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University of California, Davis

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ANNUAL REPORT TO THE U. S. ATOMIC ENERGY COMMISSION

September 15, 1967

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California Patent Group, USAEC

By *Alice Sanborn for*
F. H. Robertson, Chief

October 24, 1967

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Annual Report to the U. S. Atomic Energy Commission

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September 15, 1967

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Table of Contents

I. Progress Report

A. Experimental

1. 76" Cyclotron Operations.	1
2. Experimental Nuclear Physics.	3
a. Charged Particle Reactions	3
1. Data Analysis of Experiments Conducted with the 22-inch Cyclotron.	3
a. Elastic Alpha Particle Scattering	3
b. Elastic Proton Scattering	3
2. 30" Scattering Chamber at the 76" Cyclotron	3
b. Beta and Gamma Spectroscopy	4
c. Particle Gamma	5
d. Neutron Scattering and Reactions.	7
1. Neutron Detector Efficiency Measurements at 10-70 MeV	8
2. Neutron Proton Bremsstrahlung	8
3. Neutron Proton Scattering	9
4. Neutron Detector Efficiency Measurements at 25-175 MeV.	9
e. Atomic Beam	9
f. Experimental Tests of Quantum Electrodynamics	9
1. Double Compton Scattering and Cross Section	9
2. Triple Compton Scattering	10
g. Special Experiment Equipment.	10
1. Detector Fabrication.	11
2. Polarized Target Development.	11
List of Publications.	13
 B. Theoretical	15
 List of Publications	25

II. Scope of Work

A. Experimental

1. 76-Inch Cyclotron Operations.	28
2. Experimental Research Program	29
a. Charged Particle Reactions.	29
b. Beta and Gamma Spectroscopy	30
c. Particle Gamma.	31
d. Neutron Scattering.	32
e. Polarized Target.	33
f. Atomic Beam	33

B. Theoretical.	35
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NUCLEAR PHYSICS RESEARCH

I. Progress Report

A. Experimental

1. 76" Cyclotron Operations

During the past 12 months the 76-inch cyclotron has been brought from a state of small internal beam to a successfully operating external beam machine. We are now scheduling 58 to 64 hours of beam time per week. Present extracted beams are 40, 45, 48, and 55 MeV alphas and 22 MeV H_2^+ . Beam development of protons at 55 MeV and other energies is proceeding as fast as possible. RF problems have hindered this work but at the present time an external beam is expected during the latter part of September.

Machine reliability has steadily improved. Most of the time an experimenter can now rely on completing a run.

A chronology of the past year high lights follows:

August 1966

The coax channel deflection element was installed and tested. Diffusion pump # 2 developed new leaks in its refrigeration baffle. The electrostatic deflector curvature drive was redesigned to enable to enable operation at full rated voltage. H_2^+ was accelerated (21 MeV) to the exit of the coax channel at which point a chemical target was placed.

The trim coil and harmonic coil power supplies were found to be extremely unreliable in operation.

September 1966

The puller mechanism failed so the machine was shut down for repair. A heater element in each of the trim coil and harmonic coil power supplies was removed as one step in a reliability improvement program. The electrostatic deflector developed water leaks. The problems in patching the old unit influenced a decision to design and build a new one. The iron channel deflecting element was installed.

October 1966

The iron channel deflecting element burned up due to a water blockage. Fortunately it was rather easily repaired. Special filters were purchased and installed to help prevent such future problems. (The coax and iron channel water circuits can not be fully protected both thermally and through flow switches).

November 1966

An external 43 MeV alpha beam was achieved.

December 1966

An external 42 MeV alpha beam was achieved into the north experimental cave.

January 1967

The deflector drive mechanisms were installed and tested.

April 1967

External beam for experimental purposes was scheduled. Initial runs were not always too successful. The master RF oscillator output stage was modified.

June 1967

The water system was treated with special cleaning compounds which brought the conductivity to below 5 micromhos. The beam optics control and display panel was layed out and wired into the system. Additional signal cables to experimental areas were installed and installation of radiation safety chain started. The installation of a low level paging system was started also. The chemical target and 30" scattering chamber beam lines were completed. Beam collimators were installed. Beam steering magnets patterned after Colorado University units were designed and tested. Air cooling ducts were run into all trim and harmonic coil power supplies in an effort to improve their reliability.

July 1967

A 21 MeV H_2^+ chemical target was run. Many parts of the RF servo system were redesigned and rebuilt. Attempts to operate at high frequency failed. The RF system runs reasonable well at low frequencies.

August 1967

The second attempt to obtain 55 MeV protons failed when the beam puller - RF system collapsed. This necessitated a complete machine

disassembly. New damage to the RF system was discovered and required extensive rework. During the machine down time, several tasks were completed.

- A. Beam optics display panel
- B. Chemical target transfer mechanism
- C. Neutron beam line
- D. Cleaning and test of water flow switches in all power supplies.
- E. Changes in control logic circuitry of trim and harmonic coil power supplies to prevent operation (previously possible) when water interlocks opened.
- F. An RF "bleed-off" around the ion source has been added. Better RF grounding of the trimmers has been made.

2. Experimental Nuclear Physics Program

a. Charged Particle Reactions

1. Data Analysis of Experiments Conducted with the 22-inch Cyclotron

- a) Elastic Alpha Particle Scattering, (F. P. Brady, J. A. Jungerman and J. C. Young)

The optical model analysis of the data taken at 8.71, 9.33 and 10.15 MeV was finished and the results were published in Nuclear Physics A98 (1967) 241. More details are given in UCD-CNL 57 and 58. It was necessary to fix the geometrical parameters in the search routine in order to obtain consistent potential strengths for a given nucleus at the three energies.

- b) Elastic Proton Scattering, (F. P. Brady, J. E. Draper, and J. A. McCray)

Optical model analysis of the data was completed using an automatic search routine. The best fit parameters agreed quite well with those suggested by Rosen for this energy range. The results appear in UCD-CNL 54 and Nuclear Physics A94 (1967) 449.

2. 30" Scattering Chamber at 76" Cyclotron, (C. Badrinathan, F. P. Brady, A. Springer, P. J. Symonds and P. Martins*)

* Summer Only

There have been basically two developments in the last year. A 45 MeV alpha beam was extracted and 100 n amps was put on a carbon target. This permitted us to test out our electronics and detectors. We were especially interested in the performance of a Goulding particle identifier. There was good separation between proton, deuteron, triton, helium-3 and helium-4 peaks. Simultaneous spectra of $C^{12}(\alpha, d)N^{14}$, $C^{12}(\alpha, t)B^{11}$, $C^{12}(\alpha, He^3)C^{12}$, and $C^{12}(\alpha, \alpha')C^{12*}$ were observed at two angles, 20° and 40° in the laboratory.

The second development was a modification in the central region of the ORTEC 30" scattering chamber. In going from the 17" to the 30" scattering chamber, ORTEC left the center region; that is the rotating vacuum feed throughs and the target mechanism on the 17" scale. This proved to be inconveniently crowded and it was decided to replace the existing target mechanism with a chrome plated brass cylinder and two Wilson seals. This rearrangement permitted larger targets and also allowed exchange of targets without letting the main chamber up to air.

- b. Beta and Gamma Spectroscopy, (J. E. Draper, J. A. McCray, C. G. Patten, N. F. Peek, G. Carlson, R. Fegley, M. Gillin, G. Smith, W. Sperry, and R. Warner)

The investigation of the energy levels of Sm^{145} begun with the 22-inch cyclotron has been completed and published.

The "beta-gamma box" and angular correlation apparatus has been used by Carlson for his thesis research on energy levels in Bi^{211} . The work consisted in coincidence angular correlation measurements of transitions in Bi^{211} done with J. McCray and measurement of the electron conversion coefficients done with J. Draper. The result of this work was to ascertain spins and parities of levels in Bi^{211} .

The beta-gamma box has been refined with the addition of an oil-less pumping system, improvements of the silicon detector resolution, and installation of variable thermal coupling between the LN and the detector. A representative spectrum is shown in figure 1 in which the electron resolution is 4.5 keV at 125 keV.

The primary effort was to prepare this system for experiments with cyclotron produced sources. Preliminary experiments have now begun.

* Summer Only

The Ge-NaI annulus has been remounted for use with the cyclotron. The Ge portion is now mounted on roller bearings and can accurately and easily be positioned. The system is distinctive in having a rather small NaI annulus for use with in-beam cyclotron experiments. However, it has excellent performance in both the anticoincidence mode (suppression of continuum while retaining fast timing) and pair mode. Results are shown in figures 2 and 3.

