS. If the model was correct, (p,n) IAS data measured the asymmetry term of the nucleon-nucleus optical potential.

The Nuclear Physics Laboratory carried out a systematic and precise study of (p,n) IAS reactions which spanned 33 target nuclides ranging from ^9Be to ^{232}Th . The Lane Model interpretation of this reaction was beautifully confirmed and our knowledge of the asymmetry term in the optical potential was vastly improved. A practical consequence is that it is now rather straightforward to convert an easily measured proton optical potential for a given target and beam energy to a neutron optical potential for that target. This enables more reliable calculations to be carried out for both the fission and fusion power programs.

C. Multinucleon Transfer

A systematic study of the ($^3\text{He}, ^7\text{Be}$) reaction was carried out by the Nuclear Physics Laboratory from 1970 to 1972. Our preliminary studies involving selection rules showed that the ($^3\text{He}, ^7\text{Be}$) reaction was dominated by direct transfer of an alpha-like cluster with the quantum numbers of the ground state of the alpha particle. The ($^3\text{He}, ^7\text{Be}$) alpha-transfer reaction was then used as a tool to study the variation of alpha particle spectroscopic factors for targets ranging from $A=12$ to $A=93$. These studies extended our knowledge of alpha "clustering" far beyond the region of mass 60 which was the limit prior to our work. In addition, a careful comparison of alpha clustering was made for ^{40}Ar and ^{40}Ca . The near identity of the results were in strong opposition to a then-current explanation of anomalous α -particle elastic back-scattering from ^{40}Ca . This explanation invoked enhanced alpha cluster probability for self-conjugate $4N$ nuclides but was not

supported by our results. A heavy ion focal plane detector has been developed to allow these studies to be continued with the energy-loss spectrometer system.

The (α, p) , (α, n) and (p, α) three-nucleon transfer reactions are well-suited to the study of high-spin final states due to their large momentum mismatch. Our early studies dealt mainly with levels of known spin, but we now understand this reaction well enough to deal with states of spins as high as 11^- (by $^{39}\text{K}(\alpha, p)^{42}\text{Ca}$) and $21/2^+$ (by $^{116}\text{Sn}(\alpha, p)^{119}\text{Sb}$). These reactions thus offer the specific benefits of a direct reaction to the simply structured high spin states usually best known from inclusive compound reaction data.

D. Nuclear Astrophysics

The ease and range of energy variation with the cyclotron have permitted a study of nuclear reaction rates important for stellar nucleosynthesis. Beam energies as low as 200 keV were provided to the target, accelerating on the fifth harmonic of the RF. A thick target technique was developed for these low energies, where there can be no thin target measurements. Important non-statistical contributions to (p, γ) reaction rates were included by measuring reaction yields in fine steps over isobaric analog states; this technique is more commonly associated with Van de Graaff accelerators. Over one-hundred proton and ^4He induced thermonuclear reaction rates have been determined, covering in some cases up to 40 decades of rate as a function of temperature. This corpus of data has been of the utmost importance for modern understanding of stellar nucleosynthesis.

Thermonuclear reaction rates have also been determined by this technique for a variety of questions relevant to the thermonuclear power program.

E. Pre-equilibrium Reaction Mechanism Studies

In 1978, we began to study light-ion induced pre-equilibrium reaction mechanisms. Due to the long history of neutron detection here and the relatively small amount of experimental information available concerning compound or nearly-compound reactions in which neutrons were emitted, the $(\alpha, xn\gamma)$ and $({}^3\text{He}, xn\gamma)$ reactions were targeted for study. During the course of the investigation both inclusive and exclusive spectra of neutrons emitted in α - and ${}^3\text{He}$ -induced reactions have been obtained for about twenty targets in the range $80 < A < 210$ using beam energies from 24 to 35 MeV for α 's and 25 to 43 MeV for ${}^3\text{He}$'s.

The accumulation of this large data set has allowed us to observe systematic features of the reaction mechanisms involved which are not evident in studies of a single target. The most prominent such feature is a pronounced relation between the pre-equilibrium reaction cross section and the neutron excess parameter $(N-Z)/A$. Such a relation is unexpected in at least one current view of such reactions, the massive-transfer model. We have also developed techniques for the analysis of $n\text{-}\gamma$ coincidence data which show in some detail the feeding pattern of the yrast states from the entry region. Using these techniques, we have in several cases been able to place fairly strict limits on the J-width and location of the entry clouds for specific reactions.

