Nuclear Reactions Resulting from the Proton Bombardment of Aluminum*

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The energy dependence of reaction product yields from aluminum bombarded by protons has been measured in the energy range from 1.4 Mev to 4 Mev with fairly high energy resolution. Yield curves are shown for elastically scattered protons, alpha-particles (both full energy and those leaving the residual nucleus Mg^{24} in the first excited state), gamma-radiation, and, over a limited range, inelastically scattered protons leaving the residual nucleus Al^{27} in the first two excited states. The gamma-ray yield at proton energies above 2 Mev is shown to be principally from the excited residual nuclei. All reactions show a pronounced resonance structure.

I. INTRODUCTION

THE interaction of high energy protons with aluminum nuclei was first studied by measurements[1] of the dependence on bombarding proton energy of the yield of gamma-radiation. These yield curves indicated that the gamma-rays are produced by resonance reactions with the resonance energies associated with high-lying levels in the compound nucleus Si^{28}. Secondary electron absorption measurements of the gamma-radiation showed that it must be due to the radiative capture process. Subsequent work on this reaction includes that of Brostrom, Huus, and Tangen,[2] who measured absolute cross sections for resonances up to 1.4 Mev, and Bender, Shoemaker, and Powell,[3] who attempted to determine the total width of one level by bombarding thin targets with a proton beam of small energy spread.

Other reactions have also been studied. The work of Dicke and Marshall[4] and Fulbright and Bush[5] on inelastically scattered protons showed the existence of low-lying energy levels in the Al^{27} residual nucleus. Freeman and Baxter[6] measured the yield of alpha-particles up to a proton bombarding energy of 1 Mev. Their yield curve showed several broad resonances, but no correlation could be made with the gamma-ray yield curves, because of inadequate resolution. The energy dependence of the elastic scattering of protons in the neighborhood of one resonance was recently studied in this laboratory by Bender, Shoemaker, Kaufmann, and Bouricius.[7] From the amplitude of the variation from Rutherford scattering, with the assumption of zero angular momentum for the incident protons, an estimate was made of the width of the level. Although this work was very limited in scope, it showed that proton scattering was potentially a useful tool for studying resonance levels.

A program was planned for continuation of work on proton resonance reactions at this laboratory, with the aim of determining the partial widths (transition probabilities) for the various possible modes of decay of the energy states of compound nuclei, and the eventual assignment of angular momentum quantum numbers to these states. The decision to use aluminum for the target material for the first work was made in view of certain disadvantages—the data for a target nucleus with spin 5/2 is more difficult to interpret than data for a target nucleus with spin zero, and the sharpness of the levels in the low energy region makes the measurement of the widths difficult (reference 7). Aluminum, however, has the advantage of having only one isotope, and targets of this material are easy to prepare. Its high proton-neutron threshold was also thought to be an advantage, since an intense neutron yield could interfere with measurement of other disintegration products.

II. APPARATUS

For the observation of charged reaction products, some form of particle analyzer was needed. After consideration of various possibilities, a focusing homogeneous-field magnetic analyzer was found to satisfy the requirements. Materials were on hand for the construction of a magnet with pole pieces $8\frac{1}{2}$ inches square. For 90° deflection, this size allows a deflection radius of 19.1 cm so that a field of 15,200 gauss is sufficient for 4-Mev protons or alpha-particles. The magnet as constructed gave a maximum field strength of 16,000 gauss with 34,000 ampere turns for a gap of $\frac{1}{2}$ inch. To eliminate fluctuations in the magnetic field, the voltage developed across a resistance in series with the coils was compared with a battery; the error signal so obtained was amplified and applied to the control field of an Amplidyne generator which supplied the coil current. The gain and stability of the circuit were such

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1 Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937); W. Gentner, Z. Physik **107**, 354 (1937); Plain, Herb, Hudson, and Warren, Phys. Rev. **57**, 187 (1940).
2 Brostrom, Huus, and Tangen, Phys. Rev. **71**, 661 (1947).
3 Bender, Shoemaker, and Powell, Phys. Rev. **71**, 905 (1947).
4 R. H. Dicke and J. Marshall, Phys. Rev. **63**, 86 (1943).
5 H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).
6 J. M. Freeman and A. S. Baxter, Nature **162**, 196 (1948); J. M. Freeman, Proc. Phys. Soc. (London) **A63**, 668 (1950).
7 Bender, Shoemaker, Kaufmann, and Bouricius, Phys. Rev. **76**, 273 (1949).

that over a three-hour period the current was constant to 0.01 percent.

