CYCLOTRON RESEARCH

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Department of Physics

Cyclotron Research

PROGRESS REPORT FOR YEAR ENDING JUNE 15, 1959

PROGRAM "A"--EXPERIMENTAL PHYSICS PROGRAM (CYCLOTRON)

UNDER

U.S. ATOMIC ENERGY COMMISSION CONTRACT A.T.(45-1)-293

PREFACE

This report reviews the work done at the 60-inch cyclotron at the University of Washington during the year ending June 15, 1959.

The general areas of investigation remain in good part the same as they have been for the past several years, but some rather new problems are being looked into in virtually every area. For example, the "beta-ray" group has been looking into problems of beta decay and nuclear reactions through measurements of the longitudinal polarization of beta particles and the circular polarization of gamma rays.

Among the variety of results that have been obtained in the field of fission physics, perhaps the most striking is the extreme steepness of the fission excitation curves in bismuth and lighter elements.

Other studies of nuclear reactions include: (1) the setting of an upper limit to the part of the strong interaction Hamiltonian that is not invariant under time reversal (this was done by the detailed comparison of the angular distributions in a chosen reaction and its inverse); (2) the observation that Be^7 fragments are emitted with sizeable cross sections in alpha particle bombardments of oxygen and aluminum; and (3) the study of the (α, 2p) reaction in targets around nickel by means of coincidence techniques. The results of the (α, 2p) study seem to suggest that most of the protons observed in the bombardment of Ni^{58} are "evaporated" from a compound nucleus.

In addition to these and other investigations of reactions, there has been considerable work on the scattering of alpha particles. In one of these studies the anomalous inelastic excitation groups have been observed in rather light elements.

Another of the newer activities being pursued this year at the cyclotron involves the study of stopping powers. A new method is being developed to measure stopping powers directly (i.e., without the usual subtractions) by a determination of the momentum transferred to a foil by a beam of measured intensity.

A considerable amount of effort is being spent on the development of new equipment which is necessary for experiments. The new 60-inch scattering chamber is installed and operating. A magnetic heavy particle spectrometer is being built and so is a neutron time-of-flight apparatus.

Research at the cyclotron is performed by the staff members and graduate students of the University of Washington Physics and Chemistry Departments. Present support for the Cyclotron Project comes entirely from the State of Washington and the Atomic Energy Commission.

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BETA-RAY AND GAMMA-RAY SPECTROSCOPY

1. Introduction

During the past year the so-called Beta-Ray Group has completed a difficult positron polarization experiment on oxygen-14. It then branched out into several new areas of experimentation where each individual in the group assumed the primary responsibility for one of the experiments, while still retaining a strong interest in the whole program. The new experiments now underway are in several instances the direct result of the experience gained in the course of the oxygen-14 work. In addition, each piece of equipment for the latter work is being utilized in one or another new capacity.

2. The Polarization of O^{14} Positrons Which Annihilate in Flight

In our 1958 Progress Report a preliminary account was given of an experiment to measure the longitudinal polarization of positrons from the 1.8-Mev transition of O^{14} (see Fig. 1). This work was completed during the past year and was reported at the Los Angeles Meeting of The American Physical Society in December[1] and is also the subject of a paper to be published shortly in The Physical Review.[2] It is appropriate, however, to review the experiment briefly in this report inasmuch as several of the experiments described below are direct outgrowths of the polarization experiment.

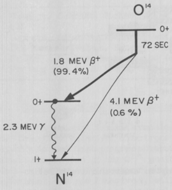

Figure 1

Decay scheme of O^{14}.

Our motivation for determining the O^{14} positron polarization was the hope of clarifying the nature of the parity properties of the Fermi beta-decay interactions. The O^{14} 0+ → 0+ transition is one of the few allowed decays involving only the Fermi interaction and is certainly the best known. Consequently this transition is an ideal subject for the investigation of a problem with great theoretical interest and considerable experimental difficulty. The currently accepted two-component neutrino theory predicts that the O^{14} positrons will have longitudinal polarization (v/c), and our experimental work was designed to test this hypothesis.

Two severe experimental problems had to be surmounted in the course of this work. The first was to produce a source of the short-lived O^{14} that could be maintained continuously at high intensity. This was accomplished by a continuous gas-flow system in which N_2 was fed to the cyclotron where it was bombarded with 11-Mev protons. O^{14}, produced in the gas by the N^{14} (p,n) O^{14} reaction, was carried off in the gas stream, filtered and combined with H_2 to form water vapor. Finally the gases containing the active water vapor were passed over a cooled copper button in the experimental apparatus where the H_2O^{14} was trapped. In this manner 7 millicurie sources of O^{14} were produced which could be maintained for days at a time. The success of this production scheme has been important in making feasible two further experiments with O^{14} discussed below.

A second experimental difficulty was presented by the 2.3-Mev gamma ray which promptly follows each O^{14} positron. If allowed to enter the polarization apparatus along with the positrons, this gamma ray would mask the effect we wanted to observe, so it was essential to separate the positrons and gamma rays by means of the small magnetic spectrometer shown in the diagram of the apparatus (Fig. 2). Of course the spectrometer, in addition to separating positrons and

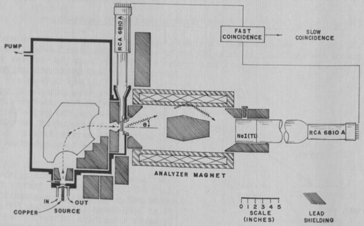

Figure 2

Schematic diagram of apparatus to detect Compton scattered annihilation-in-flight radiation.

gamma rays, selected positrons only over a small range of energies, thus increasing the already stringent source strength requirements. However, this loss was partly compensated by the advantages gained by being able to analyze the data for only the one focused energy used (1.2 Mev).

As indicated in Fig. 2, the 1.2-Mev positrons were focused on a plastic scintillator where they were allowed to annihilate. A small fraction of them annihilate in flight producing characteristic high energy gamma rays in the forward direction and characteristic small pulses in the plastic scintillator. The gamma rays, which are circularly polarized if the positrons are longitudinally polarized, passed into the interior of a cylindrical analysing magnet where they were Compton scattered from the polarized electrons in the iron magnet walls. By means of conventional fast-slow coincidence circuits the spectrum of pulses in the NaI counter from scattered gamma rays in coincidence with small pulses in the plastic scintillator was observed. The asymmetry in this coincidence spectrum upon reversal of the analyser magnet field was in this way found to be (1.94 ± 0.46) percent.

The observed asymmetry in the scattered gamma radiation is related to the amount of circular polarization of the gamma rays and hence to the amount of initial longitudinal polarization of the positrons. The exact relation between these quantities was calculated with the aid of a high speed digital computer, and the positron polarization corresponding to the observed asymmetry was found to be (0.73 ± 0.17) (v/c). The error quoted here represents only the statistical uncertainty of the data. Though this result is somewhat less than the (v/c) polarization expected from the two-component neutrino theory it may be influenced by unknown systematic errors. It is consistent with the few other data on polarization in Fermi transitions that are available.[3]

In order to further clarify this result a second measurement of the O^{14} positron polarization by the method of Bhabha scattering is underway which makes use of part of the apparatus described above. This experiment is discussed in more detail below. (H. Bichsel, J. B. Gerhart, J. C. Hopkins, and F. H. Schmidt)

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1 Gerhart, Schmidt, Bichsel, and Hopkins, Bull. Am. Phys. Soc. Ser. II, 3, 406 (1958).
2 Gerhart, Schmidt, Bichsel, and Hopkins, Phys. Rev. (to be published).
3 Deutsch, Gittelman, Bauer, Grodzins, and Sunyar, Phys. Rev. 107, 1733 (1957); Frankel, Hansen, Nathan, and Temmer, Phys. Rev. 108, 1099 (1957); and R. S. Preston and S. S. Hanna, Phys. Rev. 110, 1406 (1958).

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3. The Study of Electron Polarization by Møller and Bhabha Scattering

An experiment for determining the polarization of O^{14} positrons by scattering them from polarized electrons in a thin magnetized iron foil was outlined briefly in the last progress report. This experiment was postponed, however, to permit completion of the O^{14} positron polarization experiment described above and work on the scattering experiment did not begin again until last winter. The new experiment, as now conceived, will permit the determination of either electron or positron polarizations at several incident particle energies, including the 1.2-Mev positron energy employed earlier with O^{14}. In addition to the O^{14} polarization it is planned to use this apparatus to study the polarization of P^{32} electrons as a function of (v/c). As well as providing data on the velocity dependence of the P^{32} electron polarization, this will allow a comparison of the performance of this apparatus with similar experiments done elsewhere. This comparison was not possible for the apparatus used earlier to detect the O^{14} positron polarization.

The scattering apparatus (see Fig. 3) includes the small beta-ray spectrometer used in the earlier polarization experiment. The approximately monoenergetic positrons selected by the spectrometer pass into a solenoidal magnetic lens and

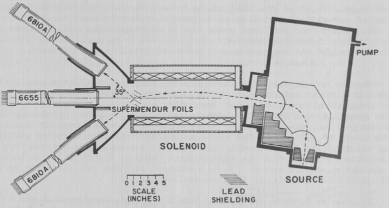

Figure 3

Schematic diagram of Møller and Bhabha scattering apparatus.

are focused at the other end of the lens on a thin Supermendur foil. The lens serves both to magnetize the foil and to separate the foil from the spectrometer. Because of the axial symmetry of the lens its magnetic field can be reversed to reverse the magnetization of the foil without disturbing the focusing properties of the lens. The scattered electrons and the recoil electrons from the foil are detected in coincidence by two plastic scintillators placed at about 35° with the solenoid axis. A conventional fast-slow coincidence circuit is employed to count the electrons. Parts of this equipment are transistorized.

This apparatus has been assembled and is in the final stages of testing. It will be ready for use with O^{14} and P^{32} during the summer. (J. B. Gerhart, J. C. Hopkins, F. H. Schmidt, and J. E. Stroth)

4. Equipment for the High Resolution Uniform Field Spectrometer

During the past year the uniform field, solenoidal beta-ray spectrometer[1] and its accessory equipment were moved from their original location in Physics Hall to new quarters on the second floor of the recent addition to the Cyclotron Laboratory, thus bringing the laboratories of the beta- and gamma-ray spectroscopy group into a single area for the first time. Aside from this obvious gain in efficiency of operation, the move has greatly enhanced the value of the high resolution spectrometer as a research tool since its close proximity to the cyclotron makes possible precision beta-ray spectrometry of short-lived cyclotron produced activities which could not be transported to the old site. To further increase the solenoidal spectrometer's range, the Department of Physics has purchased a new 20 kw motor-generator set capable of supplying up to 190 amperes direct current to the spectrometer field windings. With the new power supply the spectrometer can be used to study electrons of energies up to 4 Mev, a significant extension of its range into a higher energy region.

Moving the spectrometer required disconnecting all water, electrical and vacuum lines, and reconnecting them at the new site. In the process a number of modifications in the interlock system were made, providing more complete protection of the generator and the spectrometer coils. Furthermore, since the new generator requires more field current at full output than the old current supply, a transistorized output stage was designed and installed in the current regulator system replacing the bank of 6L6 vacuum tubes formerly used to control the generator. With this modification, solenoid current stability of one part in 4,000 has been observed over short intervals. Careful testing of this regulator has not been completed, but so far the new circuit appears to be the equal of the old system and ultimately may be somewhat better.