These studies nicely supplement the traditional interest in reaction mechanisms at Colorado, and are of particular interest for heavy ion reaction mechanisms, where the simpler features noted with helium beams clarify the more complex reactions.

F. Nuclear Spectroscopy

The energy-level schemes of many nuclei have been investigated at the NPL. With a variety of beams and the ability to detect a range of particles, a wide range of nuclei have been studied. In some cases, the spin, spectroscopic factor or other observables for a single state have been determined for cases of special interest. A recent example is the determination of the $9/2^+$ spin and rotational nature of the 9.50 MeV state in ^{13}C .

We have also mounted heavy attacks to determine the general properties of some nuclei. A good example may be found in ^{106}Ag , where $(\alpha, xn\gamma)$, (p, d) , $(^3\text{He}, d)$, $(^3\text{He}, p)$ and $(^3\text{He}, t)$ reactions were all used to provide a level scheme and a shell model interpretation. Previous to this study only a single isomeric state was known for this nucleus. These studies provide the ore to be mined by detailed shell model or other calculations.

G. Two-Proton Pairing Studies

An important area of research growing out of the neutron time-of-flight facilities was the $(^3\text{He}, n)$ studies on medium to heavy nuclei. Such work had been initiated at Rochester, in Berlin and Munich. However, when this laboratory started its investigations, it so dominated this field of nuclear research that now no other laboratory anywhere can compete. As a result the field has been left exclusively to this laboratory.

The $(^3\text{He}, n)$ reaction excites preferentially elementary modes of nuclear excitation with the two protons coupled to angular momentum zero. Up to mass 60 such studies have been completed by others. This laboratory carried on the work from mass 60 to 230 as well as some studies below mass 60. About 11 papers have been published on this topic from this laboratory. The work has

temporarily ceased while improvements in energy resolution and luminosity are being made. There is a great deal more to do with improved capability.

Near the closed nuclear shells at $Z=40$, 50 and 82 the phenomena of paired proton particle or hole states are particularly simple. The corresponding systematics for neutron states in nuclei with $N=40$, 50 , 82 and 128 , as well as in other regions, have been extensively studied by (p,t) and (t,p) reactions. However, no comparable work with proton transfer reactions was available. The proton work confirmed rather nicely the systematics predicted by the neutron pairing vibration studies when the proper corrections for Coulomb effects were included. A matter of interest was the interaction of the proton and neutron pairing states. A very small residual interaction in ^{208}Pb was confirmed by systematics from studies in ^{204}Hg and ^{206}Pb .

Some studies on odd- A nuclei to show the effects of coupling single particle states with pairing vibration states have been done. However, questions remain because of insufficient resolution. Also, additional strength at much higher excitation energy is expected; preliminary work on light targets indeed shows strong, discrete states at very high excitations. Future $(^3\text{He},n)$ studies are certain to be rewarding.

H. Proposals

Although valuable research with the 30 MeV cyclotron has been our main interest, it has also been realized that future work would be aided by light ion beams of greater intensity and energy. A series of proposals (1970, 1978, and 1980) was submitted requesting a second cyclotron to boost our proton energy to 75 MeV. Higher beam currents were to be obtained, sufficient to allow time-of-flight studies at very long flight paths and to

study neutron induced reactions. In the more recent proposals a polarized hydrogen beam was also requested to allow more detailed studies of reaction mechanisms. A large effort was dedicated to these proposals, and several innovative designs were developed. The advantages and technical difficulties of a light ion storage ring have been examined, for example.

IV. INTERMEDIATE ENERGY PHYSICS

A program of experimental research in intermediate energy nuclear physics was begun in 1970, with the first funding through Task C in 1973. Theoretical work in this field is described elsewhere in this report. The research at higher energy accelerators follows the same general lines developed at the cyclotron, with emphases on reaction mechanisms and the structure of complex nuclei. We have been closely associated with the accelerators at LAMPF, TRIUMF and IUCF, particularly in their high resolution beam lines. Design and construction of the EPICS system at LAMPF was an important element of our effort for many years.

Four important classes of experiments have been undertaken. Pion induced nucleon removal ($\pi, \pi N$) was studied to test whether this reaction was related to the more familiar single nucleon pick-up reactions such as (p,d), or proceeded by a statistical process.