The modified internal mechanism for the precision beta ray spectrometer has been partially constructed. This mechanism permits operation of the spectrometer with a resolution as poor as 0.5%, allows much greater luminosities and at the same time focuses the electron beam on a solid state detector. Some of the electron focusing coils have been completed and tested. UCD-CNL 61 describes the design of the mechanism.

The radio chemistry laboratory is now operable and used mainly for chemical target processing. The target transfer apparatus is functional although a modification to its junior cave is necessary in order to disassemble the target blocks remotely.

The molecular plating technique for producing thin beta sources has been used successfully. In some instances where short half life materials were to be studied, it was found useful to plate the target material on a thin aluminum backing previous to the cyclotron bombardment.

Work continues on the excited levels of Gd^{156} (Peek), Gd^{154} (Sperry), Lu^{170} , Yb^{170} (Fegley), Pm^{142} and Nd^{142} (Gilllin) all of which are being produced by either (α , xn) or (p, xn) reactions with the 76" cyclotron.

c. Particle Gamma, (J. E. Draper, D. McCauley, G. Smith, R. Warner, and W. Wyckoff)

The dominant reaction from bombardment with high energy alphas or protons is (α , xn) or (p, xn). Since x can vary from 1 to 5 with the particle energy available from our cyclotron, and since the incident beam supplies up to ~ 20 units of angular momentum, a wide variety of isotopes can be produced at high excitation in high spin states. This permits a systematic study of families of isotopes with levels fed from high excitation energy and high spin, in contrast with studies of radioactive decay.

The large incident orbital angular momentum provides large alignments of spin. This affords the capability of measuring angular distribution of deexcitation gamma rays in a singles experiment which gives the same kind of information as the familiar coincidence angular correlation experiments in radioactive decay. It further provides a simple and precise means to measure the magnetic moment of excited states of a variety of nuclides by studying the precession of the angular distributions of the gamma rays when the sample is immersed in a magnetic field.

The shortness of the cyclotron beam bunch (less than 2.1 ns) also provides a powerful tool for studying lifetimes of transitions in the 2 to 200 ns range. This can be extended to longer lifetimes by sweeping the cyclotron beam to reduce the beam bunch repetition rate below the RF frequency by an integral factor.

Our initial objective is to study the gamma ray energy, time and angle distribution obtained with (alpha, xn) and (p, xn) reactions. We have now achieved this capability in preliminary form and have begun preliminary data. The electronics is shown in the block diagram of figure 4. By measuring the time distribution of elastically scattered particles into a plastic scintillator and timing with respect to the RF on the cyclotron dees, we have obtained the beam bunch time distribution shown in figure 5. This shows rather clean beam bunches with full width at half maximum of 2.1 ns. These beam bunches have been found to vary considerably in shape depending on the tuning conditions of the cyclotron, but have been found to be reasonably stable once the proper conditions have been achieved.

The scattering chamber for the particle detectors for beam diagnostics and for use in subsequent gamma coincidence experiments with inelastically scattered particles is now in use. The Ge gamma ray detector, fabricated here, is presently mounted for manual variation of angle (angle between beam direction and gamma direction) from 30° to 150°. The Ge detector is of the planar type in order to minimize variation of collection times. With this we have obtained time distributions of gamma rays, measured with respect to the RF, of 5.5 ns, full width at half maximum. We hope to be able to improve this since the cyclotron beam bunches are shorted by a factor ~ 2 .

It will also be necessary to remove the 'walk' from the system. We expect to achieve this by analog correction of the TAC.

Initial data taking was of the diagnostic variety, since the cyclotron and all of the experimental equipment are new. Since then we have taken preliminary data with 45 MeV alpha particles on a series of separated barium isotopes and a series of separated tin isotopes with additional data at 48 MeV. In order to sort out the components of the energy spectra among the various isotopes (i.e., the various values of x in $[\alpha, xn]$) it will be necessary to employ the variable energy feature of the cyclotron in approximately 5 MeV steps. Most of these data were taken at 90° with some auxiliary data at 140° . Examples are shown in figures 6 and 7. It is clear in these figures that several of the transitions are prompt and that several have longer half lives. The capability of separating the transitions according to time greatly facilitates the interpretations.

The experiments now under way concern the study of properties of gamma transitions and energy levels in Te nuclides from Te^{112} to Te^{126} and in Ce nuclides from Ce^{130} to Ce^{140} . These nuclides are inside, on the border, and outside of the proposed domain of deformed nuclei in this mass region.

- d. Neutron Scattering and Reactions, (C. Badrinathan, F. P. Brady, M. McGie, J. Morales, P. J. Symonds, J. Romero and J. C. Young)

The neutron beam facility at Davis has been given low priority during calendar 1967 in an effort to provide charged particle beams to the north cave area. Since external α particle beams were readily produced, but proton beams require cyclotron development time, the proton beams are just currently being developed. When the proton beam is available, a beam line, which has been installed, will bring it to focus on a liquid N_2 cooled gaseous deuterium target for production of the neutron beam. A clearing magnet and power supply have also been installed to sweep the protons out of the neutron beam. A five foot steel collimator, which forms the neutron beam, has also been placed in position. The gas target has been leak tested. The .005" dural windows successfully

hold 20 atmospheres, but leaks develop in the window joint when the target is cooled to liquid nitrogen temperatures. Aside from this difficulty the neutron beam line is ready.

Pending the establishment of a neutron beam at Davis, experiments in n-p elastic scattering and n-p bremsstrahlung have been performed at the 184" cyclotron at the Lawrence Radiation Laboratory, University of California, Berkeley (200 MeV neutrons). The experimental equipment used there is largely from Davis so that it can be readily adapted to use with the neutron beam here.

1. Neutron Detector Efficiency Measurements at 10-70 MeV, (F. P. Brady, J. A. Jungerman, J. Romero, P. J. Symonds, and J. C. Young)

The 200 MeV neutron beam at the 184" cyclotron at Lawrence Radiation Laboratory, Berkeley was used to measure the neutron detection efficiency of a plastic scintillator. The detector is to be used in neutron experiments at the Crocker Nuclear Laboratory. The results are given in UCD-CNL 59 and have been submitted to Nuclear Instruments and Methods for publication.

2. Neutron Proton Bremsstrahlung (C. Badrinathan, F. P. Brady and J. C. Young)

In recent years there has been considerable interest in p-p - bremsstrahlung (pp γ) as a means of studying off-mass-shell behavior of the p-p interaction and testing potential models of the latter. It is likely due to experimental difficulties that no measurements of the free np γ cross section have been reported. An experiment at Rochester (Kochler et al., Phys. Rev. Letters 18 [1967] 933) used a proton beam and a deuterium target to measure "almost free" np γ . From their results they estimated that the np γ cross section is roughly 50 times that of pp γ . Using the 200 MeV neutron beam of the 184" at LRL Berkeley we have measured the np γ cross section in the so-called Harvard geometry and also at a symmetric angles. For symmetric angles our preliminary results at 30°, 35° and 38° are approximately 25, 50, and 100 $\mu\text{b}/\text{sr}^2$ (Figure 8). They imply that the ratio $\sigma_{\text{np}\gamma}/\sigma_{\text{pp}\gamma}$ in this kinematic region is almost an order of magnitude smaller than found at Rochester. Direct comparison with their data is difficult because they detect protons and photons of energy $E_Y > 40$ MeV while protons and neutrons were detected here. At this time no theoretical predictions exist for this

geometry. A short communication containing our results is being prepared to be sent to Phys. Rev. Letters.

We plan to do npy at the Crocker Nuclear Laboratory when the neutron beam is ready.

3. Neutron Proton Scattering, (F. P. Brady, M. McGie, J. Morales, J. Romero and J. C. Young)

The n-p cross section is being measured at 200 MeV neutron energy at the 184" cyclotron at Berkeley. It is planned to repeat the experiment at lower neutron energies, 30-60 MeV at Davis.

4. Neutron Detector Efficiency Measurements at 25-175 MeV, (F. P. Brady, M. McGie, J. Morales, J. Romero and J. C. Young)

The efficiency measurements will extend the range to higher neutron energies. These are needed for the npy and np measurements being made at 200 MeV. Using Kurz's computer code will allow us to extend the efficiency to $E_n \gtrsim 200$ MeV. With this information an absolute measurement of the beam flux and hence the n-p cross section can be made.

- e. Atomic Beam, (D. McColm and G. Penaranda)

In the past year an atomic beam apparatus has been constructed: the vacuum system has been assembled and preliminary tests made; the magnet system is now being tested, and the internal arrangement of pole-pieces and electrodes has been completed. A bake-out oven has been built, and an effort to reach the 10^{-8} torr operating pressure is underway.