To facilitate the use of scintillation counters with the spectrometer, a new piece of accessory apparatus has been designed and built during the past year. Because of the high magnetic fields in the spectrometer, it is not possible to operate a photomultiplier in the interior of the spectrometer unless unusual measures are taken to shield the multiplier magnetically. To accomplish this in the solenoidal spectrometer, bucking coils have been constructed which are placed in the spectrometer vacuum so as to surround the source and detector probes near the points where they pass through the end plates of the spectrometer. The windings of the bucking coils, together with μ-metal shielding, are arranged so that with a current of roughly 1/14 the current in the main field windings the magnetic field within them is effectively cancelled in a region large enough to accommodate an RCA 6810A photomultiplier. The bucking coils, which are connected in parallel with the main spectrometer windings, are supplied with current from the spectrometer generator. Heat generated in the bucking coils is removed by conduction to water cooled plates. The bucking coils permit the use of photomultipliers separated from scintillators by only relatively short light guides (6 inches), and consequently make it possible to achieve pulse resolutions reduced by only 20 percent from those obtained with no light guide. The fact that both source and detector probes are supplied with bucking coils will make possible beta-gamma coincidence studies with good-resolution scintillation counters. (J. B. Gerhart, H. Nutley, F. H. Schmidt, and G. Sidhu)

1 F. H. Schmidt, Rev. Sci. Instr. 23, 361 (1952)

5. The 4.1-Mev Positron Spectrum of the O^{14} Beta Decay

Although it had long been intended to transfer the spectrometer laboratory to the new cyclotron building, the immediate motivation for the shift described in the preceding paragraphs was to make possible the study of the positron spectrum shape of the weak ground state transition between O^{14} and N^{14} (see Fig. 1). This transition, though allowed by Gamow-Teller selection rules, is greatly inhibited compared to the dominant, less energetic $0+ \rightarrow 0+$ transition to the first excited state of N^{14}. This occurs because of almost complete cancellation of the leading term in the nuclear matrix element for the transition. Consequently this spectrum presents an ideal subject for the study of the higher order terms which are expected to occur in the expression for the transition probability, but which are usually unobservable in the presence of the large leading term. Particularly interesting in this case is the possible occurrence of terms predicted by the Feynmann-Gell-Mann conserved current interaction theory which would cause the spectrum shape to deviate markedly from the normal allowed shape. At the present time there is no conclusive evidence in favor of this attractive theory from beta-decay studies. It is possible that a study of the 4.1-Mev O^{14} spectrum may provide such evidence even though it is not as good a subject for this purpose as the detailed comparison of the N^{12} and B^{12} beta spectra. Unfortunately, experimental attempts to make the latter comparison have not yet been successful.[1]

Experimentally, previous studies of the 4.1-Mev O^{14} beta spectrum[2] have not been sufficiently accurate to distinguish deviations from allowed shape in the spectrum. The present experiment is designed to make use of the very strong O^{14} sources developed in this laboratory for the study of the O^{14} positron polarization (see Section 2), and to take full advantage of the excellent properties of the solenoidal spectrometer for spectrum studies. The chief experimental problem, aside from obtaining sufficiently strong O^{14} sources, is the detection of the very weak 4.1-Mev transition in the presence of a strong background of scattered 2.3-Mev O^{14} gamma rays. It is proposed to accomplish this by employing a detector for the spectrometer which consists of a proportional counter followed by a scintillation counter, similar to the Geiger counter-scintillation counter used earlier in the study of this spectrum by Sherr, Gerhart, Horie, and Hornyak.[2] A coincidence between the two counters is required, the positrons focused by the spectrometer being required to pass through both detectors. Because of the low sensitivity of the proportional counter to gamma rays and the possibility of pulse height analysis with the scintillation counter this arrangement provides good discrimination against gamma rays.

The detector system for the solenoid spectrometer has been constructed and is now ready for testing. A suitable mechanism for forming an O^{14} source inside the solenoidal spectrometer, employing the same freezing-out technique mentioned above, has been designed and is currently being constructed. It is expected that this experiment will be completed during the coming summer. (J. B. Gerhart and F. H. Schmidt)

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1 Henry Hilton, Bull. Am. Phys. Soc., Ser. II, 3, 408 (1958).
2 Sherr, Gerhart, Horie, and Hornyak, Phys. Rev. 100, 945 (1955).

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6. Neutron-Deficient Isotopes of Silver

In recent months work has begun on an investigation of the neutron-deficient isotopes of silver produced by alpha particle bombardment of rhodium. This work was suggested by the recent experiments of Reynolds et al.[1] in which a spin 2 isotope of silver of mass number 102 or 104 and half life 1.2 hours was discovered. In addition, these authors found a second spin 2 silver isotope of half life 26 minutes which they associate with mass number 104. This latter activity has also been observed by other investigators.[2] In order to clarify the mass-assignments of these silver activities it is proposed to produce them by

α-bombardment of Rh^{103} (isotopically pure in nature) using the reactions Rh^{103} (α, xn) Ag^{107-x}. With the full α-particle energy of the cyclotron it should be possible to achieve x = 5. To obtain different bombarding energies aluminum degrading foils will be used, and the activation curves for the various silver isotopes will be determined using the solenoidal spectrometer, and gamma ray scintillation spectrometers to detect the characteristic radiations of the different isotopes. Thus far the isotope Ag^{105} has been identified by means of its known gamma ray spectrum, and a second, as yet unidentified, isotope having a higher activation energy has been observed. (J. B. Gerhart and H. Nutley)

1 Reynolds, Christensen, Hamilton, Hooke, and Stroke, Phys. Rev. 109, 465 (1958).
2 F. A. Johnson, Can. J. Phys. 33, 841 (1955).

7. The Decay of Ta^{176}

During the summer of 1958, Dr. J. O. Rasmussen initiated an investigation of the decay of Ta^{176}, utilizing the solenoidal spectrometer. At that time extensive preliminary work was done yielding evidence for several previously unknown gamma rays and for positron emission. Because of the moving of the spectrometer laboratory this work has been halted temporarily. (H. Nutley)

8. The Orange-Peel Spectrometer

Construction of the 38-gap orange-peel spectrometer discussed in previous reports has been completed. A test site for the spectrometer has been established and various equipment necessary for testing of this new instrument has been built. Most of the test equipment has been checked and it is hoped that preliminary testing will begin in a few weeks. (F. J. Bartis, F. H. Schmidt)

9. The Circular Polarization of Photons Emitted in Nuclear Reactions

An experiment is being prepared to test whether nuclei are polarized following inelastic scattering. The scheme is to search for circularly polarized deexcitation gamma radiation emanating from a nucleus in coincidence with an inelastically scattered or ejected reaction particle. If the nuclear system is polarized prior to emission of the gamma ray, then one expects the gamma rays emitted along the polarization axis to be circularly polarized.

Specifically, the experiment will first be performed with a C^{12} target bombarded with α particles. As shown schematically in Fig. 4, α particles enter along the y axis and inelastically scatter to α counter No. 1 or α counter No. 2 which are lying in the x-y plane at scattering angles $\pm\theta$, respectively. The deexcitation gamma radiation traveling approximately along the z axis will be detected by the γ counter after Compton Scattering from a magnetized iron cylinder. If the radiation is circularly polarized, an asymmetry should be observed in the α'-γ coincidence rates upon reversal of the direction of magnetization. We have chosen to investigate C^{12} because its energy levels are well-known; in

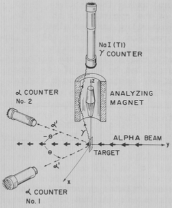

Figure 4

Schematic diagram for nuclear polarization experiment.

addition the characteristics of inelastic α scattering from the first excited state at 4.4-Mev have recently been measured.[1] This state has spin 2 and even parity. Hence, the γ radiation to the 0+ ground state is electric quadrupole. Although our intent is first to study inelastic α scattering from C^{12}, the apparatus will immediately lend itself to related studies with other targets and other types of reactions.

Stated simply, the motivation for the experiment is to determine whether nuclear scattering with a transfer of angular momentum from the projectile to the nucleus occurs with a greater probability from one "side" of a nucleus than from the other. That is, we ask whether a nucleus is left spinning with a preferred sense to the spin vector. In a recent theoretical treatment of inelastic diffraction scattering[2] Blair has assumed that each diffraction zone around a nucleus contributes equally to the scattering amplitude. If this view is correct, we expect that no polarization will be found. On the other hand, for nuclear excitation by a reaction $X(a,b)Y^*$, according to Blair one might expect to find the residual nucleus Y^* polarized.

The apparatus for the experiment is nearly completed. We will utilize the new 60-inch scattering chamber (see the section on cyclotron development). A cylindrical analyzing magnet, which was used in the O^{14} positron polarization studies (Section 2) will be placed above the target in the 60-inch chamber. Two symmetrically located plastic scintillation counters will be used to detect scattered α particles at angles of $+\theta$ and $-\theta$. We thus hope to observe an asymmetry between $+\theta$ and $-\theta$, for a given direction of the analyzer magnetic field. This asymmetry should reverse upon reversal of the field. In order to minimize background gamma counts from scattered neutrons and other sources, high speed coincidence circuitry will be used. It is intended to utilize the natural bunching of the cyclotron beam as a means for elimination of accidental coincidences. New fast coincidence circuitry, especially adapted for this experiment and incorporating both transistors and vacuum tubes, is under construction. It is expected that the experiment will be brought to fruit during the summer. (J. B. Gerhart and F. H. Schmidt)

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1 A. I. Yavin and G. W. Farwell, Nuclear Physics (in press).
2 John Blair, Inelastic Diffraction Scattering, to be published.

STOPPING POWER INVESTIGATIONS

1. A New Direct Method for Measuring Stopping Power

A new method for precision measurement of the stopping power for particles in metals (10 Mev protons in Al) has been proposed and is being developed. It requires the determination of the momentum transferred to a foil by a transmitted beam (5 microamps) of particles. (See Fig. 5.) The momentum transfer and hence

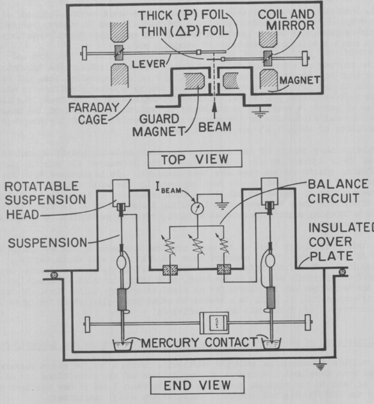

Figure 5

Two views of the proposed apparatus for measuring stopping power.

the energy loss are determined by a single measurement rather than as a small difference, as in other methods. The force (0.01 dyne) on the foil (thickness 0.005 cm), acting on a lever-arm (5 cm) produces a torque on a rotor carried by a vertical suspension (quartz, aluminum plated, 20 micron diameter x 10 cm length). An adjustable fraction of the beam current is directed through a galvanometer unit utilizing the same rotor and suspension, and produces a reverse torque. A null deflection of the rotor (after a 10 sec bombardment) indicates a balance condition, and permits the determination of the mean momentum transfer per particle. A second unit, basically similar but employing a thick absorber, permits the determination of the mean total momentum of the emerging particles.

The beam current is collected by a Faraday cage that encloses all the aforementioned apparatus. The locations of the two suspensions are chosen to insure automatic compensation for a lateral motion of the centroid of the beam; this requires a rough preliminary knowledge of stopping power.

Some sources of error and difficulty are: oblique incidence on the thick absorber (but not the thin absorber) resulting from a nonparallel beam and from scattering in the thin absorber; momentum carried by ejected electrons or neutrons or back-scattered particles; deuteron contamination of the beam; the distribution of particle energies in the beam; incomplete collection of the beam current; thermal distortion of the absorber and nonuniformity of the absorber. An uncertainty of about 0.25 percent is expected.