High energy proton beams have been used to study the (p,d) reaction on several targets, at several beam energies, and in some cases, with polarized beam. The objective of this work is to examine the high momentum components of nuclear wave functions and to test the distorted wave theories at higher energies. Extensive theoretical work and studies of proton elastic and inelastic scattering have also been needed for this work, which has resulted in a great increase in our understanding of nuclear reactions. As needed, data have also been taken with our cyclotron to complement these studies. Some work on the (π^+ ,p) reaction has also been undertaken, also picking up a neutron at a large momentum mismatch, but has not yet been addressed in much detail.

Data on elastic and inelastic pion scattering have been a main goal of

our program. Very low energy data were important for understanding the many-body aspects of a pion optical potential. At the 3-3 resonance the striking isospin properties of the basic pion-nucleon system have been used to study pion-nucleus reactions. Ratios of yields to states of known isospin or ratios of π^+ to π^- yields have provided a fairly model-independent probe of the spin-isospin properties of the interaction on a number of light nuclei. Many questions of nuclear structure relevant to the pion studies have also been investigated with the cyclotron.

The most fundamental study in this pion elastic scattering program has been a determination of the validity of nuclear charge symmetry by a comparison of π^- and π^+ elastic scattering on the deuteron. The systematic uncertainties and Coulomb effects have been well understood, and we affirm that nuclear charge symmetry is valid to much better than one percent.

The very successful (p,n) program at the cyclotron has been supplemented at higher energies at the IUCF. The bulk, analog, effects noted at lower energies are dominated by single-particle effects at energies above 100 MeV. This coherent study of charge exchange is also complemented by ($^3\text{He},t$) data with the cyclotron, with better energy resolution and a wide range of momentum transfers.

We have found it possible to study problems of reaction mechanism or nuclear structure with the most specific probe by operating programs both at the cyclotron and at the appropriate national accelerators.

V. NUCLEAR THEORY

The main thrust of our work has been toward the understanding of nuclear structure by means of nuclear reactions, usually simple inelastic, charge-exchange or particle transfer reactions. The interplay of the continuum reaction theory with the bound nucleus provides a large variety of fascinating questions, many of which can be addressed in the framework of nuclear models. The simplest models--involving few degrees of freedom in a "direct" reaction--have provided much of our current knowledge of nuclear structure.

A basic question in applying direct reaction analyses is delineating the range of validity of the method. This has led naturally to the study of two-step processes, of deuteron breakup effects in stripping, and to intermediate pion effects which are discussed in many of the publications in our bibliography. In these studies we have focussed on reactions involving light projectiles (usually $A \leq 4$) although our computer codes are often used by others in the heavy-ion domain. In recent years the experiments at LAMPF and TRIUMF have led us into the higher energy domain with protons and pions as nuclear probes. The pion experiments have led to a study of the basic π -nucleon interaction as well as its N^* and Δ resonant states. The proton experiments have led to the extrapolation of low energy reaction theory to the intermediate energy regime.

For almost all nuclear reactions, distortion is an important and even dominant feature. In the last decade a distorted wave Born approximation code DWUCK was developed with care taken to ensure accuracy, speed and flexibility. The demand for this program was outstanding--as evidenced by more than 140 other research groups currently using this program.

The complications of analyzing inelastic scattering reactions when the coupling is strong resulted in the development of the coupled channels code CHUCK, which was designed to allow for strong coupling in particle transfer modes as well. For situations where the zero-range approximation is inadequate (e.g. at high energies) a full finite-range calculational scheme using an efficient plane wave expansion method was incorporated into the program DWUCK5. The three programs together form a direct reaction analysis package which the nuclear physics community has used extensively. More specialized codes for pion projectiles have also been developed.

In the low energy region, a continuing interest has improved our understanding of two-particle transfer reactions. The role of a second-order process, the sequential transfer of the two neutrons, has been studied using several simplifying assumptions. In addition, work has been continuing on the calculations for the usual first-order dineutron transfer. A finite-range calculation has been formulated and can now be made with the ease of a zero-range calculation. One finds that with the correct treatment of the repulsive term in the nucleon-nucleon potential the first-order term does not predict the magnitude or relative energy dependence of the experimental cross sections over a range of energy from 25 MeV to 80 MeV. Thus there are still unresolved questions to answer in this simple basic reaction.