The beam tube used to carry the α -particle cyclotron beam to the target has been completed, and a test apparatus to evaluate prototype targets is operating satisfactorily. A counter system to detect the radioactive atomic beam is in preparation and will shortly be tested for background with this prototype apparatus.

- f. Experimental Tests of Quantum Electrodynamics (F. P. Brady, W. J. Knox and M. McGie)

1. Double Compton Scattering and Cross Section, (F. P. Brady, W. J. Knox and M. McGie)

The double Compton (DC) cross section was measured for 0.662 MeV incident photon energy and one set of detector angles. The data on this third-order process agreed with quantum electrodynamics (QED) to within the experimental error. The results were presented in Phys. Rev. 152 (Dec. 1966) 1190. More recent data at another set of detector angles is compared with theory.

2. Triple Compton, (F. P. Brady and M. McGie)

A fourth order process of QED has been measured. This might be named the Triple Compton (TC) because of its relationship to the Compton and Double Compton. In a TC event a photon interacts with an electron and is "split" into three photons. We believe this is the first observation of a fourth order QED free process.

The TC cross section has not been calculated although in principle the theory is straight forward. The 24 Feynman diagrams in the amplitude lead to 576 terms in the cross section. Professor Glen Erickson and Bob Devine (UCD Physics) have reduced this number by using symmetry but have found that the evaluation of even one term is very tedious.

A letter giving the experimental results has been submitted for publication. For photons of $E_\gamma = 13$ keV the average cross section for the geometry $(\theta_1, \theta_2, \theta_3, \phi_{12}, \phi_{23}) = (90^\circ, 90^\circ, 90^\circ, 120^\circ, 120^\circ)$ was found to be

$$\overline{\Delta^3_{\sigma 5}} = 8.1 \pm 2.4 \times 10^{-33} \text{ cm}^2/\text{sr}^3.$$

Here

$$\Delta^3_{\sigma 5} \equiv \frac{1}{\Omega_1 \Omega_2 \Omega_3} \int d\Omega_1 \int d\Omega_2 \int d\Omega_3 \int dE_1 \int dE_2 \frac{\partial^5 \sigma(E_0 E_1 E_2 \theta_1 \theta_2 \theta_3 \phi_{12} \phi_{23})}{\partial \Omega_1 \partial \Omega_2 \partial \Omega_3 \partial E_1 \partial E_2}$$

and the angle integrals are over $\Omega_1 = \Omega_2 = \Omega_3 = 0.378$ sr and $E_0 = 0.662$ MeV. In progress is the construction of a detector geometry which will allow a more accurate measurement.

g. Special Experimental Equipment

1. Detector Fabrication, (J. E. Draper and D. McCauley)

All aspects of Ge(Li) gamma ray detector fabrication were successfully performed this year. This included the slicing and shaping of Ge, Li diffusion and drifting, testing of detectors and utilization in thesis research projects involving a Ge(Li)-NaI angular correlation experiment and a Ge(Li) -NaI annulus apparatus.

Four Ge(Li) gamma ray detectors fabricated in this laboratory are available for use. Two nominal sizes were fabricated, one being 7 mm drift depth by 1 sq. cm, and the other being 7 mm drift depth by 5.2 sq. cm. These detectors have been planar detectors for use at the best possible time resolution in coincidence experiments. Present time resolution is 5-6 ns. The best energy resolution has been 1.5 keV at 122 keV and 2.7 keV at 1173 keV.

An important objective in this work is to develop thick charged particle detectors for high resolution measurement of high energy protons from the cyclotron. For this purpose a simple evaporation system has been built for depositing the gold surface barrier. In addition a variable-position alpha particle test chamber has been built for incorporation into the vacuum system of the detector. A detector is being drifted for this apparatus now. It will be drifted to within ~ 0.5 mm of the back face and a well will be etched into the compensated material with a thin evaporated gold layer. The detector will be tested with alphas in the above mentioned chamber. There will not be the loss of resolution which would otherwise be produced by a thin window. For use with the cyclotron a cryogenic holder with a thin window is being designed. It is expected that this will be supplied with LN by a flexible hose in the vacuum system, thus permitting the variation of the angular position of the detector with respect to the beam.

Another objective is to fabricate the largest Ge detector which will fit into the Ge-NaI annulus. The block has been diffused and sliced to exact size. It will soon be drifted.

The second drifter is now in operation and will be used to drift large area planar detectors for fast-timing, high-efficiency gamma-ray experiments.

2. Polarized Target Development, (O. Leifson, J. A. McCray, E. Vogel and R. Walraven)

Since the last progress report of August 16, 1966 the stainless steel liquid helium cryostat has been completed and initially leak tested. Microwave paramagnetic resonance has been observed in a cavity mounted on the dewar. Components of the system are now mounted on the magnet as they will be used during target operation. Crystal fabrication facility has been set up and is preparing crystals for testing. The magnet system with modulation coils has been set up and is operating.

The current status of the project and problems being worked on are:

1. A new microwave cavity, and horn are being constructed to more efficiently couple microwave energy into the cavity. The present cavity system is poor in that respect. It should be noted that this portion of the project remains a "cut-and-try" proposition.
2. Because of difficulties with the surplus APR-4 superheterodyne receiver to be used for the Q-Meter measurement of the nuclear polarization, an alternate method for initial use is being constructed.
3. Crystals will be tested to check on growth procedure, impurity content of chemicals and polarizations produced.

The primary goal for the remainder of calendar 1967 is to produce and measure large polarizations in the system. This will be with protons being polarized in $\text{La}_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{H}_2\text{O}$, with Nd^{3+} as the paramagnetic "impurity". (Nd^{3+} : LMN)

PUBLICATIONS

1. "Measurement of the Double Compton Cross Section"
by M. R. McGie, F. P. Brady and W. J. Knox
Phys. Rev. 152 (1966) 152, issued as UCD-CNL 53
2. "Elastic Scattering of 7-9 MeV Protons by Y^{89} ,"
by F. P. Brady, J. E. Draper and J. A. McCray
Nucl. Phys. A94 (1967) 449, issued as UCD-CNL 54
3. "Energy Levels in Sm^{145} from the decay of Eu^{145} ,"
by J. E. Draper, R. O. Mead and R. A. Warner
Nucl. Phys. A95 (1967) 209, issued as UCD-CNL 55
4. "Beam Steering with Quadrupole and with Rectangular Box Magnets"
by J. E. Draper
Rev. Sci. Instr. 37 (1966) 1390, issued as UCD-CNL 46
5. "Simple System for Dispersionless Deflection of Beam of Particles"
by J. E. Draper
Rev. Sci. Instr. 37 (1966) 969
6. "Construction and Operation of Thin Parallel Plate Proportional Counter"
by R. H. Hilberg, J. E. Draper, and W. J. Alston
Nucl. Instr. and Meth. 50 (1967) 121
7. "Elastic Alpha-Particle Scattering at 8.75, 9.35 and 10.15 MeV"
by F. P. Brady, J. A. Jungerman and J. C. Young
Nucl. Phys. A98 (1967) 241, issued as UCD-CNL 57 and 58
8. "New Internal Mechanism for the Davis Solenoidal Beta-ray Spectrometer
Including Post Momentum Analysis Beam Focusing"
by W. C. Sperry
UCD-CNL 61
9. "Directional Correlation Attenuation Coefficients with Ge Detectors"
by G. A. Carlson
UCD-CNL 74
10. " Pb^{208} (d, d) Pb^{208} Near $E_d = 2.225$ MeV"
by J. A. McCray and C. A. Barnes.
UCD-CNL 62

ARTICLES SUBMITTED FOR PUBLICATION

11. "Detection Efficiency of a Plastic Scintillator for 10-70 MeV Neutrons"
by F. P. Brady, J. A. Jungerman and J. C. Young
Submitted to Nucl. Instr. and Meth. and UCD-CNL 59.
12. "Directional Correlation Measurements in Bi²¹¹"
by George A. Carlson
Submitted to Nucl. Physics and UCD-CNL 77.