A preliminary design of the apparatus has been made and possible sources of error and their correction are being studied. The techniques for making, plating, and fastening quartz suspensions have been acquired. It is expected that the apparatus will be installed in the duct adjacent to the water shield; this is not a customary point of operation and it has been necessary to investigate the formation of a focus there by means of a traveling Faraday cup; it is found that with the deflecting magnet operated at slightly reduced excitation, a satisfactory focus is obtained.

A crude preliminary test of the more critical elements of the apparatus will be made in June, 1959. It is expected that observations will begin before November, 1959. The first detailed observation will probably be a precise measurement of the particle energy of the beam, with only the thick absorber in place; the technique may be useful for an absolute energy calibration. If the method is successful, it will be extended to other particles, other energies and other absorbers. (J. F. Streib and C. Zafiratos)

2. Calculations of Multiple Scattering and Shell Corrections for Stopping Powers

A reliable treatment of multiple scattering corrections for range measurements has been developed. A number of computations of the corrections for Al, Cu, Ni, Ag, and Au for various proton energies between 1 and 35 Mev has been executed on the IBM 650 digital computer. Results are still preliminary.

A determination of the shell corrections of the stopping power has been made from the experimental range measurements. Results for Ni, and Ag were presented at the Gatlinburg conference on stopping power (September, 1958) and at the APS meeting at UCLA, December, 1958. Final results have not yet been obtained. (H. Bichsel and E. A. Uehling)

3. Stopping Measurements for Low Energy Protons

A cooperative experiment was started with the Van de Graaff group at Hanford for the measurement of dE/dx in gases for protons of 1 to 2 Mev. Protons enter a gas absorption chamber through a thin foil. After they travel a distance S through the gas they produce the reaction Al (p,γ) at one of the resonances E_1. Keeping the incident proton energy constant, the distance S is gradually increased until the next lower resonance E_2 of the Al (p,γ) reaction is observed. The accurate measurement of gas pressure and temperature and ΔS gives the mass of the gas per cm^2 through which the proton travels, when it loses an energy $\Delta E=E_1-E_2$.

The experiment was temporarily dropped when Spangler left the University. (J. Spangler, H. Bichsel, W. Roesch [at Hanford])

THE SCATTERING OF ALPHA PARTICLES AND ALPHA-GAMMA ANGULAR CORRELATIONS

1. Introduction

In several previous Progress Reports the results of a series of investigations of angular distributions for elastic and inelastic scattering of alpha particles by light elements have been reported. This work has been continued and extended to elements of medium weight during the past year, and work on alpha-gamma angular correlations has progressed considerably. Studies of those scattering reactions which lead to the breakup of the residual nucleus are reported below in the section on reactions in which charged particles are emitted in coincidence.

A special motivation for the recent angular distribution and angular correlation work has been provided by the extensive experiments of Cohen and Rubin[1,2] on inelastic scattering of protons. These experiments have definitely established the strong excitation of levels at about 2-4 Mev above the ground state for nuclei of intermediate mass. The first excited state, which has even parity and spin 2, can be explained in terms of quadrupole surface vibrations. It has been suggested that the strong excitation of higher levels might be understood in terms of octupole surface vibrations. Current experiments in this laboratory suggest (a) that a low-lying state associated with octupole deformation occurs in each of several "4n" nuclei with N = Z ranging from O^{16} to Ca^{40}, with the excitation energy decreasing slowly with increasing A; and (b) that several even-even nuclei in the intermediate mass region exhibit inelastic angular distributions compatible with strong collective excitation of low-lying states having large quadrupole or octupole deformations. Thus it appears that the "anomalous" scattering observed in the proton investigations does not start in sharply at about Z = 30, but instead is observable for considerably lighter elements.

A simple diffraction model for elastic and inelastic scattering of charged particles recently proposed by Blair[3] gives predictions consistent with the present observations on magnitudes and the angular dependence of scattering cross sections and has the additional advantage of bringing interaction radii for best fit to both elastic and inelastic angular distributions into agreement.

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1 B. L. Cohen, Phys. Rev. 105, 1549 (1957).
2 B. L. Cohen and A. G. Rubin, Phys. Rev. 111, 1568 (1958).
3 J. S. Blair, Phys. Rev., to be published; Theoretical Physics Progress Report, University of Washington, 1959, unpublished.

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2. He^4 - He^4 Elastic Scattering

The experimental results reported last year[1] for scattering at several incident laboratory energies have been prepared for publication.[2] A phase shift analysis is being performed with the Illiac computer by A. I. Yavin (now at the University of Illinois). (G. W. Farwell and A. I. Yavin)

1 1958 Progress Report, Cyclotron Research, University of Washington; A. I. Yavin, Ph.D. Thesis, University of Washington, 1958 (unpublished).
2 A. I. Yavin and G. W. Farwell, to be published.

3. Scattering by B^{10}, B^{11}, and S^{32}

In order to establish a more accurate scale of absolute cross sections for the angular distributions previously reported,[1] several normalization runs were made.

A reinterpretation of the S^{32} data in terms of a diffraction inelastic scattering model[2] gives strong support to the suggestion of a collective quadrupole transition to the 2.24-Mev (2+) state and a collective octupole transition to the 4.98-Mev state.

Final results will be published in the near future.[2,3] (G. W. Farwell, D. McDaniels and P. C. Robison)

1 1957 Progress Report, Cyclotron Research, University of Washington; Paul C. Robison, Ph.D. Thesis, University of Washington, 1958 (unpublished).
2 J. S. Blair (reference 3 of Introduction).
3 P. C. Robison and G. W. Farwell, to be published.

4. Scattering by C^{12}, N^{14}, O^{16}, and A^{40}

The results previously reported[1] have been prepared for publication[2] following a reanalysis of the elastic scattering data. The elastic scattering angular distributions are characterized by sharply defined diffraction-like structure at the forward angles with maxima and minima spaced very regularly in sin $\theta/2$ (c.m.), deep minima near 90° (c.m.), and appreciable cross sections at angles beyond 90°. A black nucleus diffraction interpretation gives reasonable absolute cross sections for the forward maxima and good agreement with observed locations of maxima and minima. Inelastic scattering angular distributions were obtained for C^{12} (Q = -4.43, -7.65, and -9.61 Mev); for O^{16} [Q = -6.06 and -6.14 Mev (unresolved), -6.91 and -7.12 Mev (unresolved)]; and A^{40} (Q = -1.462 Mev). Conventional direct interaction analysis verifies previously assigned spins and parities and indicates an assignment of 0+ or 2+ to the 9.61-Mev level of C^{12}. Integrated cross sections for inelastic scattering to individual levels may be as high as 6 percent of πR^2. Interaction radii determined from diffraction analysis of the elastic scattering data are (in units of 10^{-13} cm) 5.11 ± 0.20 for C^{12}, 5.37 ± 0.17 for N^{14}, 5.64 ± 0.29 for O^{16}, and 6.38 ± 0.32 for A^{40}. Compound nuclear contributions to observed cross sections appear to be small or zero.

The angular distribution for inelastic scattering to the 6.14-Mev (3-) level in O^{16} suggests that this is another example of collective excitation of a state associated with octupole deformation,[3] though the evidence would be improved by a clear separation of this level from that at 6.06 Mev. (G. W. Farwell and A. I. Yavin)

1 1958 Progress Report, Cyclotron Research, University of Washington; A. I. Yavin, Ph.D. Thesis, University of Washington, 1958 (unpublished).
2 A. I. Yavin and G. W. Farwell, Nuclear Physics (in press).
3 J. S. Blair (reference 3 of Introduction).

5. Scattering by Elements of Intermediate Mass

Elements investigated to date include iron, nickel, zinc, and strontium. Strontium is of special interest since Sr^{88}, the principal isotope, is known to have a 3- level at 2.76 Mev excitation.

The experimental arrangement for measuring the angular distributions was similar to that used previously for lighter elements. A typical scintillation counter arrangement made use of a CsI crystal (cut to the minimum thickness required to stop elastically scattered alphas) with photomultiplier, amplifier, and 40-channel pulse-height analyzer. Effective resolution and discrimination against protons and deuterons were sometimes improved by placing an aluminum absorber between the crystal and the detector collimator. The largest error in the differential cross sections came from the subtraction of the background present in the scattered particle spectra at some angles.

Figs. 6, 7, and 8 give the absolute differential cross sections in the center-of-mass system as a function of c.m. angle for nickel, zinc, and strontium, respectively. The errors in individual points are usually less than 10 percent except at the forward angles where the elastic cross section becomes extremely large compared to the inelastic. The upper limit to the angle of observation is

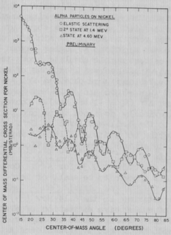

Figure 6

Angular distributions for elastic and inelastic scattering of alpha particles of incident laboratory energy 41 Mev by nickel (principal isotope Ni^{58}). Preliminary data are given.

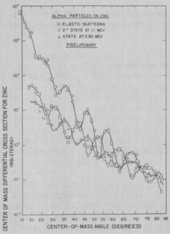

Figure 7

Angular distributions for elastic and inelastic scattering of alpha particles of incident laboratory energy 41 Mev by zinc (principal isotope Zn^{64}). Preliminary data are given.

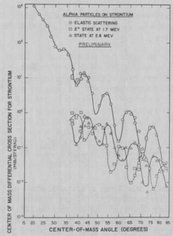

Figure 8

Angular distributions for elastic and inelastic scattering of alpha particles of incident laboratory energy 41 Mev by strontium (principal isotope Sr^{88}). Preliminary data are given.

in most cases set by the rapid fall-off of the cross sections with increasing angle.

Consideration of the Figs. 6-8 indicates that in each case the angular distribution for the 2+ state is out of phase with the elastic angular distribution, and that the "anomalous" state distribution is out of phase with that for the first excited state and in phase with the elastic.

A comparison of the experimental data was made with the diffraction analysis results recently given by Blair (see above). For elastic scattering, the differential cross section is given by

$$\frac{d\sigma}{d\Omega} = k^2R^4\cos^2\frac{\theta}{2}\left(\frac{J_1^{\,2}\,(2kR\sin\theta/2)}{(2kR\sin\theta/2)^2}\right) \quad ,$$

the usual Fraunhofer relation. (Here k = c.m. wave number, R = interaction radius, θ = c.m. angle.) For inelastic scattering, the weak coupling approximation gives

$$\frac{d\sigma}{d\Omega}(0 \rightarrow 2) = (kR^2)^2 \frac{5}{8\pi} \frac{\hbar\omega_2}{c_2} \left\{ \frac{J_0^2(2kR \sin\theta/2)}{4} + \frac{3}{4} J_2^2(2kR \sin\theta/2) \right\}$$

and

$$\frac{d\sigma}{d\Omega}(0 \rightarrow 3) = (kR^2)^2 \frac{7}{8\pi} \frac{\hbar\omega_3}{c_3} \left\{ \frac{3}{8} J_1^2(2kR \sin\theta/2) + \frac{5}{8} J_3^2(2kR \sin\theta/2) \right\}$$

for transitions from a ground state of spin 0 to vibrational states of spin 2 and spin 3, respectively. As is evident from these expressions, the differential cross sections for the 2+ excitations are out of phase with the elastic cross sections while those for the 3- levels are in phase with the elastic and out of phase with the 2+. Less consistent phase relationships result from application of the simple direct interaction theories, which yield spherical Bessel functions rather than Bessel functions in the differential cross section expressions. The same results apply equally well to rotational transitions; the present interpretation of the data leans toward vibrational excitations, however.

The present work seems to verify clearly the odd parity of these higher levels. The spin assignments are by no means as unambiguous; it is hoped that improved and more extensive data at small angles will resolve this difficulty to some extent.