The interaction of pions with nuclei has been a major item in our research in the last decade. This has included calculation of the various N^* and Δ admixtures in the deuteron, the effects of nuclear spin either as an aligned target or in a radiative deexcitation, as well as the more common analyses of elastic and inelastic scattering. An interesting discovery was that low-energy π^+ and π^- scattering involved the isovector part of the

nuclear density distribution coherently and sensitively. This was turned around to study neutron density distributions relative to the known proton distributions. Several experiments at the meson factories have exploited this idea.

Another discovery occurred when we found great difficulty in understanding the ${}^4\text{He}(p,d){}^3\text{He}$ reaction at high energies (200-800 MeV). The resolution of our difficulties turned out to be the neglected meson exchange currents which should be removed in constructing a "bare" nucleon density distribution using electron scattering form factors. This provided the first verification of the effect of these exchange currents in a hadronic scattering process.

The nuclear theory research at the University of Colorado is closely tied to experimental nuclear physics programs. The theorists have offices at the cyclotron building and often collaborate with experimental work at the national labs as well as at the Colorado cyclotron. It is expected that this collaboration will continue and that a large fraction of our future research will be involved with interesting (or anomalous or puzzling) experiments yet to be done.

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Appendix B

Research Appointees from 1961-1981, Nuclear Physics Laboratory

Year	Name	Present Location
1961	William P. Johnson	Michigan State Univ.
1962	R. A. Kenefick	Texas A & M, College Station, TX
1962	Michaya Kondo	Osaka University, Osaka, Japan
1963	Rubby Sherr	Princeton Univ.
1965	B. W. Ridley	U. of Colo. On leave
1965	P. W. Allison	Los Alamos Scientific Laboratory
1965	R. R. Johnson	University of British Columbia, Vancouver
1966	R. S. Dingus	Los Alamos Scientific Laboratory
1966	S. I. Hayakawa	Wasada University, Tokyo, Japan
1966	G. D. Jones	University of Liverpool, England
1966	Marc Chabre	I.P.N., Orsay, France
1967	R. J. Griffiths	University of London, England
1968	J. E. Glenn	Mallinckrodt Nuclear, Carlstadt, NJ
1968	L. W. Put	KVI, Groningen, The Netherlands
1969	H. W. Baer	Los Alamos Scientific Laboratory
1969	J. H. Jett	Los Alamos Scientific Laboratory
1969	B. E. Klank	Dept. of Integrated Studies, U. of Colo.
1969	C. E. Moss	Los Alamos Scientific Laboratory
1969	P. Schwandt	University of Indiana, Bloomington
1970	C. Detraz	I.P.N., Orsay, France
1970	R. J. Peterson	U. of Colorado
1970	H. Rudolph	Bureau of Radiological Health, Rockville, MD
1971	Reinhard Graetzer	Pennsylvania State Univ., Univ. Park, PA
1971	P. D. Ingalls	Applied Physics Lab., Univ. of Washington
1972	R. L. Bunting	Aerojet Nuclear, Idaho Falls, ID
1972	G. W. Edwards	Northridge College, CA
1972	W. L. Fadner	Univ. of Northern Colorado, Greeley
1972	M. J. Fritts	Naval Research Labs, Washington, D. C.
1972	L. D. Rickertsen	Oak Ridge, TN
1973	R. E. Anderson	University of North Carolina, Chapel Hill
1973	N. A. Roughton	Regis College, Denver
1973	M. J. Schneider	Krasdale Foods, Bronx, NY

Year	Name	Present Location
1974	F. E. Cecil	Colorado School of Mines, Golden
1974	L. L. Nunnelley	Chemeketa Comm. College, Salem, OR
1974	D. A. Sparrow	U. of Pennsylvania, Philadelphia, PA
1974	H. H. Wieman	Lawrence Berkeley Laboratory, Berkeley, CA
1975	P. A. Batay-Csorba	Computer Sciences Corp., Silver Spring, MD
1975	H. P. Blok	The Free University, Amsterdam, Netherlands
1975	N. Ensslin	Los Alamos Scientific Laboratory
1975	J. R. Shepard	Univ. of Colorado, Boulder
1976	R. L. Boudrie	Los Alamos Scientific Laboratory
1976	Hideo Kubo	Massachusetts General Hospital, Boston
1977	R. A. Emigh	Rocky Mtn. Energy Co., Broomfield, CO
1977	W. S. Pong	Technical School, Hong Kong
1977	L. E. Samuelson	Princeton University, NJ
1977	P. A. Smith	Molitor Industries, Inc., Englewood, CO
1978	M. L. Gartner	Houston, TX
1978	E. R. Sugarbaker	Ohio State University, Columbus, OH
1979	T. G. Masterson	University of Colorado, Boulder
1979	S. S. DasGupta	University of Burdwan, India
1979	R. J. McLeod	Nucl. Phys. Lab, U. of Colorado
1979	R. S. Raymond	Nucl. Phys. Lab, U. of Colorado
1979	F. W. N. de Boer	SIN, Villagen, Switzerland
1980	E. R. Siciliano	Nucl. Phys. Lab, U. of Colorado
1980	M. Yasue	Nucl. Phys. Lab, U. of Colorado
1980	M. B. Chen	Nucl. Phys. Lab, U. of Colorado
1981	H. C. Bhang	Nucl. Phys. Lab, U. of Colorado