ARTICLES IN PREPARATION

13. "A Final Report on the Davis 22-Inch Cyclotron"
by J. A. Jungerman, L. J. Kibbe, W. J. Knox, N. F. Peek, E. O. Russell and J. L. Wood
UCD-CNL 56.
14. "The Relative n-p Cross Section at 193 MeV"
by A. R. Barnett, F. P. Brady, J. A. Jungerman, W. J. Knox, J. Romero and J. C. Young
UCD-CNL 60.
15. "Inelastic Scattering of 8 and 9 MeV Protons by Y⁸⁹"
by F. P. Brady, J. E. Draper, and J. A. McCray
UCD-CNL 63.
16. "Decay of Zr⁸⁹"
by J. E. Draper and J. A. McCray
UCD-CNL 64.
17. "Decay of Levels in Y⁸⁹ with the use of Y⁸⁹ (p,p' γ) Y⁸⁹"
by J. E. Draper, J. A. McCray and G. Smith
UCD-CNL 65.

B. Theoretical

The low energy theoretical physics program at Davis continues to progress in a satisfactory manner. The program supports five faculty members, four research associates at the post-doctoral level, and several graduate students. This progress report will describe the theoretical research at Davis from last fall to the present. The work which is expected to be done during the rest of this year and during 1968 will be discussed later in this report.

Professor Greider has been investigating various aspects of nuclear scattering theory, especially in relation to three-body problems. Three graduate students are at present working on problems in this field under his supervision. Mr. Peter Kazaks has been continuing a study of mathematical properties of the singular integral equations that arise in three-body problems. His work this past year has focussed on the spurious solutions that arise when a non-Fredholm integral equation is made to be solvable in Fredholm form. There is at present in the literature a paradox and some controversy over the existence and importance of spurious states. Mr. Kazaks' thesis work is helping to clear up this point and will be of considerable practical importance in solving three-body problems. Another graduate student, Mr. Frank Serduke has recently picked a research thesis subject on the use of the nucleon-nucleon t-matrix in a full shell-model calculation, instead of the nucleon-nucleon potential, which is presently used in the literature. That the t-matrix represents a better approximation than the potential in this type of calculation was discussed by Greider and Dodd in a Physical Review paper last year, Phys. Rev. 146 675 (1966), and is also the subject of a report being prepared by Professor Greider. This paper shows that the possible divergence problems inherent in solving a three-body scattering problem are also present when one expands the exact three-body (scattering or bound state) wave function in a truncated set of eigenfunctions of a simpler two-body subsystem, as is done in both the coupled-channel and in the shell-model calculations. The divergence problems can be overcome in these calculations, however, if the two-body t-matrix replaces the two-body potential for the interaction in the matrix

elements to be calculated.

A third student, Mr. Jonathon Storer, has been working this past summer on extending some of Professor Greider's earlier unpublished work on a Fourier-Bessel transform representation of two-body scattering amplitudes. This method is particularly useful at high energies in obtaining closed-form analytic expressions for the two-body t-matrix in terms of the potential. It is expected that this work can be extended to obtain the off-shell amplitude, or t-matrix, at high energies (>50 MeV), for which the analytic form should be of significant value in applications to three-body problems.

Professor Dodd's research has been concerned with various aspects of the non-relativistic three-body problem. A report, UCD-CNL 68, describing a soluble three-body model of stripping, arising from the earlier work of Professors Dodd and Greider, was submitted to the Internal Conference on Nuclear Physics, Gatlinburg, Tennessee, September 12-17, 1966. This work will be published in the conference proceedings.

An approach to making practical calculations for atomic and nuclear systems, based on the reduction of the Faddeev equations to an equivalent two-body problem for the elastic amplitude, has been investigated. In collaboration with Dr. Strobel, Professor Dodd has applied the theory to atomic deuterium, obtaining a closed-form expression for the effective interaction between the electron and deuteron, which takes into account the structure of the deuteron. The effects of the polarizability of the deuteron on the Lamb shift in deuterium have been calculated. Mr. Frank Serduke and Professor Erickson assisted with these calculations. This work has been written up as a report, UCD-CNL 79, and has been submitted for publication in the Physical Review.

Currently Professor Dodd is computing the binding energy of a one-dimensional system of three particles interacting through δ -function potentials. The problem is of interest for two reasons. First, although simple, this system includes the essential features of more complicated three-body systems. Second, for the special case of identical particles, analytic solutions are known which provide useful checks on

the validity of the approximation methods of the general theory. Mr. James Liu spent some time this summer on this project.

Professor Dodd is also using the SU_3 algebra of the three-dimensional isotropic harmonic oscillator to evaluate certain matrix elements in the theory of transfer reactions. This research depends on the results of Moshinsky relating the R_3 and SU_3 representations of the oscillator.

Professor Erickson and a number of graduate students and others at UCD (principally Mr. R. Devine, Mr. P. Chang, and Mr. H. Liu) have been active individually and collectively in the field of Quantum Electrodynamics. Personal contact has been maintained with other groups, notable the group SLAC, doing related work.

An example of the nature and results of these contacts has been the discovery of the possibility that the proton may have a "halo", a small part ($\sim 1\%$) of its charge distributed over much larger distances (~ 10 F) than the rest of the proton (~ 0.8 F). This idea was mentioned as a possible resolution of the discrepancy between theoretical and experimental values of the Lamb shift during discussions at SLAC, Yale, and UCD, and was found (by Professor Erickson) to be not inconsistent with the agreement between theoretical and experimental values of the hfs in hydrogen. This stimulated further work which has been summarized in a SLAC report (or UCD-CNL 85) which has been submitted to Physical Review by Professor Erickson with Dr. Brodsky of SLAC, Dr. Barrett of the Berkeley Radiation Laboratory, and Mr. Goldhaber of SLAC and Stanford University. These initial findings are that a proton halo is not merely not inconsistent with the relevant data but is even indicated by some of these data, including muonic X-rays in bismuth. More detailed and/or related works is being continued. For example, a graduate student at UCD, Mr. H. Liu, is working with Professor Erickson on the analysis (in terms of nucleon halos) of nucleon form factors at low momentum transfers.

Another example of individual work involving contact with others has been the calculation of triple Compton scattering by Mr. R. Devine, a graduate student of Professor Erickson. Unlike much work in Quantum Electrodynamics, both the experiment (see section 1-A-2-f of this report) and the calculations are being done in the same laboratory and there have been many useful discussions between Dr. M. McGie and Mr. Devine and the others involved. The lengthy calculations call for the Dirac algebra to be done on a computer using existing programs which have

been discussed with and obtained from their authors, Professor Hearn at Stanford University, Mr. Swanson at Stanford, and Dr. Levine at UCSD. The latter's Dirac algebra program was being prepared for our use at the Livermore Radiation Laboratory when Mr. Devine found that round-off error prevents the direct numerical evaluation by the computer of the algebraic output of any of the available programs unless costly double-precision techniques are used. The same problem also arises for the double Compton cross section radiative correction, or for any calculation involving as many terms in the output, and seems to provide an insurmountable limit to the usefulness of computers in evaluating higher order Feynman diagrams. Work is now being done to consider the relative merits of hand reduction of the output algebra for triple Compton scattering and of using approximations relevant to the experimental situation used.

In order to see if deviations from QED might be detected by the double Compton scattering experiments done here, UCD-CNL 53 and Phys. Rev. 152, 1190 (1966), Mr. Devine has been considering the radiative corrections which might mask the effects of modifications of QED. During this work, he has provided an independent verification of Mandl and Skyrme's lowest order calculation (of double Compton scattering) and has isolated the (infra-red) divergence in the radiative corrections and reduced the remainders to quadratures. The integrals can be numerically evaluated, but the entire results, as noted above, probably cannot be satisfactorily evaluated in general and approximations may be used to obtain the radiative corrections in the appropriate limits. In the course of investigating possible gauge-invariant modifications of QED, Mr. Devine has (tentatively) found that modifications considered by Kroll may have effects as large as 1% in single Compton scattering.

Mr. P. Chang has been investigating the existing calculations of the hyperfine structure of positronium and has calculated some of the higher order contributions. His results have not disagreed with Professor Erickson's estimate of $(2 \pm \frac{2}{\pi}) \frac{\alpha^4 \text{Ry}}{n^3}$ for the entire contribution of relative order α^2 . When this estimate is added to the lower order results of $\frac{\alpha^2 \text{Ry}}{n^3} \left[\frac{1}{6} - (\frac{16}{9} + \ln 2) \frac{\alpha}{\pi} \right]$, the recent measurement of $203,403 \pm 12$ MHz by Theriot, Beers, and Hughes, Phys. Rev. Letters 18, 767 (1967), may be used to yield a value of the (inverse) fine

structure constant $\alpha^{-1} = 137.0349 \pm 0.0060$, in agreement with the previous value $\alpha^{-1} = 137.0388$ but favoring the newer value $\alpha^{-1} = 137.0359 \pm 0.0004$ obtained from the ac Josephson effect measurement of $2e/h$ by Parker, Taylor, and Langenberg, Phys. Rev. Letters 18, 287 (1967).