Other elements in the range $60 < A < 140$ are being investigated. (S. W. Chen, G. W. Farwell, D. McDaniels)

6. Alpha-Gamma Angular Correlations in Alpha Scattering by Intermediate Elements

This is an extension of the (α,α') angular distribution experiments with particular emphasis on the study of anomalous levels of the type reported by Cohen and Rubin.[1] Due to experimental difficulties in obtaining the angular distributions for inelastic scattering at very small angles, the spin values of these levels cannot usually be determined uniquely by this means. Therefore we proceed to study the de-excitation processes of the residual nucleus and the angular correlation between the de-excitation γ-rays and the inelastically scattered alphas. The angular correlation pattern depends less ambiguously upon the spin and parity of the state.

The alpha counter consists of a thin NaI crystal coupled directly to a DuMont 6291 phototube. The crystal is made just thick enough to stop 40-Mev alpha particles in order to minimize the background pulses. The gamma counter consists of a Pb-shielded NaI crystal, 2" x 1 3/4", coupled to a 6292 phototube.

The effective solid angle is 0.427 sterad. Standard fast-slow coincidence technique is used. The resolving time of the fast coincidence circuit is about 30 $m\mu sec$.

With the alpha counter at one of the peaks of a particular angular distribution curve, we can study the α-γ angular correlation by changing the angle of the gamma counter. Fortunately, a peak in the angular distribution for the anomalous alpha group usually coincides with a valley in the corresponding distribution for the lower-lying 2+ state (see Section 5 above). Therefore, even with a comparatively thick target, the appropriate alpha group is relatively easily distinguished. However, due to the rapidly oscillatory nature of the angular distribution, the size of the alpha counter aperture is restricted to less than 1.5°; in addition, the cross section for excitation of the anomalous level is usually small in comparison with those for excitation of the low-lying states of the light elements, so that the counting rates for these experiments are very low.

So far only Zn (α, $\alpha'\gamma$) Zn with $Q \cong -3$ Mev has been studied. (The principal contribution comes from the level at 2.8 Mev in Zn^{64}.) Preliminary results indicate that most of the de-excitation occurs in cascade via the 2+ state at $\sim$ 1.1 Mev. This strongly suggests that the anomalous level is a 3- state instead of 1- state.

Correlation patterns have been calculated according to Satchler's theory[2] assuming different possible spin values for the anomalous state and different decay modes. If decay occurs directly to the ground state, the angular correlation with respect to the momentum transfer axis is $\sin^2\theta$ for dipole excitation, $\sin^2 2\theta$ for quadrupole excitation, or

$$(P_3^{\ 1})^2$$

in the case of octupole excitation. If decay occurs in cascade via the 2+ state, it is easier to detect the first γ-ray, which has higher energy than the second. The correlation functions are $(2-\cos^2\theta)$ and $(21-5\cos^2\theta)$ for octupole and dipole excitations, respectively. Experimentally, it is much simpler if the decay occurs directly to the ground state.

Our next step will be to study the γ-ray spectra from nickel and iron in coincidence with the anomalous alpha group. For these two elements, the anomalous levels are about 5 Mev from the ground state. With more energy available, there is a better chance for the de-excitation to bypass the 2+ state and occur directly to the ground state.

The results reported last year[3] on alpha-gamma angular correlations for inelastic scattering by C^{12}, Mg^{24}, and Ca^{40} will be published soon.[4] (S. W. Chen, D. McDaniels, and I. Naqib)

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1 B. L. Cohen and A. G. Rubin, Phys. Rev. 111, 1568 (1958).
2 L. C. Biedenharn and M. E. Rose, Revs. Mod. Phys. 25, 729 (1953).
3 1958 Progress Report, Cyclotron Research, University of Washington; G. B. Shook, Ph.D. Thesis, University of Washington, 1958 (unpublished).
4 G. B. Shook, Phys. Rev. (in press).

1. Introduction

During the past year new measurements have been started and new results have been obtained on a variety of fission problems. The investigations have been largely, but not exclusively, concerned with the fission of elements lighter than thorium. Both radiochemical and "physical" techniques have been used.

2. Alpha Particle Induced Fission in Elements Between Tungsten and Bismuth

Studies of fission excitation functions and mass yield curves have been made for helium-ion induced fission of target elements from tungsten through bismuth.[1] The mass yield curves were measured for Au^{197}, Pb^{204} and Pb^{206} targets at 42 Mev and are shown in Figs. 9, 10, and 11. These curves show that fission of these

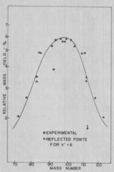

Figure 9

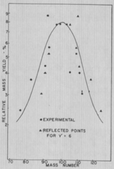

Figure 10

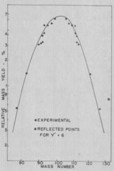

Figure 11

Fig. 9--Mass-yield curve for fission products from Au^{197} bombarded with 42-Mev helium ions. Fig. 10--Mass-yield curve for fission products from Pb^{204} bombarded with 42-Mev helium ions. Fig. 11--Mass-yield curve for fission product from Pb^{206} bombarded with 42-Mev helium ions.

nuclides is of the symmetric type. However, the widths of the curves are different for all three cases. Au^{197} has the widest mass-yield curve, 34 mass units wide at half the maximum yield. This is twice the width observed[2] for deuteron-induced fission of Bi^{209}. The mass yield curve measured for Pb^{206} target was the narrowest, being 22 mass units at half-maximum.

Excitation functions for fission induced in target elements from tungsten through bismuth were measured for helium ion bombarding energies between 25 and 42 Mev. The results are shown in Fig. 12, plotted against the excitation energy

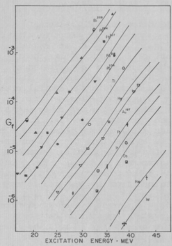

Figure 12

Total probability of observing fission in the bombardment of various target nuclei with helium ions of energy between 25 and 42 Mev.

of the compound nucleus. The regular spacings between elements and the steep energy dependence are to be noted. From the regularities evident in these curves the following empirical equation was derived for the total probability of fission, G_f, of a nuclear species Z, A, as a function of initial excitation energy, E (in Mev):

$$\log G_f = -6 + \frac{\frac{Z^2}{A} - 31.6}{0.6} + \frac{35 - E}{7}$$

This expression reproduces the data for the "light" fissioning species of Fig. 12 to within a factor of 2 or 3 over a range of G_f of the order of 10^5, and is valid up to energies of at least 45 Mev.

One important conclusion follows from these results: Γ_f/Γ_n is a strongly increasing function of excitation energy up to energies at least as high as 40 Mev for the elements lighter than polonium. At a given excitation energy the results obtained with enriched lead isotopes show that about 80 percent of the total observed fission occurs before the evaporation of a neutron. The regularities exhibited in Fig. 12 imply that a similar situation prevails for the other elements which were investigated.
(A. W. Fairhall and E. F. Neuzil)

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1 E. F. Neuzil, Ph.D. Thesis in Chemistry, June 1959.
2 A. W. Fairhall, Phys. Rev. <u>102</u>, 1335 (1956).

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3. The Fission of Radium with Protons and Deuterons

Studies of mass distributions of fission fragments from radium targets bombarded with 11-Mev protons, 43- and 31-Mev helium ions, and 21-Mev deuterons have been reported in previous progress reports. Part of this work was published in the Proceedings of the Second Geneva Atoms-for-Peace Conference.[1] This series of studies was concluded with a study of the mass distributions of fission products from fission of Ra^{226} by 14.5-Mev deuterons. This energy was chosen because neutron evaporation from the compound nucleus gives the same nucleus at the same excitation energy as Ra^{226} bombarded with 11-Mev protons. By comparison of fission cross sections and mass-yield curves for 14.5-Mev deuteron-induced fission and 11-Mev proton-induced fission of Ra^{226} it was hoped that it would be possible to learn two things: (1) how much fission had occurred before neutron evaporation from the compound nucleus which was formed in the deuteron bombardment, and (2) the mass distribution of fission fragments from such "prompt" fission.

The mass-yield curve obtained from 14.5-Mev deuteron-induced fission of Ra^{226} is shown in Fig. 13. This mass distribution curve is to be compared with the data of Fig. 13, p. 26, of the Annual Progress Report of 1957 which shows the results for 11-Mev proton-induced fission of Ra^{226}. There the mass-yield curve is distinctly triple-humped, with the central peak, corresponding to symmetric fission, being comparable in height to the two outer peaks, which correspond to asymmetric fission. So far as the mass distributions themselves are concerned it is evident that there is an enhanced yield of symmetric fission fragments relative to asymmetric fragments. The cross section for 14.5-Mev deuteron-induced fission, 35 mb, is obtained from the measured formation cross section of Ag^{111} (1.6 mb) and its fission yield, 4.6 percent, is obtained from Fig. 13. It must be emphasized that there is considerable uncertainty in both the formation cross section of Ag^{111} and in the normalization of the curve of Fig. 13 so that the fission cross section is probably uncertain by at least $\pm$ 50 percent.

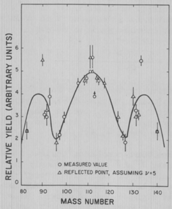

Figure 13

Mass-yield curve for fission products from Ra^{226} bombarded with 14.5-Mev deuterons.

Owing to the strong dependence of the cross section on the bombarding energy, and to the uncertainties in the determination of this energy (particularly in the 11-Mev proton bombardment), one can only make qualitative statements about the nature of the prompt fission occurring in 14.5-Mev deuteron-induced fission of Ra^{226}. The total reaction cross section for 14.5-Mev deuterons on Ra^{226} is about 560 mb.[2] Fission therefore makes up about 6 percent of the total cross section. For 11-Mev protons the total cross section is estimated to be 170 mb of which 2 $\pm$ 1 mb, or about 1 $\pm$ 1/2 percent is fission. Evidently most of the fission observed in the deuteron bombardment precedes neutron evaporation, and from the character of the mass distribution evidently this fission is predominantly symmetric in character. Owing to the uncertainties in the cross sections, however, it is not possible to say how much, if any, asymmetric fission occurs prior to neutron evaporation. (A. W. Fairhall and R. C. Jensen)

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1 A. W. Fairhall, R. C. Jensen, and E. F. Neuzil, Paper P 677, Second U.N. Conference on Peaceful Uses of Atomic Energy, 1958.
2 M. Shapiro, Phys. Rev. 90, 171 (1953).

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4. Angular Distributions of Fission Fragments from "Light" Elements

Measurements are being made of the fragment angular distributions in the alpha induced fission of bismuth, lead, and gold. Fragment anisotropies for bismuth and heavier targets are already known[1] and the analysis of these results suggests that it should be interesting to pursue the anisotropy measurements to lighter targets. It was found that the anisotropy $(d\sigma/d\Omega(0^\circ) : d\sigma/d\Omega(90^\circ))$ increases smoothly as Z^2/A decreases as one proceeds from plutonium to radium. The anisotropy for bismuth apparently does not continue this trend but is roughly the same as that for radium. In the explanation[2] given of the results for the heavier elements the anisotropy depends on a single parameter. This parameter is the ratio of the average value of the square of the angular momentum of the fissioning nucleus to the average square of the projection, K, of this momentum on the "fission" axis. The latter quantity increases rapidly with excitation energy. In similar bombardments of thorium and plutonium, the thorium shows the larger anisotropy because here the fissioning nuclei have smaller average values of K. The reason that this is so is that a large fraction of the nuclei in a thorium bombardment fission only after neutron emission since the fissionability of the uranium compound nuclei which are formed is relatively small. Thus there tends to be more fission at low excitation energy after neutrons are evaporated. The values of K in these fissions are small and therefore the anisotropies are large.