Among the recent visiting faculty have been E. R. Flynn (LASL), J. E. Kitching (McGill University), E. F. Gibson (Sacramento State University), W. P. Alford (Western Ontario University), and F. D. Becchetti (University of Michigan).

APPENDIX C

Ph.D. Graduates of the Nuclear Physics Laboratory

Year	Graduate	Thesis Title and Advisor	Present Position
1960	J. D. McCullen	A Study of the Low Excited States of ^{42}Ca and ^{44}Ca Advisor: J. J. Kraushaar	Professor Physics Department U. of Arizona Tucson, AZ
1963	J. K. Kliwer	Method for the Measurement of the Longitudinal Polarization of Electrons and a Nuclear Level Study of ^{44}Sc Advisor: J. J. Kraushaar	Professor Physics Department University of Nevada Reno, NV
1964	C. G. Hoot	A Study of (p,d) and (p,t) Reactions on Nickel and Iron at 28 MeV Advisor: M. E. Rickey	at Intelcom Radiation San Diego, CA
	W. S. Gray	Inelastic Proton Scattering from ^{40}Ca , ^{50}Ti and ^{54}Fe Advisor: J. J. Kraushaar	Faculty Physics Department U. of Michigan Ann Arbor, MI
	J. G. Kelly	Elastic Scattering Cross Sections of 14.5 MeV Protons for Medium Weight Nuclei Advisor: D. A. Lind	Physicist, Sandia Corp. Albuquerque, NM
	W. C. Anderson	The Decay of ^{40}Sc and ^{32}Cl Advisor: J. J. Kraushaar	at E, G and G Los Alamos, NM
1965	B. M. Bardin	Study of the (p, α) Reaction on Medium-Weight Nuclei at 28 MeV Advisor: M. E. Rickey	Computer industry Fullerton, CA
	P. Henning	Development of High Resolution Gamma Ray Spectroscopy for use with the University of Colorado Cyclotron Advisor: D. A. Lind	Self-employed
	P. W. Allison	Elastic Scattering of Protons by ^4He from 20 to 28 MeV Advisor: W. R. Smythe	Staff Physicist LAMPF LASL Los Alamos, NM

Year	Graduate	Thesis Title and Advisor	Present Position
1965	D. E. Heagerty	Measurement and Analysis of Proton Elastic Scattering from Medium Weight Nuclei at 14.5 MeV Advisor: D. A. Lind	Nuclear Personnel Placement Service Charleston, SC
1966	R. G. Matlock	The Study of Nuclear Coulomb Energy Systematics Advisor: M. E. Rickey	Reactor Division Argonne National Laboratory
	M. M. Stautberg	Nuclear Structure Studies of ^{88}Sr , ^{89}Y , ^{92}Zr , and ^{94}Zr using 19 MeV Proton Induced Reactions and the $^{88}\text{Sr}(^3\text{He},d)$ Reaction Advisor: J. J. Kraushaar	Professor of Physics De Paul University Chicago, IL
	E. F. Gibson	Scattering of ^3He from Medium Weight Nuclei at 37.7 and 43.7 MeV Advisor: J. J. Kraushaar	Professor of Physics Sacramento State College Sacramento, CA
1967	R. L. Hutson	Polarization of 40 MeV ^3He Ions Elastically Scattered from ^{12}C Advisor: J. J. Kraushaar	Staff member, Los Alamos Scientific Laboratory
1968	R. W. Barnard	Study of ^{60}Ni , ^{46}Ti and ^{28}Si with the $(^3\text{He},d)$ Reaction Advisor: J. J. Kraushaar	Physicist, Sandia Corp. Albuquerque, NM
1969	M. E. Cage	A Study of Particle-Hole States in Medium Weight Nuclei by the $(^3\text{He},d)$ Reaction Advisor: D. A. Lind	Physicist, National Bureau of Standards Washington, D. C.
	J. H. Jett	A Study of Rotational States of ^{158}Dy , ^{162}Er , ^{164}Er , ^{168}Yb and ^{174}Hf Advisor: D. A. Lind	Staff member, H-Division Los Alamos Scientific Laboratory
	Benno Klank	An Electron-Transport Solenoid Si(Li) Detector Spectrometer and On-Line Conversion Electron and Gamma Spectroscopy Advisor: R. A. Ristinen	Assoc. Professor Integrated Studies University of Colorado Boulder