Mr. Chang and Professor Erickson have also calculated the state-dependence of some contributions of the Bethe-Salpeter equation to level shifts in two-body systems. This has removed some uncertainties from the calculated Lamb shifts in the $n = 3, 4$ states and allows a relatively unambiguous interpretation of the measurement being made for ionized Helium at Yale.

Mr. George Drury has independently verified Professor Erickson's previous numerical evaluation of the various Lamb shifts and has also worked on resolving a discrepancy between a published calculation (without details) of the anomalous magnetic moment of the muon and an unpublished approximate calculation of Professor Erickson's.

Mr. H. Liu took over this muon moment problem and has resolved the discrepancy (in Professor Erickson's favor) by an exact calculation of the relevant double integral. The published value had been corrected in an Erratum (still without details) by the author, so Liu and Erickson's exact calculation will not be published, but is being prepared (with details) as a report, UCD-CNL 81.

Dr. G. Strobel, with Professor Erickson, has calculated cross sections for proton-proton bremsstrahlung, using Tabakin's proton-proton interaction and ignoring a difficult double scattering term. The work has been summarized in a report, UCD-CNL 75, and the abstract is published in Bull. Am. Phys. Soc. 12, 997 (1967) and Rev. Mod. Phys. (July 1967) with the proceedings of the International Conference on the Nucleon-Nucleon Interaction held in Gainesville, Florida in March of 1967.

The analysis of Hamiltonian Path-Integral Methods carried out by Professor Garrod, UCD-CNL 35, and mentioned in last year's progress report has been published in the Reviews of Modern Physics. He has also studied the possibility of avoiding the apparent contradiction (discovered by Currie and Sudarshan) between the principle of Lorentz covariance and the canonical Hamiltonian form of classical mechanics. He has shown that by formulating the theory in an explicitly covariant way one can avoid the difficulty, but

only at the price of introducing interactions which are non-local in time. This work has been written up as a report, UCD-CNL 71, and has been submitted for publication in the Physical Review.

Professor Garrod has continued his research on the variational calculation of reduced density matrices of many-particle systems. The work has advanced in two directions. First, in the special case of translation-invariant systems such as nuclei or quantum fluids the method can be simplified in important ways. This simplification was reported in an article recently published in the Physics of Fluids. The simplified variational method is now being applied to calculations of the ground state properties of small nuclei by Mr. Peter McReynolds under the direction of Professor Garrod. Secondly, a method developed by Professors Garrod and Percus is being applied to a numerical calculation of the ground-state density matrix of beryllium and will be used to calculate the density matrices of other closed-shell atoms.

Professor Garrod also presented three papers, UCD-CNL 82, UCD-CNL 83, UCD-CNL 84, on his work at the Density Matrix Conference held at the Queens University at Kingston, Ontario during August of 1967.

Dr. Paul Shanley joined the theoretical group at Davis last year. Dr. Shanley is interested in applying recently developed methods of solving the three-body problem to nuclear bound state and scattering problems. The approach being used is to parameterize the scattering amplitudes in each of the two-body subsystems in terms of separable potentials and to solve the resulting three-body integral equations numerically. The separable interactions are chosen to fit the low energy two-body equations to sets of one-dimensional integral equations. Some work involving deuteron elastic scattering and stripping has been done in collaboration with Professor Aaron of Northeastern University and has been written up as a report, UCD-CNL 73, and will be published in the Annals of Physics.

This preliminary work has been extended by Dr. Shanley to treat spin-dependent forces in higher partial waves of the two-body subsystems. Such an extension is necessary to treat the nucleon-nucleus interaction in a realistic manner. These spin-dependent equations are presently

being applied to deuteron-alpha scattering and to the energy levels of Li^6 . In this work the nucleon-alpha potential has been chosen to reproduce the low energy neutron-alpha phase shifts and polarization and the neutron-proton potential to fit the deuteron binding energy and the triplet scattering length. In this formulation there are as many as ten coupled integral equations in some partial waves and this represents a rather formidable numerical problem. These equations are presently being solved numerically and results are expected shortly.

Dr. Corbett, a research associate, who also joined the theoretical group last year, has been studying the structure of the non-relativistic three-body scattering problem within the framework of functional analysis. In particular, the properties of the Born series for the transition amplitudes have been examined. There are three types of Born series which can be constructed from the mathematical entities which make up the transition amplitude. The wave operators for the entrance or exit channels can be expanded in a series of operators. The complete state vector in the entrance or exit channels can be expanded in a series of vectors. The transition amplitude itself can be expanded in a series of matrix elements (complex numbers). A Born series can be defined for each of these structures. The operator Born series is well known because it is equivalent to the expansion of the total Green's function. As this last names operator series is divergent, it has often been stated that the Born series for the three-body transition amplitude diverges. Dr. Corbett has shown, using the theory of vector valued functions of a complex variable, that the divergence of the operator series does not imply the divergence of the other two types of series. Therefore, if the Born series for a transition amplitude is taken to be the series of matrix elements, and this is the series closest to the numbers obtained from experiment, then this result reveals that the Born series for the three-body process may be convergent.

This classification of series also removes a contradiction that had appeared in the literature when a counter example to the generally accepted divergence of the Born series was proposed. The general result refers to the operator series while the counter example was displayed through the convergence of a series of matrix elements. Dr. Corbett constructed a model of the counter example in a Hilbert space and showed that for this example the vector series is also convergent. This work has been submitted for publication in the Journal

of Mathematical Physics and has been written up in a report, UCD-CNL 80.

The same general results on the comparison between the convergence properties of the various types of series are applicable to the distorted wave Born series. Using the distorted wave formalism set up by Professors Greider and Dodd, Dr. Corbett is exploring the way in which the convergence of the vector and matrix element series can be improved through choices of the distorted potentials.

Professor Mitsuo Sano from Osaka University, Toyonaka, Japan, spent the past year at Davis in a post-doctoral position and worked on the structure of vibrational states of spherical nuclei. His work has been written up in a Crocker Nuclear Laboratory report, UCD-CNL 78, and will be submitted to Nuclear Physics for publication. This work is well summarized by the abstract to the report which is: Deviations from the random phase approximation are considered in the framework of the microscopic theory of the collective excitations of spherical even nuclei. Phonon-phonon and phonon-quasi-particle pair interactions are obtained by taking into account the difference of a quasi-particle pair operator from a pure boson. Corrections to the vibrational spectrum and wave functions are given by them. They are able enough to reproduce all of the observed orderings of the triplet (0^+ , 2^+ , 4^+) in the excited states. Formulae are also given for the electromagnetic moments and transition matrix elements of the nuclear states. Most of the numerical calculation, which was based on the conventional pairing plus quadrupole force, has been made for Cd^{114} . It was shown that fairly good agreement with experiment is obtained except for sign of the quadrupole moment in the first 2^+ state. We could not predict a sufficient large theoretical value of Q with negative sign. The large magnitude and the sign of the Q in the first 2^+ state are mainly determined by those of the mixing amplitudes of one- and two-phonon states. The relative sign of the amplitudes depends on the details of the interaction that causes the mixing of the one- and two-phonon states. It may not be difficult to think of the phonon-phonon interactions that predict the negative sign to Q .

Dr. George Strobel left this summer after spending two years at Davis. Besides working on theoretical problems which are described elsewhere in this report, Dr. Strobel continued his study of J-forbidden

stripping reactions. Dr. Strobel's previous works on this subject which was described in last year's report, have been published. He has also written up his recent work in a report, UCD-CNL 70, and has submitted it for publication in the Physical Review. During this time, Dr. Strobel developed a diagrammatic technique for summing a series of products of Clebsch-Gordan coefficients. This technique was written up in a report, UCD-CNL 69, and has been published in Nuclear Physics.

Dr. John Philpott and Dr. Paul Szydlik left Davis last fall after spending two years at Davis. Their work on oxygen 16 which was described in a report, UCD-CNL 51, has been published in the Physical Review.

Dr. Szydlik and Dr. Philpott also studied the excited states of He^4 and reported on this work at the 1967 meeting of the American Physical Society in New York.

Professor True spent the past year on sabbatical leave at M.I.T. While at M.I.T., Professor True continued to collaborate with Professor L. S. Kisslinger of Western Reserve University, who also spent the year at M.I.T., on their study of the odd-odd nuclei in the $A = 120$ region. The first phase of this work has been completed and is being written up as a report, UCD-CNL 87, and will be submitted for publication.