This cannot be the explanation for the sizeable anisotropy in the alpha particle fission of bismuth. Here almost all of the fission takes place at high excitation energies because of the nature of the energy dependence of the fissionability (see Section 2). There must be another reason for the smallness of the average K's in bismuth fission compared to those in, say, plutonium fission. Probably the K's in bismuth are small simply because the fission threshold is very high. (K presumably increases with the nuclear excitation energy <u>measured from the fission threshold</u>.) A rough analysis of the excitation curves in Section 1 indicates that the fission threshold in bismuth may even be higher than 20 Mev and that the observed anisotropy in bismuth fission is roughly in accord with expectations based on this value of the threshold. We are investigating the anisotropies of fission induced in some lead isotopes and in gold for comparison with predictions that one can make on the basis of presently available theory. Only preliminary results (Fig. 14) are available so far. It is seen that the anisotropy in Pb^{207} is roughly the same (perhaps slightly larger) than that in Bi^{209}. (I. Halpern and W. J. Nicholson)

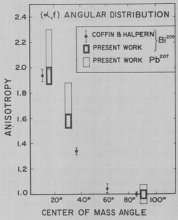

Figure 14

Angular distributions of fragments from 42-Mev alpha particle induced fission of Bi^{209} and Pb^{207}.

1 C. T. Coffin and I. Halpern, Phys. Rev. 112, 536 (1958).
2 I. Halpern and V. M. Strutinski, Paper 1513, Second U. N. Conference on the Peaceful Uses of Atomic Energy, 1958.

5. The Energy Dependence of Fission Anisotropies Induced by Alpha Particles

A recent theoretical treatment of angular anisotropies of fission products by Halpern and Strutinski[1] predicts that as new thresholds are reached for fission following neutron emission from the compound nucleus there will be a sudden change in the character of the angular distribution of the fission products. In particular, for particle-induced fission, there should be a pronounced forward peaking of asymmetric fission fragments at the new fission threshold whereas symmetric fragments would not show a sudden change in the character of their angular distributions.

This effect has been looked for in the following experiments. A thin thorium target was placed several inches away from and parallel to an aluminum foil which served to collect fission fragments emitted from the target when a narrow beam of helium ions was passed through it. After the bombardment the catcher foil was cut into concentric annuli centered about the axis of the beam, and each annulus was analyzed for Ag and Ba activities, representing symmetric and asymmetric fission, respectively. This experiment was repeated at several bombarding energies near 27 Mev where the sought-for effect was expected to be observed. The results are shown in Fig. 15, where Ba^{139}/Ag^{113} ratios are plotted as a function of bombarding energy for several ranges of angles of the annuli. It appears from these results that somewhere near 26 Mev there is an enhancement in the yield of asymmetric fission fragments at small angles to the beam direction. The results are qualitatively in agreement with the theoretical predictions. (J. A. Coleman and A. W. Fairhall)

1 I. Halpern and V. M. Strutinski, Paper P/1513, Second U.N. Conference on the Peaceful Uses of Atomic Energy, 1958.

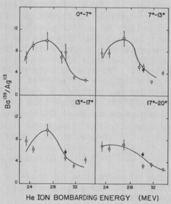

Figure 15

Silver-to-barium ratios for various energies of helium ions incident on a thorium target. The fragments are collected at various angles with respect to the helium ion beam.

6. The Anomalous Anisotropies in High Energy Fission

An explanation is suggested[1] for the fact that in high energy proton bombardments more fission fragments come off at right angles to the beam than along it. The fragment angular distribution is thus opposite in character to those normally observed in moderate energy particle bombardments. The elements of the suggested explanation of the high energy anisotropy reversal are these: (1) Even heavy nuclei tend to be somewhat transparent to high energy nucleons and many reactions begin with but one or two nucleon-nucleon collisions of the incident particle within the nucleus. (2) A large fraction of these collisions result in a low energy sideways-moving nucleon whose partner is still fast and forward and likely to escape from the nucleus. This is because the nucleon-nucleon differential cross section is largest for "transverse" collisions. (3) The angular momentum deposit (which determines the angular distribution of the fission fragments) is dominated by the contributions of these transverse low energy nucleons. It is as though a collection of beams is incident on the nucleus at right angles to the actual beam. From available medium energy data, one can obtain a semi-quantitative estimate of the anisotropies that such beams should produce and they seem to be in accord with the actual observations with high energy incident protons. One implication of the detailed analysis is that the sideways-moving fission fragments should be associated with abnormally small deposits of excitation energy in the struck nucleus. The evidence on this point is conflicting[2] but recent measurements[3] seem to support this implication of the model. (I. Halpern)

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1 I. Halpern (to appear in Nuclear Physics, 1959).
2 Lozhkin, Perfilov, and Shamov, JETP USSR 29, 292 (1955); J. W. Meadows, Phys. Rev. 110, 1109 (1958).
3 H. Faissner, CERN (private communication); N. Sugarman, University of Chicago (private communication).

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7. Correlations Between Mass and Angular Distributions

Studies have begun on the question of the apparent correlation between angular anisotropy and mass asymmetry in fission.[1,2,3] It may be possible to understand these results in terms of two modes, one representing symmetric fission occurring prior to neutron evaporation, the other asymmetric fission occurring mostly at lower excitation energies.

The first experiment will be to study the anisotropy-mass asymmetry for a case of pure symmetric fission. The experiment is difficult owing to the very low fission cross section of the lead target which is used. Preliminary results for fission fragments Y^{92} and Ag^{111} have not been reproducible, presumably owing to chemical difficulties of carrier-tracer exchange. Further work is in progress. (A. W. Fairhall and R. E. Wilson)

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1 A. W. Fairhall, I. Halpern, and E. J. Winhold, Phys. Rev. 94, 733 (1954).
2 Cohen, Ferrell-Bryan, Combe, and Hullings, Phys. Rev. 98, 685 (1955).
3 A. W. Fairhall and M. P. Hickenlooper, Annual Progress Report, Cyclotron Research, University of Washington, 1957, p. 27.

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8. Kinetic Energies of Fission Fragments

In a further study of the fission of bismuth and lighter elements, the kinetic energies of fission fragments will be measured with a specially-constructed ion chamber. To minimize the effects introduced into a kinetic energy measurement by counter windows, the beam of incident (alpha) particles will be allowed to pass through the ion chamber in a narrow shielded tube. The fission target will be at the center of the tube and two (grid-covered) holes in the tube will permit fission fragments to pass directly from the tube into the ion chamber proper. The chamber will be calibrated with a Cf^{252} source whose loan to us was kindly arranged by Dr. E. P. Steinberg of the Argonne Laboratory.

There are a number of reasons to be interested in fragment kinetic energies in the fission of the "light" elements. In view of the steep excitation functions in these elements (Section 2) fission takes place "promptly" and not after neutron emission. Hence one can investigate the dependence of the fragment kinetic energy on the initial excitation energy of the compound nucleus with less confusion than in heavy elements where there is a considerable amount of de-excitation (by neutron evaporation) before fission. Knowledge about the apportionment of initial excitation energy between the kinetic and excitation energies of fission fragments would help with one's understanding of the dynamics of the fission process.

Another reason that the "light element" kinetic energy measurements should prove interesting is that fission here is mass symmetric rather than asymmetric as in heavier elements. This suggests that fission in the lighter elements may perhaps be different in other ways from heavier element fission. For example, in the heavier elements, the average total kinetic energy of the fragments is proportional to $Z^2/A^{1/3}$ suggesting that the actual scission or cutting-off takes place from similar configurations in all of these elements. A very preliminary comparison of bismuth with uranium indicates that the relative kinetic energy release in bismuth fission is approximately 5 percent higher than one would expect on the basis of an assumed scaling according to $Z^2/A^{1/3}$. (I. Halpern and W. J. Nicholson)

9. Alpha Particles Emitted in Coincidence with Fission

Work is continuing on the study of charged particles emitted in coincidence with fission. When 42-Mev alpha particles are used to produce fission the coincident charged particles are emitted roughly at 90° to the fragments just as in thermal neutron fission. Preliminary results also indicate that the fission of uranium at moderate energies is accompanied by charged particles about as often (0.3 percent of the time) as is thermal fission. Targets to be studied in the future include Pu^{239} and possibly Bi^{209}. (I. Halpern and W. J. Nicholson)

10. Direct Interaction Effects in Medium Energy Fission

The measurement on direct interactions in which fission is used as an indicator and which was described in last year's progress report has been completed.[1] In this experiment, the angular distribution between pairs of coincident fission fragments is measured to determine the linear momentum deposit by the incident projectile. In direct interactions in which enough energy is deposited in the nucleus to lead to fission, the amount of linear momentum deposited may however differ from that of the incident particle. The results of measurements on uranium show that at most a small fraction of the encounters which lead to fission involve an "abnormal" momentum deposit. More particularly 2 ± 3 percent of the fission events produced in uranium by 42-Mev alpha particles are due to direct interactions and 5 ± 5 percent of the events induced by 21-Mev deuterons are associated with direct interactions. (I. Halpern and W. J. Nicholson)

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1 W. J. Nicholson and I. Halpern (submitted to the Physical Review).

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11. The Effect of Angular Momentum on the Probability for Fission

It has been suggested by Wilets,[1] and others, that angular momentum may play a significant role in determining fissionability. That is, for a given excitation energy the fissionability of a given nucleus may depend measurably on its angular momentum. Experiments are underway to investigate this possibility by comparing the fission cross section for deuteron-induced fission of Bi^{209} with the cross section for He^4-induced fission of Pb^{207}. The bombarding energies are chosen so as to have the compound nucleus (Po^{211}) excited to the same energy in both cases. The He ion brings in more angular momentum (ℓ_{max} = 23) than does the deuteron (ℓ_{max} = 13). However, the high spin of Bi^{209} (9/2) compared with Pb^{207} (1/2) may tend to even things out somewhat. A better comparison would perhaps be between Tl^{205} (He^4, f) and Pb^{207} (d,f), where both target nuclei have spin 1/2. Preliminary results using helium ions on a natural lead target give the same fission branching ratio as for deuteron-bombarded bismuth, implying that the effects of angular momentum are small. However, further work will be required to settle this point. (J. A. Coleman and A. W. Fairhall)

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1 L. Wilets, private communication.

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12. A Review of Nuclear Fission

A review article on nuclear fission has been prepared for the Annual Reviews of Nuclear Science. (I. Halpern)

1. Time Reversal Invariance and the Inverse Reactions $C^{12} + \alpha \rightleftharpoons N^{14} + d$

It was pointed out by Henley and Jacobsohn[1] that although time reversal invariance in strong interactions can be investigated by examining detailed balance in an appropriate nuclear reaction and its inverse, no very precise comparisons of this nature were then available.[2] Subsequently, relatively precise polarization and asymmetry measurements have indicated that for p-p scattering at energies near 200 Mev the magnitude of the time reversal noninvariant term of the scattering matrix is not more than a few percent of the average magnitude of invariant terms.[3] The experiment described here approaches the problem through the study of detailed balance in nuclear reactions. It further differs from the p-p experiments in that it also involves n-p forces and is in a quite different energy region.

Following the suggestion of Henley and Jacobsohn, we have measured the angular distributions for the inverse (ground state) reactions C^{12} (α, d) N^{14} and N^{14} (d,α) C^{12}. The observed angular distributions, converted to the center-of-mass system, are shown in Fig. 16. As no attempt was made to establish absolute cross sections, the distributions are arbitrarily normalized to give the closest over-all agreement. The two angular distributions show striking qualitative agreement, and more than half the points for each reaction lie within one probable error (typically about 4 percent) of the common smooth curve.