Year	Graduate	Thesis Title and Advisor	Present Position
1969	Temple Smith	The Deuteron Amplitudes from a Composite Particle Nuclear Scattering Theory Advisor: P. D. Kunz	Faculty University of Northern Michigan, Marquette, MI
1970	P. M. Abraham	A Microscopic Investigation of the Collective Model of Nuclei Advisor: E. Rost	Faculty Belmont Abbey College NC
	R. E. L. Green	A Double-Focussing Quadru- pole Lens Spectrometer and Its Use in Nuclear Reaction Studies Advisor: D. A. Lind	Faculty Department of Physics Simon Fraser Univ. British Columbia
	In Ki Oh	The (^3He , ^6Li) Reaction on Light Nuclei Advisor: C. S. Zaidins	Nuclear Engineer Rockwell International Rocky Flats, CO
	A. Rappleyea	Coulomb Energies of Isospin Triplets in the 2s-1d Shells Advisor: P. D. Kunz	Faculty City College of San Francisco, CA
	D. L. Spenny	L & M Subshell Internal Con- version Ratios for Electric Quadrupole Transitions Advisor: A. A. Bartlett	Faculty Univ. of Minnesota Bemidji, MN
	P. P. Urone	Study of the Mass-3 Optical Potential for Medium-Weight Nuclei Advisor: B. W. Ridley	Faculty Department of Physics Sacramento State College Sacramento, CA
1971	N. S. P. King	A (p,n γ) Study of Excited States in ^{58}Cu , ^{54}Co , ^{50}Mn , and ^{46}V Advisor: R. A. Ristinen	Staff Member, J-Division Los Alamos Scientific Laboratory
	W. L. Fadner	Nuclear Structure and Reac- tion Mechanism Studies with the (^3He , t) Reaction Advisor: J. J. Kraushaar	Faculty Dept. of Physics Univ. of Northern CO Greeley, CO
	T. R. King	A Study of $^2\text{H} + ^3\text{He}$ Elastic Scattering and the Reaction $^2\text{H}(^3\text{He}, ^4\text{He})^1\text{H}$ Between 17.5 and 44.1 MeV Advisor: W. R. Smythe	Staff Member, Los Alamos Scientific Laboratory, Los Alamos, NM

Year	Graduate	Thesis Title and Advisor	Present Position
1971	D. M. Stupin	A Study of Final-State Proton-Proton Interactions and the $^{28}\text{Si}(^3\text{He}, 2p)$ and $^{12}\text{C}(^3\text{He}, 2p)$ Reactions at 40 MeV Advisor: R. A. Ristinen	Staff member, Los Alamos Scientific Laboratory
1972	G. E. Edwards	Pion-Nucleus Inelastic Scattering in the Distorted-Wave Born Approximation Advisor: E. Rost	Faculty, Northridge College, San Fernando Valley, CA
	R. F. Bentley	A Fast Neutron Spectrometer, (p,n) Reaction Studies and Microscopic Analysis Advisor: C. D. Zafiratos	New England Nuclear, Billerica, MA
	J. R. Shepard	The (p,t) Reaction on Medium-Mass Nuclei at $E = 27$ MeV Advisor: J. J. ^P Kraushaar	Asst. Professor Physics Department Univ. of Colorado, Boulder, CO
	J. D. Carlson	Quasi-elastic (p,n) Studies and the Isospin Dependence of Nucleon-Nucleus Optical Potentials Advisor: C. D. Zafiratos	Group Leader Lord Corp. Erie, PA
1973	S. D. Schery	The (p,n) Reaction on High Z Elements Using a Rotating Beam Neutron Time-of-Flight System Advisor: D. A. Lind	Research Faculty New Mexico Tech Socorro, NM
1974	R. H. Ware	Analyzing Power of Polarized ^3He for 27 MeV Protons and 15 MeV Alphas Advisor: W. R. Smythe	Research Associate, CIRES University of Colorado Boulder, CO
1975	H. H. Chang	The Nuclear Optical Model for ^3He and ^4He Projectiles Advisor: B. W. Ridley	Geophysics Co. Houston, TX
1976	F. M. Edwards	Studies of Thick Target Fast Neutron Production and Proton Activation of the Stable Isotope Tracer ^{48}Ca as Applications of Nuclear Physics in Medicine Advisor: J. J. Kraushaar	Medical Physicist, Univ. of Missouri Medical School, Columbia, MO