While at M.I.T., Professor True also applied the shell model to Pb^{206} . Pb^{206} had previously been described by True and Ford, Phys. Rev. 109, 1675 (1958). Since that time, new machines with better energy resolution and higher beam intensities along with advancements in detecting equipment enabled the experimentalists to find a discrepancy between the experimental results and the theoretical predictions. By including all the neutron orbitals between $N = 82$ and $N = 126$, it was shown that this discrepancy was essentially removed while still staying within the framework of the shell model. This work was written up as a M.I.T. report and has been submitted for publication in the Physical Review.

Professor True continues to collaborate with Professor Pinkston at Vanderbilt University in a study of Pb^{208} . This study has only met with partial success and is progressing rather slowly at present. It is hoped that some improved techniques and another approximation besides the random-phase-approximation will yield better agreement between theory and experiment.

J. C. Hafels and R. Woods, Phys. Letters 23, 579 (1966), point out that

6 levels in Bi^{209} around 2.60 MeV might be described by weakly coupling a $1h_{9/2}$ proton to the 2.60 MeV 3- octupole vibration of the Pb^{208} core. Professor True in collaboration with Professor Shakin and Dr. da Providência at M.I.T. worked out the theoretical details for this problem. The theoretical calculations did not agree with the experimental results. It is felt that the difficulty was because a correct description of the 3- octupole vibration of the Pb^{208} was not used. This work will continue when a better description of the 3- state in Pb^{208} is obtained.

Professor True has also collaborated with Dr. L. F. Chase of Lockheed Palo Alto Research Laboratory and Dr. E. K. Warburton of Brookhaven National Laboratory in a study of the low lying levels in B^{12} . A preliminary report on this work was given at the American Physical Society Meeting in New York in 1964. This work has been completed and has been written up as a preprint for publication. Using the experimental results and a code designed for triple correlation cascades, it was possible to determine the spin and parity of the 0.95, 1.67, and 2.62 MeV levels of B^{12} .

Professor True and Dr. Philpott will write up their work which describes the lower lying levels in Cr^{53} . This work was described in some detail in last year's report.

PUBLICATIONS*

1. "J Forbidden Stripping Reactions" (and "Theory of J Forbidden Stripping Reactions", UCD-CNL 48)
by G. L. Strobel
UCD-CNL 50 and Phys. Rev. 154 941 (1967).
2. "Hamiltonian Path-Integral Methods"
by C. Garrod
UCD-CNL 35 and Rev. Mod. Phys. 38, 483 (1966).
3. "Density Matrices of Quantum Fluids"
by C. Garrod
Phys. Fluids 9, 1764 (1966).
4. "Higher RPA Studies of the Structure of $O^{16} - I$ "
by R. J. Philpott and P. P. Szydluk
UCD-CNL 51 and Phys. Rev. 153, 1039 (1967).
5. "Soluble Three-Body Equations for Deuteron Stripping"
by L. R. Dodd
UCD-CNL 68 and Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee (1966).
6. "Radiative Level Shifts III. Hyperfine Structure in Hydrogenic Atoms"
by S. J. Brodsky and G. W. Erickson
UCD-CNL 42 and Phys. Rev. 148, 26 (1966).
7. "Distorted Wave Calculations of Low Energy Deuteron Stripping Reactions"
by G. L. Strobel
UCD-CNL 45 and Nucl. Phys. 86, 535 (1966).
8. "On the Convergence of the Born Series"
by J. V. Corbett
UCD-CNL 80 and to be published in the Journal of Mathematical Physics.
9. "Three-Body Effective Interaction in Deuterium"
by L. R. Dodd and G. L. Strobel
UCD-CNL 79 and to be published in the Physical Review.
10. "Covariant Hamiltonian Dynamics with Interactions"
by C. Garrod
UCD-CNL 71 and to be published in the Physical Review.
11. "A Lower Bound to the Pressure in One-Dimensional Systems"
by C. Garrod
UCD-CNL 76
12. "Density-Matrix Variational Principles at Finite Temperatures"
by C. Garrod
UCD-CNL 82 and presented at Density Matrix Conference, Queens University Kingston, Ontario (1967).

13. "Properties of the 2-Matrix Due to the Integer Character of Occupation Numbers" by C. Garrod
UCD-CNL 83 and presented at Density Matrix Conference, Queens University, Kingston, Ontario (1967).
14. "Variational Calculations with Density Matrices"
by C. Garrod
UCD-CNL 84 and presented at Density Matrix Conference, Queens University, Kingston, Ontario (1967).
15. "Vibrational States of Spherical Nuclei"
by M. Sano
UCD-CNL 78 and to be published in Nuclear Physics.
16. "Three-Body Approach to Direct Nuclear Reactions"
by P. E. Shanley and R. Aaron
UCD-CNL 73 and to be published in Annals of Physics.
17. "Construction of Invariants from Clebsch-Gordan Coefficients"
by G. L. Strobel
UCD-CNL 69 and Nucl. Phys. A96, 229 (1967).
18. "Target Interaction Calculation of J Forbidden Reactions"
by G. L. Strobel
UCD-CNL 70 and to be published in the Physical Review.
19. "P-P Bremsstrahlung Using a Separable Nuclear Interaction"
by G. L. Strobel and G. W. Erickson
UCD-CNL 75, abstract included in the International Conference on the Nucleon-Nucleon Interaction, Gainesville, Florida (1967), Bull. Am. Phys. Soc. Ser. II, 12, 997 (1967), and Rev. Mod. Phys. (July, 1967).
20. "Shell Model Prediction of the Excited States of He⁴"
by P. P. Szydluk and R. J. Philpott
Bull. Am. Phys. Soc. Ser. II, 12 47 (1967).
21. "Exact Evaluation of the Lowest Order Vacuum Polarization Contributions to the Magnetic Moment of the Muon"
by G. W. Erickson and H. T. Liu
UCD-CNL 81.
22. "Corrections to Muonic X-Rays and a Possible Proton Halo"
by R. C. Barrett, S. J. Brodsky, G. W. Erickson, and M. H. Goldhaber
SLAC report (or UCD-CNL 85) and to be published in the Physical Review.
23. "Spin Assignments of the B¹² 0.95, 1.67 and 2.62 MeV Levels"
by L. F. Chase, Jr., R. E. McDonald, W. W. True, and E. K. Warburton
preprint (or UCD-CNL 86) and to be published in the Physical Review.

24. "Shell-Model Theory of Ph^{206} . II"
by W. W. True
M.I.T. LNS report and to be published in the Physical Review.
25. "The Effective Neutron-Proton Interaction as Determined from Odd-Odd Nuclei"
by L. S. Kisslinger and W. W. True
UCD-CNL 87 and to be published in the Physical Review.

*The work related to the first seven publications were described in the 1966 annual report.

II. Scope of Work

A. Experimental

1. 76-Inch Cyclotron Operations

The budget proposed provides for operation of the 76" cyclotron for 16 hours per day 5 days a week. The swing shift operation is minimal in that only a professional cyclotron operator and a student assistant are provided with no electrical or mechanical support. Such support will be available on a "call back" basis only.

While alpha particle beams will continue to be provided in increasing energy range to the north cave experimenters, an increasing effort is planned for calendar 1968 in the extraction of protons. These particles will be useful in almost all experimental areas.

Interest continues in the laboratory in the acceleration of polarized ions and a request is made for purchase of a polarized ion source. The polarized ions would be axially injected through the roof shielding and upper magnet yoke into the cyclotron center as described in last year's report. The polarized beam transport system through the yoke using electrostatic quadrupole lenses is sufficiently well understood by Berkeley experience that we are planning to proceed with purchase of a power supplies for such lenses with funds presently available and previously allocated for this purpose.

A prototype steering magnet has been constructed here. Such magnets will be fabricated during calendar 1967 and installed on beam lines in calendar 1968 to provide vertical and horizontal beam centering. Experience has shown that adjustments provided by such magnets will be quite useful for the experimenters in rapid alignment of an experiment.

A budget request is also made for purchase of a valley coil power supply. The flutter control provided by actuating the valley coils may be quite useful in extraction of the highest energy proton beams. However additional operating experience is needed before the necessity of these coils is demonstrated.

2. Experimental Research Program

a. Charged Particle Reactions, (C. Badrinathan, F. P. Brady, T. Cahill, A. Springer, P. Martins and P. J. Symonds)

In the future we plan to use 50 to 75 MeV proton beams to study (p, t), (p, He³), and (p, He⁴) reactions and we are planning to improve the scattering chamber vacuum by purchasing a 560 liter/second turbomolecular pump.

In case there is a delay in extracting the proton beams, we will investigate the (α , α'), (α , He³), (α , d), and (α , p) reactions on the light nuclei until the proton beam is developed.