However, as can be seen in Fig. 16, consistent differences between the two distributions appear in certain regions, notably near 90° and near 130°. A re-examination of experimental difficulties suggests that the differences near 90° may be due to an underestimate of background contributions to the (α, d) counting rates and that the difference near 130° may be due to mechanical errors in determining the (d,α) angles. (Contributions to the errors from other sources, such as incorrect beam energies and multiple scattering losses, are believed to be comparatively small.) These differences are not outside the estimated maximum possible error, and we conclude that they do not represent significant evidence for a departure from detailed balance.

A precise assessment of the upper limit placed by these results upon the fraction of the Hamiltonian which is noninvariant with respect to a time inversion must await analysis in terms of a specific model which can account satisfactorily for the observed angular distributions and which, in addition, can predict their sensitivity to possible violations of time reversal invariance. In the absence of such a theory, we apply the approximate criterion of Henley and Jacobsohn,[1] and conclude that the present results imply that this noninvariant fraction is probably less than 3 percent.

A somewhat more complete description of the experiment and a more detailed analysis of the data have been published.[4] Further details will be presented in a forthcoming paper. (D. Bodansky, S. F. Eccles, G. W. Farwell, M. E. Rickey, and P. C. Robison)

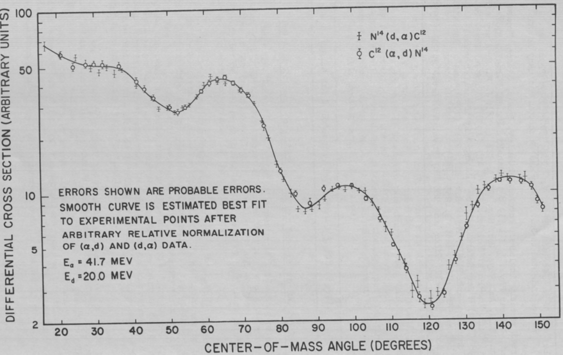

Figure 16

Angular distributions (c.m.) for the inverse reactions $C^{12} + \alpha \rightleftharpoons N^{14} + d$ at matched energies. Probable errors on experimental points include statistical errors and estimated uncertainties in the subtraction of small background contributions to the measured counting rates.

1 E. M. Henley and B. A. Jacobsohn, Phys. Rev. 108, 502 (1957); Phys. Rev. 113, 225 (1959). We are indebted to Drs. Henley and Jacobsohn for many helpful discussions.

2 Work reported recently includes: Burcham, McCauley, Bredin, Gibson, Prowse, and Rotblat, Nuclear Phys. 5, 141 (1958); Bodansky, Eccles, Farwell, Rickey, and Robison, Bull. Am. Phys. Soc. Ser. II, 3, 327 (1958); J. N. Bradbury and L. Stewart, Bull. Am. Phys. Soc. Ser. II, 3, 417 (1958); L. Rosen, Phys. Rev. Lett. 2, 98 (1959). See Reference 1 for bibliography of earlier work.

3 Hillman, Johansson, and Tibell, Phys. Rev. 110, 1218 (1958); and A. Abashian and E. M. Hafner, Phys. Rev. Lett. 1, 255 (1958).

4 Bodansky, Eccles, Farwell, Rickey and Robison, Phys. Rev. Lett. 2, 101 (1959).

NUCLEAR REACTIONS IN WHICH CHARGED PARTICLES ARE EMITTED IN COINCIDENCE

1. The 7.65-Mev Level of C^{12}

The angular distribution for the inelastic scattering of 42-Mev alpha-particles by C^{12}, with excitation of the 7.65-Mev state, has been measured. The experimental distribution shows maxima and minima consistent with 0+ or 2+ spin-parity assignment for the 7.65-Mev state, on an Austern, Butler, McManus type of direct interaction theory. A search was made for coincidences between the inelastically scattered alpha particles and recoil carbon nuclei in an attempt to determine the probability that the 7.65-Mev state decays by electromagnetic transitions to the ground state of C^{12} rather than by breakup into alpha particles. It was found that there is less than one chance in ten that this probability exceeds 0.1 percent. This low probability is not inconsistent with current theories of helium burning in stars and provides additional support for the usual 0+ assignment for the 7.65-Mev state. A more complete account of this work has been published.[1] (D. Bodansky and S. F. Eccles)

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1 S. F. Eccles and D. Bodansky, Phys. Rev. 113, 608 (1959).

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2. Possible Evidence for Compound Nuclear Behavior in (α, 2p) Reactions

There have been a large number of experiments indicating relatively large proton yields in the bombardment of nickel targets. Among these are recent studies of the (p, 2p) reaction in nickel at 23[1] and 40[2] Mev. The suggested interpretation of these results has been in terms of a "direct interaction" in which one of the observed protons is the incident proton.

We are investigating proton emission from Ni^{58} and neighboring nuclei using 30- to 42-Mev alpha particles as projectiles. If, as turns out to be the case for some targets, high (α, 2p) yields are obtained, this can hardly be ascribed to the same direct interaction mechanism which is considered in the (p, 2p) discussions. Instead it suggests that the high proton yield in the (α, 2p) reaction, as well as perhaps in other reactions, may in large part be due to compound nuclear behavior. An experimental indication that proton emission is probable in certain proton-rich nuclei is provided by Ghoshal's demonstration[3] that Zn^{64*} decays more frequently by p + n than by n + n.

In the present experiment the target is viewed in coincidence by two identical "dE/dx-E" scintillation counter telescopes. The "dE/dx" counter uses a thin plastic phosphor and the "E" counter a thicker CsI(Tl) phosphor. The energy threshold of the system is about 2.5 to 3.0 Mev. Full analysis of an event demands examination of each of the two pulses from the two telescopes. To accomplish this the four pulse heights are displayed, with appropriate delays, on an oscilloscope trace. Each coincidence event is separately photographed.

As yet only preliminary information is available. We find the following quite tentative results for bombardment with alpha particles at about 31 Mev:

(a) The total cross section is quite large in Ni^{58}, perhaps of the order of 500 mb.

(b) The total cross sections are considerably smaller in certain other targets. Yields, relative to Ni^{58}, are: Ni^{60}--about 10 to 15 percent; Ni^{62}--less than 5 percent; Fe(natural)--about 10 percent; Cu(natural)--probably less than 5 percent.

(c) The differential cross section (c.m.) of protons from Ni^{58} is rather flat, but probably somewhat greater at forward angles than at backward angles. As yet the analysis has not distinguished between high and low energy protons.

(d) The median proton energy is about 5 Mev. No information is yet available about correlations in proton energy.

A very crude application of "evaporation theory" shows that with reasonable assumptions about nuclear temperatures and barrier heights for protons, one can qualitatively account for the high yields in Ni^{58} and the lower yields in other targets. The possible reduction in cross section at backward angles for Ni^{58}, if substantiated by further data, is not consistent with usual evaporation ideas but may result from a "direct interaction" contribution at forward angles. If this is the case, one would expect Ni^{62}, in which evaporation protons are much reduced in number, to show a strong forward peaking. An additional insight into the mechanism may come from a study of correlations in the energies of the protons. In a compound nucleus model one expects successive emissions to be rather independent and uncorrelated.

A more serious attempt to interpret the results must be postponed until further runs are made and the analysis of the photographic film data is completed. (D. Bodansky, R. Cole, W. G. Cross, C. Gruhn, and I. Halpern)

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1 B. L. Cohen, Phys. Rev. 108, 768 (1957).
2 R. L. Griffiths and R. M. Eisberg, to be published.
3 S. N. Ghoshal, Phys. Rev. 80, 939 (1950).

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3. The C^{12} (α, pα) B^{11} Reaction

A preliminary study has been made of the (α, pα) reaction in C^{12}. This study was made as an outgrowth of a search in several elements for possible "quasi-elastic" (α,αp) events in which one observes both the original alpha particle and an ejected proton. While no evidence was found here for such processes, a prominent (α,αp) reaction was found in C^{12} which we interpret as involving C^{12} (α, p) N^{15*}, followed by alpha emission to the ground state of B^{11}.

These events were studied by determining the pulse height distributions of coincident protons and alpha particles in scintillation counters, during the bombardment of a polystyrene target with 42-Mev alpha particles. A proton group, corresponding in energy to excitation of a N^{15} level (or levels) near 15 Mev, was found which stood out above neighboring proton groups and the background continuum. This group is present in an ordinary (noncoincident) spectrum, as well as in the spectrum seen in coincidence with alpha particles. It was further found that an apparently monoenergetic alpha particle group is emitted in coincidence with this proton group. The energy of the alpha particles corresponds to a transition to the ground state of B^{11}.

The most convincing evidence favoring the interpretation given above for the reactions responsible for the observed coincidence events comes from runs in which the incident alpha particle energy was reduced by several Mev. The proton energy dropped appropriately for an (α, p) reaction to a definite state of N^{15}, while the alpha particle energy was virtually unchanged. This argues against, for instance, inelastic alpha particle scattering followed by proton emission. The internal consistency of the analysis is supported by runs in which the angle of the proton counter was varied and by runs in which the angle of the alpha particle was varied (with the proton counter held fixed). In each case the particle energy changed as expected.

From incomplete angular distribution measurements on the protons in the forward direction (with no coincidence requirement) we estimate the total cross section for the (α, p) process to be, very roughly, of the order of 10 millibarns. Our measurements of the angular distribution are not very reliable since much of this noncoincident data was taken using a counter which did not distinguish deuterons from protons (a better counter has recently been developed and put to preliminary use). For kinematic reasons this could produce no confusion in the coincidence runs, but could in the noncoincidence runs.

Among the experimental problems for future consideration are: (1) the determination of the number of levels (possibly one) relating to the observed proton group; (2) the measurement of the (noncoincident) proton differential cross section; and (3) the measurement of the alpha particle angular distribution (for fixed proton angle) with emphasis upon testing for symmetry about the N^{15*} recoil direction and about 90° with respect to this direction. There are fairly significant (but probably not insurmountable) experimental difficulties in such a program. In view of these difficulties, and in view of the competition of other experiments (such as the (α, 2p) reaction studies described above) we have deferred an attempt to obtain accurate data of the type outlined above.
(D. Bodansky, R. Cole, W. G. Cross, A. Lieber)

RADIATIVE CAPTURE AND HEAVY FRAGMENT EMISSION

1. High Energy Radiative Capture

The "capture" of deuterons and helium ions has been reported in two previous progress reports. Part of this work will appear in the Physical Review[1]. The reaction He^3 (α,γ) Be^7 reaction is being reinvestigated owing to the discovery (see below) that light elements give Be^7 in rather high yield by a pick-up mechanism. It is possible that air contamination of the He^3 target was responsible for the observed production of Be^7. A fresh sample of He^3 has been received from Oak Ridge and the redetermination of the capture cross section reaction is in progress. (J. B. Ball, A. W. Fairhall, and I. Halpern)

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1 J. B. Ball, A. W. Fairhall, and I. Halpern, Phys. Rev. (to be published).

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2. The Alpha Particle Induced Emission of Be^7 from Oxygen and Aluminum

In a search for Be^7 as a light fragment produced in particle-induced fission it was discovered that the observed yield of Be^7 was due to oxygen in the target. Production of Be^7 in aluminum and oxygen targets has been studied, and the excitations functions are shown in Fig. 17. From a study of the number of fragments emitted in the forward direction from the targets, compared with the number emitted backward, it is evident that the Be^7 arises from the He^4 bombarding particle picking up a He^3 fragment from the target nucleus. These results have been submitted for publication in the Physical Review. (G. H. Bouchard, Jr. and A. W. Fairhall)

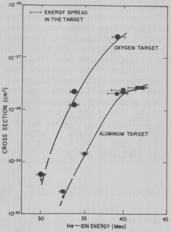

Figure 17

Excitation functions for production of Be^7 in oxygen and aluminum targets by helium ions.