Year	Graduate	Thesis Title and Advisor	Present Position
1976	M. S. Iverson	Pion-Nucleus Scattering and the Investigation of Nuclear Spin Dependent Effects Advisor: E. Rost	Kaman Nuclear Corp. Colorado Springs, CO
	R. A. Emigh	A Study of the ^{98}Tc Nucleus via the $^{99}\text{Tc}(p,d)^{98}\text{Tc}$ Reaction Advisor: R. E. Anderson	Rocky Mtn. Energy - Broomfield, CO
1977	J. D. Burch	Second Order Processes and Finite Range Effects in the $^{60,62}\text{Ni}(p,t)$ Reactions Advisor: J. J. Kraushaar	Self-employed
	W. R. Zimmerman	The Role of Two-Step Processes in the $(^3\text{He},t)$ Reaction Advisor: J. J. Kraushaar	Scientist, BDM Corp. Albuquerque, NM
	M. L. Munger	Changing Deformations and the Role of the Coriolis Interaction in Heavy Transitional Nuclei as Revealed by Single-Proton Transfer Reactions Advisor: R. J. Peterson	Senior Analyst Potomac Research, Inc. National Bureau of Standards, Boulder, CO
	E. W. Stoub	Helical Cathode Proportional Chambers with Application to the $^{40}\text{Ca}(d,\alpha)^{38}\text{K}$ Reaction at 16 MeV Advisor: R. A. Ristinen	Principal Research Scientist and Group Leader, Searle Radiographics, Inc., Des Plaines, IL
1978	B. M. Kluger	The Level Structure of ^{78}Br Advisor: R. A. Ristinen	Staff (Education) Univ. of California Berkeley, CA
	A. S. Rosenthal	Low Energy Pion Scattering Advisor: E. S. Rost	Research staff TRIUMF - Vancouver, BC
1979	N. J. DiGiacomo	The Elastic and Inelastic Scattering of 0.8 GeV Protons by ^{89}Y and ^{90}Zr Advisor: R. J. Peterson	Staff Member, P-7 LASL Los Alamos, NM
	G. R. Smith	Large Momentum Transfer Neutron Pickup with the (π^+,p) and (p,d) Reactions Advisor: R. J. Peterson	S.I.N. Villigen, Switzerland

32-

24- Publications / Year

16-

8-

1960

1970

1980

1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9

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Boulder, ColoradoMarch 12, 1981

1 ea.	<u>Keypunch Machine</u> I.B.M. Ser. 68359-J3 Mod. 026-1 GFE, Source: Argonne Nat'l Lab. Rec'd May 72 Code 5, Used- Fair	Tag 4135	\$3,997.25
1 ea.	<u>PDP-9 Computer (#2)</u> Digital Equip't Corp. Ser. M09-301 Mod PDP-9 GFE, Source: Brook Haven Nat'l Lab. Rec'd Aug '76 Code X Salvage	Tag 4450	\$60,974.00
1 ea.	<u>Computer Terminal</u> Tektronix, Inc. Ser. B067026 Mod. 40101 CP Code 4, Used-Good	Tag 4486	\$4,727.25
1 ea.	<u>Computer PDP-11/34 w/Access.</u> Digital Equip't Corp. Mod. 11/34-LM CP Dec '77 Code 4, Used-Good	Tag 4492	\$58,733.25
1 ea.	<u>Computer, PDP-9 On-Line</u> Digital Equip't Corp. (C.U. Assembled) CP Code 6, Used-Poor	Tag 3903	\$197,582.21

Raymond H. FrieseRaymond H. Friese
Government Property Officer