It is proposed to investigate the A=4 system through measurements of the differential cross-section in the p-He³ system. In the energy region from 14 to 23 MeV, significant amounts of data have been collected on the spin dependence of the p-He³ system, but this data is rendered practically unusable due to a persistent lack of good cross-section data. Experiments have been completed on the proton polarization in the p-He³ system at 6 energies by groups at Los Alamos, Berkeley, and Saclay, and recent data have been taken at Saclay on the spin correlation parameters A_{yy} and A_{xx} as well as recoil He³ polarization. The preliminary analysis is complete, there are strong indications that the only differential cross-section data taken in this energy region, at 19.4 MeV, are not good enough to fix the S-wave phase shifts. It is proposed to make these measurements in the ORTEC 30" scattering chamber, using the existing detectors and Faraday cup, but constructing a compatible low-pressure gas target and a new set of collimators for the detectors.

It is also proposed to study the scattering of charged particles at angles up to 180° by means of minor modifications to the existing vacuum tank of the 50° bending magnet and the construction of a small auxiliary chamber. To obtain the value at 180°, the target is placed in a magnetic field such that the recoiling particles are well separated from the incident beam, a technique familiar from electron scattering work. The first investigation would center around the 180° anomaly observed in the scattering of medium energy α particles by light nuclei. The ratio in the last minimum of the cross section at 168° to the estimated value

at 180° is about 80 for 49.7 MeV α particles on O^{16} , and the α -cluster calculations of Honda et al. fail to predict either the form or the remarkable enhancement observed. Further information is required on the existence of this effect in nuclei other than C^{12} or O^{16} , which are amenable to α -cluster calculations, and on the energy dependence of the effect. The angles near 180° would be extended through the use of the present 30" scattering chamber.

- b. Beta and Gamma Spectroscopy, (J. E. Draper, J. A. Jungerman, N. F. Peek, C. G. Patten, R. Fegley, M. Gillin, D. McCauley, W. Sperry, W. Wyckoff)

It is proposed that the beta and gamma ray spectroscopy program will continue as before. Mr. Sperry left the University without finishing his work on Gd^{154} , but has returned and will be with the Laboratory until December, at which time it is expected that he will finish his thesis project and obtain his Ph.D. degree. It is highly probable that Mr. Fegley will finish the Lu^{170} , Yb^{170} project by the end of 1968 in order to obtain his Ph.D. degree. Mr. Gillin has just initiated the study of excited levels of Pm^{142} and Nd^{142} .

Work will be performed using the beta gamma box and the beta ray spectrometer with a new internal mechanism as complementary instruments for determinations of energies, spins, and parities of the nuclear levels.

Of the tests remaining to be made on this system one involves the use of a long awaited ^{228}Th source to more precisely determine its efficiency and peak to continuum ratio in the pair mode, and another pertains to the amount of shielding required for in-beam spectroscopy. When these are completed, the system will be incorporated into the (α, xny) experiments in progress.

The work on the development of $Ge(Li)$ charged particle detectors will proceed as outlined in the progress report, as will the fabrication of large volume gamma-ray detectors. As they become available, larger detectors will be installed in the cryostats used with the NaI annulus and the beta-gamma box. Detectors will also be needed for at least three additional cryostats: two for use in particle-gamma angular-distribution measurements, and one for gamma-ray spectroscopy independent of the beta-gamma box. The ability to restore faulty or damaged detectors will continue to be a great asset, especially since it can be done in a short time if necessary.

c. Particle Gamma, (J. E. Draper, A. Sauter, G. Smith and R. Warner)

Work will continue on the levels in the even, neutron-deficient isotopes of tellurium and cerium, in order to explore the limits of the deformed region predicted for $Z > 50$, $N < 82$. The development of heavy ion beams would make possible the study of many new nuclides in this region. Data already collected indicate that transitions in the odd isotopes will also be easily observed. However coincidence work will probably be required before energy levels can be located in odd isotopes, which makes it desirable to have the capability for multiparameter (time, $E_{\gamma 1}$, $E_{\gamma 2}$) data accumulation. The current experiments use 512 analyzer channels for energy information (needed to exploit the energy resolution of the Ge detector) and 8 channels for time. The 8-channel digital sorter is used in the time leg to provide four narrow time channels during and immediately after the beam burst, and four channels whose width increases with increasing time. This gives an effective increase in resolution for short decay times, and still enables the measurement of longer decay times. A multiparameter data system will allow the use of up to 4096 channels in both the energy and time legs, which will make it practical to sweep the cyclotron beam for measurement of lifetimes longer than one RF period in parallel with the measurement of lifetimes comparable to the time resolution of the Ge detector.

Eventually, lifetimes down to $\approx 5 \times 10^{-12}$ seconds will be measured by a recoil method similar to that used by Alexander and Allen. The clean vacuum required for this type of experiment dictates the installation of a new vacuum pump and cold trap on the scattering chamber. This equipment will also be required before cooled particle detectors can be installed in the chamber.

Data valuable for the understanding of the associated reactions will be collected in the course of all of the spectroscopic studies planned. There is still insufficient data available to adequately check the theories on the deexcitation of highly excited compound systems. Improvements to the apparatus in use which will take place in the immediate future include remote positioning mechanisms for the target ladder, particle detector and Ge(Li) gamma ray detector, and additional electronics to improve timing measurements and allow higher counting rates. Plans for this work are nearly complete.

- d. Neutron Scattering, (F. P. Brady, C. Badrinathan, T. Cahill, J. A. Jungerman, J. Morales and J. Romero)

1. n-p Bremsstrahlung

A neutron beam will be developed at the Crocker Nuclear Laboratory. The equipment being used to complete the np γ experiment at the 184" in Berkeley can be used to do the experiment here at 25 and 50 MeV. At the present our experiment at Berkeley is the only np γ work completed. These measurements are essential to study the n-p interaction off the mass shell.

2. $n+p \rightarrow d+\gamma$

The off-mass-shell studies of the np γ process will be supplemented by this reaction, which measures the matrix elements further off the mass shell.

3. n-p Scattering

There is room here for improvement in the phase shifts (on the mass shell). The well defined beam energy, good duty cycle and RF bunching will allow us to do accurate work in the 20-60 MeV region.

4. n-x Scattering

In attempting to make double scattering corrections to our np γ data we discovered how scarce were the elastic neutron scattering cross sections above 14 MeV--even on common elements such as carbon, oxygen, etc. Not only are these of interest and use in nuclear research but are also necessary in nuclear technology. n-d elastic scattering will also be included.

It is planned initially to measure total cross sections as a function of neutron energy, and later investigate the angular distributions.

5. Measurement of P

When the polarized target is operating the unpolarized neutron beam can be used to measure the polarization in n-p scattering by observation of the left-right asymmetry in the scattering of the recoil protons. This can be done for large c.m. angles most readily where the recoil protons have the greatest energy. Using the variable energy neutron beam, P can be measured for several incident neutron energies in the 30-60 MeV region.

6. Measurement of C_{np}

If time permits, explorations are planned to develop a polarized neutron beam (by p, n reaction or elastic scattering). If adequate intensities can be produced, measurement of the spin correlation parameter C_{np} would

be attempted. This parameter has only been recently measured at 23 MeV and further work at higher neutron energies would be quite useful in order to better fix the parameter describing the n-p force and to test if the n-p nuclear interaction is equal to the p-p interaction or not.

e. Polarized Target, (O. Leifson, J. A. McCray, E. Vogel and R. Walraven)

We plan to be tuning up the system for actual operation with a neutron beam early in 1968.

Although the system will constitute an operating target, the target crystal itself is far from optimum from the point of view of ratio of polarized protons to other nuclei present. Organic materials would appear to be far more desirable although initial work (P. L. Scott, thesis - University of California, Berkeley, 1961 unpublished) was not promising. More recently (R. J. Wagner, R. P. Haddock, Physical Review Letters 16, 1116 1966) some success has been obtained largely because of the larger fields used. That the effect is not yet well understood is indicated by the discontinuity in the electron relaxation time graphs in reference 2 as well as in more recent work (Chester F. Hwang, D. A. Hill, Physical Review Letters 18, 110 1967).

Hence we propose to prepare some free radical in plastic samples (suitable for target use) and attempt to produce large polarizations. This should not entail purchasing any major equipment, since it can utilize presently operating equipment. There will be liquid helium and nitrogen required at the approximate rate of 25 liters liquid helium and 50 liters liquid nitrogen per month. The initial free radical tried will be DPPH dissolved in polystyrene. We will attempt to reduce the atomic oxygen content (this acts as an undesired impurity) by using low density polystyrene and sample preparation under vacuum.