3. A Search for Be^7 Production in the Alpha Particle Bombardment of Vanadium

Investigations have begun on production of Be^7 in other light elements. Vanadium was investigated first because production of Be^7 in V^{51} gives rise to the relatively convenient nuclide 44 h Sc^{48}. Owing to its shorter half life and its greater sensitivity for detection, this species is a more sensitive indicator for Be^7 production than Be^7 itself. The experiment has, however, turned out negative. No Sc^{48} was observed; only 3.4 d Sc^{47} from the reaction V^{51} (α, 2α) Sc^{47} was seen. This latter reaction has a cross section of 0.2

mb at 29 Mev bombarding energy, increasing to 1.5 mb at 40 Mev. An upper limit on the cross section for the production of Be^7 at 40 Mev is 4×10^{-29} cm^2. (A. W. Fairhall and C. Hower)

4. A Counter Study of Particles Heavier than Alpha Particles Emitted from Light Nuclei

To complement the radiochemical measurements on heavy ion production by alpha particles it was decided to undertake a counter experiment. A counter can have the advantage that it is not restricted to investigations of radioactive heavy fragments like Be^7. It can be used to look for Li^6 and Li^7, for example, which might be emitted in even greater amounts than Be^7 because of the generally more favorable Q-values. Offsetting this advantage of counters over radiochemistry is their greater difficulty with particle identification.

The counter that has been built for the investigation is a gridded ionization chamber with three separate collecting plates in series along the path of the particle which is being detected. The last plate is used to provide an anti-coincidence pulse and the first two plates are to be used to determine both the energy and the identity (from the pulse height ratio) of the incident particle. It may be necessary to make frequent pressure readjustments in the chamber to help with particle identification.

Only very preliminary tests have been made of the counter operation. In these tests the counter is run in coincidence with elastically scattered alpha particles from a light element target. In this way, heavy ions like Be^9 or Li^6 of a very definite energy can be sent into the counter in order to calibrate it. (A. W. Fairhall, I. Halpern, C. Hower, and W. J. Nicholson)

INSTRUMENTATION FOR RESEARCH

1. The Development and Construction of Electronic Equipment

Construction and testing is nearing completion for those parts of the 256-channel analyzer (see earlier progress reports) which are necessary for use in a standard one-dimensional analyzer. The print out device and charted recording system were designed locally and have been successfully tested. Testing of the remaining units is in progress. Construction of the additional units necessary for two-dimensional use will be started shortly. It is believed that the data storage and recording facilities of the analyzer may also prove useful in other applications, such as with the multichannel detection equipment of the heavy ion magnetic spectrometer.

Other electronic equipment constructed and tested include the following items: three 2000-volt variable regulated power supplies, two standard linear amplifiers, numerous preamplifiers, one slow coincidence unit, one intermediate speed ($\sim 10^{-8}$ sec) coincidence unit, one linear gate, one time-to-pulse-height-converter (used to investigate the effects of ripple on the cyclotron oscillator power supply), one servo-system for use in the new 60-inch scattering chamber control system, one driver and control unit which replaced the R. F. booster oscillator system on the cyclotron, several pulsers, and several power supplies.

Design, construction, and testing is also in progress on a variety of transistorized circuits. Heavily fed back preamplifiers, for use with photomultipliers, have been built and appear to be stable. A Schmitt trigger type of device for a slow coincidence chassis was constructed and tested, but it had excessive drift. We therefore plan to replace this unit by a much more stable unit similar to a Chalk River circuit which uses a Kandiah type discriminator.[1] We have designed a biased amplifier to drive this unit and preliminary tests indicate the entire chassis to have a drift of less than ± 1 percent over a three-hour period. A fast shaper-coincidence unit was designed, constructed, and tested which has a resolving time of 5×10^{-9} sec or better. A magnet control unit has been built for use on the beta-ray spectrometer.

Major projects for the immediate future include: (1) the completion of the 256-channel analyzer; (2) the design and construction of the data collection system for the heavy ion spectrometer; and (3) the construction of a high power radiofrequency system for pulsed deflection of the cyclotron beam. Much of the future electronic equipment will be placed in the new counting area made possible by the completion of the additional wing on the cyclotron laboratory. In developing and constructing new equipment we hope to make increasing use of transistorized circuits to reduce space, ventilation, and maintenance problems. (Harold Fauska)

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1 A Transistor Trigger Circuit Exhibiting an Accurate Trigger Threshold, CREL-778, F. S. Goulding and L. B. Robinson.

2. A Time-of-Flight Neutron Spectrometer

A time-of-flight neutron spectrometer is being constructed to be used in studies of fission and other nuclear reactions. With a one-meter flight path and 5 mμs over-all resolving time, the spectrometer should have about 15 percent energy resolution at 1 Mev.

The spectrometer is supported in cantilever coaxially with a thin-walled specially-constructed scattering chamber (Fig. 18). It can be rotated around the target from about 10° to about 170° with respect to the beam.

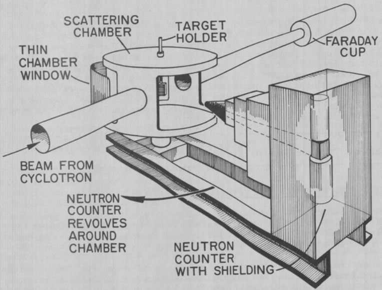

Figure 18

Neutron spectrometer.

The spectrometer will probably be used first to investigate the relative probability for fission at moderate excitation energies according to the method of Harding and Farley.[1] Here one measures the angular correlation between fission fragments (detected by a counter in the scattering chamber) and coincident neutrons. One can learn from such measurements whether the neutrons are evaporated from the moving fragments or from the nucleus before it undergoes fission. Despite the many high energy fission measurements which have been made, it is not yet clear how fissionability does vary with the excitation energy for most fissioning species,[2] and it is hoped that the new apparatus may prove to be useful for this problem. The time-of-flight detector has an advantage over more conventional neutron counters in that it can measure neutron energies as well as angular distributions and can therefore provide more complete kinematical information about the neutron emission process. Its efficiency at energies below 1 Mev can also be higher and more reliable than that of other counters.

The coincidence techniques to be used in this fission study should also be useful in studies of neutron emission in (α, pn), (α, α'n) and similar reactions. In all such measurements, the detection of the charged particle in coincidence with the neutrons provides the time reference for the neutron time-of-flight measurement.

In order to study the emission of neutrons in reactions where no charged particles are emitted, for example (α, 4n) reactions, it is necessary to pulse the cyclotron beam and to obtain time reference signals from the pulsed beam. A pulsing system is being designed by the electronics group which will allow into the scattering chamber only every third bunch of the natural rf bunches of cyclotron beam. When the modulation system is in operation we shall be able to study the angular distributions of evaporated neutrons from moderately excited nuclei. Such studies should be of some interest in alpha-particle induced reactions because of the relatively large amounts of angular momentum with which the compound nuclei are formed. (D. Drake and I. Halpern)

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1 G. N. Harding and F. J. M. Farley, Proc. Phys. Soc. (London) 69A, 853 (1956).
2 I. Halpern, "Nuclear Fission" (to be published).

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3. A Heavy-Particle Magnetic Spectrometer

Over-all design of a high-resolution magnetic spectrometer for precision analysis of nuclear reaction products has been completed. The instrument will weigh more than 20 tons. A contract for construction has been let, with delivery scheduled for between July 1 and August 15, 1959.

The spectrometer is of the single-focusing broad-range type[1] having a first order directional focal surface which allows simultaneous focusing of heavy charged particles within a range of energy 0.5 E_o to 1.1 E_o. (E_o is the particle energy for 90° deflection with the optimum radius of curvature of 35.55 inches.) A schematic diagram of spectrometer and scattering chamber is given in Fig. 19. At the maximum expected operating magnetic induction of 13 kilogauss, E_o is approximately 65 Mev for protons or alphas. The momentum resolution will be equal to or better than

$$\frac{\Delta p}{p} = \frac{1}{2000}$$

for a solid angle of 0.0007 steradians, i.e., for an acceptance angle of approximately ± 2° in a plane parallel to the gap mid-plane. (This is also the scattering plane, and is horizontal.) The maximum useful horizontal acceptance interval is ± 4°.

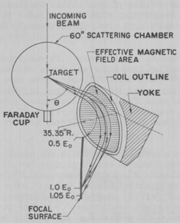

Figure 19

Schematic diagram of heavy-particle magnetic spectrometer in use with the 60-inch scattering chamber. Simultaneous focusing of charged particles extends over the range 0.5 E_o to 1.1 E_o, where E_o is the energy for the optimum deflection of 90°. At the maximum magnetic field E_o is approximately 65 Mev for protons or alphas. The angle of observation θ will range from -10° to +165°. The maximum horizontal acceptance angle is ± 4°. The gap height is 1.2 inches. The momentum resolution is estimated to be $\frac{\Delta p}{p} = \frac{1}{2000}$ for a horizontal acceptance angle of ± 2° (solid angle 0.0007 steradian).

For the present, the spectrometer will be used with the 60-inch scattering chamber at a few selected angles of observation. A continuous range of angles from -10° to +165° will eventually be accessible.

Nuclear emulsion particle observation techniques will be used in some experiments. A matrix of scintillation detectors or n-p junction detectors placed at the focal surface is planned for coincidence work (e.g., charged particle-gamma ray angular correlation experiments).

An adjustable plate or detector surface will provide a means of accommodating the apparent change of focal surface position which results from kinematic effects in light element reactions, thus strongly reducing the problem of kinematic broadening and the attendant loss of resolution. (G. W. Farwell, D. McDaniels, I. Naqib)

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1 C. P. Browne and W. W. Buechner, Rev. Sci. Instr. 27, 899 (1956).

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4. The Development of a "dE/dx-E" Scintillation Counter

A study has been made of some factors involved in obtaining good pulse height resolution in a "dE/dx-E" scintillation counter system.

One of the main troubles encountered in such systems is in the viewing of the first phosphor. For the present purposes plastic was used because uniform thin sections are readily available and it is fast (for possible coincidence applications). It was found that thin (~ 0.017") crystals could be viewed on edge with good efficiency if the end of the crystal makes good optical contact with a lucite disk which is in direct optical contact with the phototube. These optical joints were made using a relatively inert thermosetting plastic called "Unicast." (Unicast if mixed without accelerator does not react with Pilot Scintillator B or lucite and has an index of refraction equal to that of lucite. Unfortunately it does react with CsI).

Another problem in counter design is the choice of reflector. It was found that for optimum performance using MgO as the reflecting material, it is necessary to use quite thick layers of MgO. In fact a 1/4-inch thick reflector gave appreciably larger pulses than a 1/8-inch reflector under test conditions in which a phototube received only reflected light. The need for larger thicknesses probably stems from the fact that the MgO powder is composed of clear crystals of high index of refraction (1.74 for the Na "D" line), and acts as a reflector due to the cumulative effect of many refractions.

A counter including the features discussed above has been built and used (see Fig. 20). The primary purpose of the counter was to detect protons ($\sim$ 15 Mev) in the presence of deuterons. The "dE/dx" and "E" phosphors were a 0.017-inch thick plastic phosphor and a 0.100-inch thick CsI(Tl) phosphor, respectively. The pulse height resolution for 10-Mev protons were $<$ 10 percent for the plastic and $<$4 percent for the CsI. (A. Lieber)

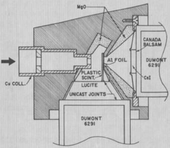

Figure 20

Cross section of "dE/dx-E" scintillation counter.

5. <u>The Design of a Gas Scintillation Counter</u>

Gas scintillation counters offer promise in the detection of heavy charged particles because the pulses are fast and the pulse height is a linear function of the energy loss. In particular they do not have the often undesirable saturation properties characteristic of other fast phosphors such as stilbene or typical plastics.

Previous investigations[1] have established that the pulse height and speed are highly sensitive to impurities. In order to solve this problem a gas handling and purification system has been developed, in which the gas is prepared for use in the following manner: (1) When a pressure of $\sim 10^{-6}$ mm Hg is obtained the gas filling system is closed off from the vacuum pump; (2) xenon from a storage bottle in the filling system is let into the entire system and is trapped with liquid nitrogen at a cold finger in the scintillation counter and purification system; (3) the trapped xenon is then pumped on for a few minutes to remove any oxygen and nitrogen which might have been trapped with the xenon; (4) after isolating the counter and purification system (attached to counter) from the gas handling system, a small amount of xenon ($\sim$ 5 mm Hg) is allowed to pass into the counter and a barium getter box and the barium getter is then flashed; (5) the rest of the gas is then allowed to pass into the counter system to be purified by the action of barium.

A gas scintillation chamber has been constructed for test purposes (see Fig. 21). The scintillation pulses are observed through a quartz window by a DuMont K-1306 photomultiplier. Approximately 300 $\mu g/cm^2$ of P-quaterphenyl was evaporated on the inner reflecting surfaces to serve as a waveshifter.

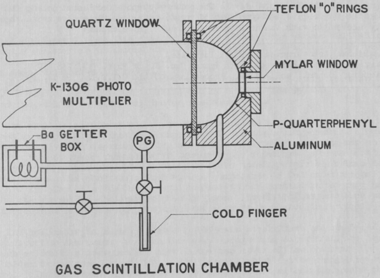

Figure 21

Gas scintillation chamber.

Preliminary results show a pulse height resolution of about 4 percent for the 8.8 Mev alpha particles from a thorium source. The pulse decay times at present are of the order of 10 $m\mu sec$ at a pressure of 25 lbs/in^2. Work at present is being directed toward obtaining more precise information concerning the pulse height resolution, the speed and the stability of the counter. (C. R. Gruhn)

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1 John A. Northrop and Ralph Nobles, Nucleonics 4, 36 (1956).

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6. The Construction of an Ionization Chamber for Neutron Detection

A large gridded ionization chamber (active volume a cylinder of diameter ~ 20 cm x height ~ 20 cm) has been under construction for the past year. This chamber is similar to one constructed by Bichsel,[1] and by Harvey et al.[2] It can be filled with either N^{14} or $B^{10}F_3$ + argon at pressures up to 4 atmospheres for high resolution neutron energy measurements. In principle, resolutions of about 30 kev should be attainable at neutron energies from 1 to 20 or even 30 Mev. The chamber makes use of the well-defined Q values of neutron induced reactions leading to the well separated final states in the reactions: N^{14} (n,α) B^{11},[3] N^{14} (n, p) C^{14} and B^{10} (n,α) Li^7. The primary purpose for constructing the chamber was to investigate the Q values of (p, n) reactions which are above those easily accessible with Van de Graaff machines. (H. Bichsel)

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1 H. Bichsel, constructed at Rice Institute.
2 Harvey, Jackson, Eastwood, and Hanna, Can. J. of Phys. 35, 258, 1957.
3 Gabbard, Bichsel, and Bonner, Proceedings of the C.I.P.N., Paris, 1958.

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1. The 60-inch Scattering Chamber

The 60-inch scattering chamber[1] has been installed in the cave and is ready for use although some of the associated equipment has not been completed as yet.

At the present time this chamber consists of an outer vacuum shell which has an inside diameter of 60 inches and an inside height of 18 inches at the periphery. The shell consists of a 1-inch thick aluminum alloy cylinder with 3/8-inch thick domed aluminum alloy covers. There are reinforcing rims on the edges of both the cylinder and the covers. The vacuum shell is so constructed that flexing or movements due to vacuum loading will not affect the position of any other components such as targets, collimator, counters, etc.

The shell is supported by an accurately machined and positioned steel frame which also supports the interior components of the scattering chamber. These consist of a 59-inch diameter table, two arms, and a target locating and holding device. Each of these components is independently rotatable by remote control by means of servo-mechanisms which operate variable speed, reversible hydraulic transmissions. The position of the various components is indicated remotely to within 0.1°. Controls for the several components are located in the cave adjacent to the chamber and in the present counting room. Provision has also been made to locate controls in the second counting room when it is placed in service.

The collimator is also supported by the main steel frame and can be adjusted with respect to the beam. Targets for normal scattering experiments are inserted through a lock in a large center port in the top cover of the chamber. The target holder is designed to hold up to five targets which can be changed by remote control. The top cover of the chamber can also support either the orange-peel β spectrometer or the polarization spectrometer which are being constructed. Access to the interior of the chamber is obtained by removing the top cover which is clamped to the cylinder rim by means of a hydraulic system. The cylinder wall of the chamber has circular ports in the plane of the beam at 15° intervals on alternate sides of the beam center lines. It also has six rectangular viewing ports. The top cover also contains six circular ports in addition to the large center port. Power and signal connections for equipment in the chamber are provided by a total of 68 coaxial cables that come into the chamber from below. They run along parallel to the axis to a point at which they are conveniently accessible to equipment on the counter trays. The scattering chamber can be moved laterally across the beam in order to place the target and collimator in an optimum position. The entire assembly is supported on braced temperature compensated columns, the bases of which rest on a welded "I" beam structure embedded in the concrete of the floor of the pit below the cave.

The beam enters the chamber through a cylindrical vacuum valve with a 2- by 10-inch aperture which also serves as the high vacuum connection between the chamber and the beam duct. A rough vacuum in the chamber may be obtained either by the main beam duct vacuum system forepump or by an auxilliary mechanical pump. All vacuum valves are air-operated and are interlocked in order to prevent accidental damage to any portion of the system. Duplicate vacuum system controls are located in the main cyclotron control room as well as in the cave. (T. J. Morgan and staff)

1 See the Progress Report, Cyclotron Research, University of Washington, 1957.

2. Building Additions and Modifications

The final design of the magnet for the heavy particle spectrometer resulted in an increase in weight over preliminary estimates. This increase necessitated a re-examination of the strength of the floor of the pit in the cave which is to serve as the foundation for the support structure for both the spectrometer and the 60-inch scattering chamber. Preliminary tests indicated that the pit floor would probably flex under the final load. The flexing of the floor indicated a lack of adequate base for the floor itself so holes were drilled through the floor at strategic locations and fluid concrete was pumped under the floor in order to fill any voids that might exist. Sufficient pressure was applied to just start lifting the floor, thus indicating that all spaces below the floor were filled.

The lower floor of the recent addition to the cyclotron building was completed and occupied in late August, 1958, with the exception of the darkroom which was completed in February, 1959. The upper floor is still unfinished but is being used at the present time by several graduate students for offices and drafting room, by the β spectrometer group for laboratory space, by the engineering and drafting staff for print files, catalog files, and the ozalid machine, and by a cabinet maker as a shop in which various items of furniture and equipment for the laboratory are being built. (T. J. Morgan and staff)

3. The Construction of a New Booster Oscillator

Recurring troubles, both electrical and mechanical, in the original booster oscillator finally led to the design and construction of a new one. The new booster makes use of semiconductor capacitors in place of the mechanical rotating capacitor to provide the frequency modulation. The power output during a duty cycle is increased by employing the pulse modulation technique. The new booster also uses cheaper, more readily obtainable tubes in the output stage and in addition is rack mounted and thus saves the floor space occupied by the old booster cabinet.

The booster oscillator consists of a 6AS6 tube in a Hartley oscillator, the cathode of which is controlled by a transistor switch. The purpose of the switch is to keep the oscillator cut off during normal operation and to delay the starting after a cyclotron spark for a time sufficient to clear the ionized gas released. This is accomplished by a delay multivibrator with a variable time constant which controls the transistor base bias. In addition the transistor switch is turned on and off by a simple pulse width modulation circuit employing a Zener diode. This allows high peak power and low average power to be used in the final power amplifier. A block diagram is shown in Fig. 22.

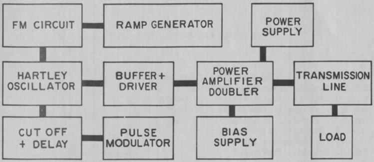

Figure 22

Booster oscillator system.

The grid circuit of the 6AS6 oscillator is swept in frequency by the action of two Vari-Caps (semiconductor capacitors) whose capacitance is varied by a voltage from a separate saw-tooth ramp generator. This results in an FM deviation frequency of 400 kc.

The final power amplifier stage is a pair of 304TL tubes in a push-push arrangement coupled to the cyclotron oscillator by a broad tuned low "Q" line to give as good as possible a ratio of power fed to the oscillator to the power fed back.

Initial experience with the unit indicates that it will prove to be more reliable than the older booster oscillator. (H. Fauska, J. Orth)

APPENDIX

CYCLOTRON PERSONNEL, 1958-1959

Faculty

Hans Bichsel,[1] Acting Assistant Professor
David Bodansky, Associate Professor
W. G. Cross,[2] Acting Associate Professor
Arthur W. Fairhall, Associate Professor
George W. Farwell, Associate Professor
James B. Gerhart, Assistant Professor
I. Halpern, Associate Professor
Fred H. Schmidt, Professor

Cyclotron Research Staff

Sheau-Wu Chen, Research Instructor
Ted J. Morgan, Research Associate Professor; Supervisor, Cyclotron

Graduate Student Research Assistants

Physics

Robert Astrue
Francis Bartis
Harry R. Blieden
Robert K. Cole
Darrel M. Drake
Samuel F. Eccles[3]
Charles Gruhn
John C. Hopkins
Albert Lieber
David K. McDaniels
Thomas Miller
Isam Naqib
William Nicholson, Jr.
Hugh Nutley
Martin Rickey[4]
Gurnam S. Sidhu
Jan Stroth
Chris D. Zafiratos

Chemistry

James Ball[5]
George H. Bouchard[6]
Joe Coleman
Charles Hower
Reilly C. Jensen[7]
Edward F. Neuzil[8]
Richard E. Wilson

Full-Time Technical Staff

Machine Shop

Harvey Bennett, Foreman
Norman E. Gilbertson
C. Denny Glad[9]
Ralph Harbottle[9]
Charles E. Hart
Floyd E. Helton
Gustav Johnson
Bernard Miller, Assistant Foreman
Byron A. Scott
Allen L. Willman

Electronic and Electrical

Robert B. Elliott
Harold Fauska, Senior Physicist, Research Electronics Supervisor
Russell E. Karns, Jr.
John W. Orth
R. W. Peoples, Jr.
Edward Warren

Design and Drafting

Peggy J. Brother[9]
Ralph D. Flaaten, Engineer
Paul Meyer
Peggy Van Arnam

Other

Charles O'Neil
Roberta Rohde, Secretary
Georgia Jo Rohrbaugh, Cyclotron Operator
Eilert Sundby[9]

Part-Time Technical Staff

Cyclotron Operators

David Hendrie
Wayne Knight
John P. Turneaure[9]

Student Helpers

Clifford Hodgkins
Wojciech A. Kolasinski
Patricia Rice
Raymond Soule[9]
Kwong Tin Tang[9]

Other

Gail Lotto

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1 Now at University of Southern California.
2 On leave from Atomic Energy of Canada Limited, Chalk River, Ontario.
3 Now at Instituut Voor Kernphysisch Anderzoek, Amsterdam, Holland.
4 Now at University of Colorado.
5 Now at Oak Ridge National Laboratory.
6 Now at Sandia Corporation, Albuquerque, New Mexico.
7 Now at San Diego State College.
8 Now at Western Washington College of Education, Bellingham, Washington.
9 Terminated.