Certain aspects of the Nd^{3+} : LMN system are only qualitatively understood, also. We propose to examine some of these in the course of sample testing and apparatus tuning up, to compare results with the phenomenological theory (C. D. Jeffries, Technical Report No. UCD-34P20-T-1, September 23, 1966).

f. Atomic Beams, (D. McColm and G. Penaranda)

Preliminary cyclotron runs to evaluate targets and counting system

design are planned for the early fall 1967 concurrent with the use of atomic beams of stable cesium in the atomic beam apparatus to evaluate its performance. Late in the fall, cyclotron runs on one of the short-lived cesium isotopes are planned with a purpose of measuring its spin (the most easily produced isotope will be chosen). A lamp system will be installed in the winter, and runs on the isotope shift for this most easily produced isotope are planned for the spring 1968.

B. Theoretical

This part of the report will describe what the theoretical group at Davis plans to do during the rest of 1967 and during 1968. Since many of the research projects are of a continuing nature and have been described previously in this report, these projects will only be summarized briefly.

Professor Greider's students will continue work on their thesis problems during the next year. Mr. Kazaks is sufficiently close to finishing so that he is expected to write up his work on the spurious solutions to integral equations for his Ph.D. thesis during the year. Mr. Serduke will continue on the shell-model with a t-matrix interaction and should have some calculations completed during the next year.

A preliminary report of the Fourier-Bessel transform method will be written in the near future by Professor Greider, and Mr. Storer will investigate the off-energy-shell extensions of this method.

Professors Greider and Dodd will write up and publish the work on the cross sections for heavy-ion nucleon-transfer reactions that includes both finite range for the nucleon-nucleus interaction as well as the effect of the recoil of the cores.

In the coming year Professor Dodd will continue his work on the three-body problem. In particular he wishes to extend his calculations for the δ -function model to the case of scattering and to carry out a quantitative comparison of various nuclear reaction models within the framework of this one-dimensional system. He also intends to apply his work on effective potentials to the problem of the determination of the deuteron optical potential. Finally he hopes with Professor Greider to complete their study of transfer reactions.

Professor Erickson and others (including R. Devine and H. Liu) will continue their activity in Quantum Electrodynamics and their communication with related groups at SLAC, Yale, and other laboratories.

Investigations related to a proton halo will be extended by Professor Erickson, including analyses of nucleon form factors with H. Liu and study of the possible causes (low mass virtual particles, anomalous two-photon interactions, etc.) of a proton halo, perhaps with Dr. Brodsky of SLAC.

Mr. Devine will continue his calculations of the effects of modifications of QED on the various Compton scattering experiments and will write up the

results in a thesis, possibly by the summer of 1968. His study of the limited usefulness of computers in evaluating Feynman diagrams will be continued and included in reports.

Professor Erickson will continue to serve as a "clearinghouse for information on the Lamb shift". In particular, the He^+ experiments at Yale and the $Z \gg 1$ experiments being planned at Arizona will be considered.

The HFS of positronium is being measured even more accurately at Yale, so Professor Erickson and/or his students may calculate a better value of the higher order contributions when the present "educated guess".

Mr. Liu will continue his calculations on nucleon form factors and his investigations of vacuum polarization effects, but will concentrate his work on a thesis topic to be selected this fall.

The work, just begun by Mr. McReynolds, on the ground-state density matrices of small nuclei will be continued under Professor Garrod's direction. The calculation of the beryllium ground-state density matrix is proceeding reasonably well and should produce the first numerical check of density matrix variational methods. Professor Garrod intends to study the rotational symmetry properties of density matrices derived from angular momentum or spin eigenstates.

Dr. Shanley intends to continue his study of deuteron-alpha scattering and to calculate the phase shifts and vector and tensor polarization for this process.

It is also intended to study the break-up reaction $d + \alpha \rightarrow n + p + \alpha$ by an extension of the elastic scattering equations. This process is interesting because the final state contains overlapping resonance which can be studied exactly by three-body methods.

Since the three-body formulation treats spin effects exactly, Dr. Shanley intends to study spin-dependent effects in deuteron stripping reactions, including the effect of the neutron-proton tensor force.

Although the results obtained by Dr. Corbett on the convergence of the various series associated with a transition amplitude are mathematically exact, the techniques used in this work are amenable to calculations of specific radii of convergence for only the simplest physical problems. Dr. Corbett is therefore searching for simpler ways of computing the radii of convergence.

From a preliminary examination of the vector and matrix element series for rearrangement collisions at large angular momenta, the transition amplitude appear to be well represented by the Born approximation. Dr. Corbett proposes to test this preliminary result in greater detail, and also to use these series to check if the Born approximation is valid at high energies. The investigation of the dependence of the radius of convergence of the distorted wave Born series on the distorting potentials will be maintained.

Dr. Corbett, in collaboration with Mr. E. Thiel of the UCD Mathematics Department, is planning to use Rigged Hilbert spaces to describe scattering processes. These spaces are interesting because they give a well defined meaning to the generalized eigenfunctions associated with the continuous spectrum of the Hamiltonian operator. By using these spaces they hope to be able to give a more rigorous discussion of some of the properties of scattering systems.

Professor True will continue his studies of the nuclear structure of the bound states of nuclear systems and continue the projects which were mentioned earlier in this report.

Professor True also plans to investigate methods and approximations which will give a better description to nuclear matter than the current nuclear models.

Dr. S. A. Lebedeff has just joined the theoretical group here at Davis after three years of post-doctoral work at NYU. Dr. Lebedeff shall continue the investigation of the possibilities to use the time dependent formulation of the collision theory to obtain semi-classical approximations for the potentials that are not spherically symmetric and may depend on time. The validity of these methods will be tested on some simple problems, by comparing them with the exact solution and with the WKB approximation. As another problem he will investigate the possibility of developing a numerical method for the rapid determination, with the help of continuous fraction interpolation, the positions of the Regge poles in the potential scattering.

Dr. D. M. Clement will join the theoretical group at Davis this fall after finishing his graduate work at the University of Pittsburgh. It is anticipated that Dr. Clement will continue to work in the general field of the relationship between nuclear models and nuclear structure.

The proposal submitted includes summer salaries for Professors True, Greider, Dodd, Erickson, and Garrod. Full time support is requested for four post-doctoral people: Dr. Clement, Dr. Corbett, Dr. Lebedeff, and Dr. Shanley. Half-time support for a Senior Clerk and summer support and partial support during the school year for six graduate students is requested. Funds for travel, computing, publication expenses, and costs of supplies and equipment are also included.

Fig. 2. Anti-Compton and singles spectra of ^{137}Cs . The suppression of the Compton distribution ranges from a factor of 2 to 4.

Fig. 3. Pair spectrometer and singles spectra of ^{228}Th . The pair spectrum was accumulated for a longer time than the singles spectrum, due to the reduced efficiency of the detector when operated in the pair mode.

BLOCK DIAGRAM: GAMMA-RAY ENERGY VERSUS TIME

Fig. 4. Block diagram of equipment used to obtain spectra displayed in Figs. 6 and 7. Double lines mark paths of linear signals, and single lines mark logic paths.

Fig. 5. Pulse height distribution from a time-to-amplitude converter started by photomultiplier pulses from elastically scattered alphas and stopped by pulses derived from the cyclotron dee voltage. Counts arriving later in phase with respect to the dee voltage are found on the left side of the figure. There is a cross marking every tenth analyzer channel.

Fig. 6. The 512 channel (energy) by 8 channel (time) gamma-ray spectrum produced by bombardment of a powdered $\text{Ba}(\text{NO}_3)_2$ target, enriched to 99.8% in ^{138}Ba , with 45 MeV alpha particles. Note that not all time channels have the same width. This effective increase in resolution in the early time channels is made possible by the use of the spectrum sorter.

Since these are preliminary spectra energy assignments are approximate (± 5 keV); also, no attempt is made here to assign these lines to transitions in particular isotopes.

Fig. 7. The gamma-ray spectrum obtained by bombardment of a SnO_2 target enriched to 78.8% in ^{117}Sn with 45 MeV alpha particles. This spectrum is otherwise similar to that in fig. 6.

N-P- BREMSSTRAHLUNG CROSS SECTION
MEASURED IN THE HARVARD GEOMETRY

FIG. 8

$(\theta_N = \theta_P = \theta_{Lab})$ for $E_N^{(Inc)} = 208 \text{ MeV}$

THE INDICATED ERRORS ARE STATISTICAL
ONLY