In the first parts of the experiment the magnetic field was measured by a flip coil and fluxmeter. The precision of these measurements was marginal, and considerable operator fatigue was involved, so that this was replaced by a balance which measured the torque on a coil carrying a known current.[8]

Figure 1 shows a plan section of the analyzer and target chamber. The incoming proton beam passed through a 2-mm×2-mm tantalum aperture which defined the illuminated area on the target, which in turn acted as the entrance slit of the magnetic analyzer. The solid angle subtended by the analyzer at the target was 0.0028 steradian. It was defined by an aperture located close to the pole pieces so that it prevented secondary small angle scattering from the pole faces. The exit slit was 1.0 cm wide, considerably wider than

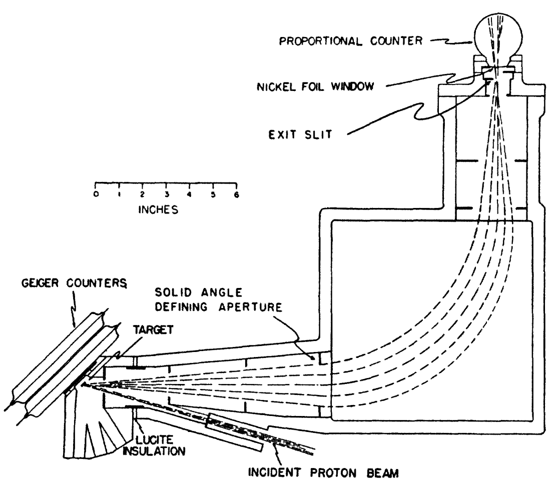


FIG. 1. Schematic of the experimental arrangement. The 90° magnetic analyzer served to separate the various charged particle groups from one another and from the scattering by the target backings. Alpha-particles were distinguished from protons by counter pulse-height discrimination.

the image formed by the magnet, to give a flat-topped window function, and the jaws were staggered so that they lay in the image plane. The energy dispersion was 16.7 cm, and the width of the flat top of the window function was about 4 percent in energy. The target chamber was constructed with four ports for the incoming proton beam, to make possible yield measurements at several angles with respect to the incident beam. The port used in the present experiment was the one which gave the closest approach to the backward direction. Since the analyzer accepted particles over a 10° range, the angle of observation of scattering and charged particle disintegrations extended from 159° to 169° with respect to the incident proton beam.

To inhibit the formation of an oil film on the target surfaces, the targets were mounted on a heated support, and a liquid air trap was used between the diffusion pump and the analyzer chamber. The target support could be moved to change targets without disturbing the vacuum, and without disturbing the vacuum the target support could be transferred to an evaporation chamber for deposition of the target film.

The target chamber was insulated from the remainder of the apparatus by Lucite plates so that it formed a faraday cage. Electrons released by the proton beam striking the target or the beam defining aperture were prevented from passing into or out of the target chamber by electron barriers maintained at minus 300 volts. A circuit[9] was arranged to turn off the scalers after a specified quantity of charge had been collected. This circuit is believed to be dependable to ±0.1 percent.

Charged particles were counted by a proportional counter consisting of a 2-inch brass tube with a 0.003-inch coaxial molybdenum wire for the anode. The window was of nickel foil, 0.0001-inch thick for the first parts of the experiment, and 0.00005-inch thick for the later parts when alpha-particles had to be counted. The counter gas was argon with 2 percent CO_2 added. The pressure varied between 2 cm and 20 cm, depending on the energy and type of particle being counted. Gamma-rays were counted by Radiation Counter Laboratories' thin-wall beta-counters. A sheet of lead was placed between the counters and the target to improve the counting efficiency.

III. EXPERIMENTAL PROCEDURE AND RESULTS

The data were taken in a number of different runs, with somewhat different experimental procedures. Although these data are in some cases grouped together for ease of comparison, the different runs will be discussed individually.

Run 1

Before proceeding with detailed studies on any one resonance or small group of resonances, it appeared desirable to make a relatively rough survey of the elastic scattering and gamma-ray yields, which would indicate where resonance levels were to be found. Since the previous work by Plain *et al.*[1] and Brostrom *et al.*[2] gave a clear picture of the energy region up to 1.4 Mev, it was decided to extend this survey from 1.4 Mev to the limit of the electrostatic generator, about 4 Mev. Targets for this run were prepared by evaporation of aluminum (specified purity, 99.99 percent) onto diamond chips. The diamonds provided smooth surfaces and were sufficiently free from impurities. The magnetic analyzer was thus able to separate the protons scattered by the aluminum film from all other scattering. The field in the analyzer was changed at intervals to follow the energy of the scattered protons. Because of the flat-topped window func-

[8] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[9] G. M. B. Bouricius and F. C. Shoemaker, Rev. Sci. Instr. **22**, 183 (1951).

tion, the proton energy could be varied 4 percent between changes in the magnetic field. After each change in the magnetic field, the last point taken before the change was repeated as a check on the accuracy of the field setting. Sharp resonances in the elastic scattering could be missed if either the energy spread due to target thickness and proton beam inhomogeneity were large compared with the resonance width, or if the energy steps between points were appreciably larger than this energy spread. Therefore, the energy interval between points, 1.5 kev, was made as small as practicable for a survey covering an energy region this large, and the instrumental energy spread was maintained about equal to this energy step. The data are shown in Fig. 2, labelled "Elastically scattered proton yield." The gamma-ray data taken in this run are now shown because the background from the carbon target backing was so intense as to render them almost meaningless.

Run 2

For comparison of the level structure in this energy region with the structure below 1.4 Mev which had been found by previous workers, it was felt that a gamma-ray yield curve was needed. In addition, because the work of Freeman and Baxter[6] showed that the (p,α) reaction could be an important competing process, it was decided to take an alpha-particle yield curve at the same time. Since the (p,α) reaction is exothermic, the alpha-particles could be separated readily by the magnetic analyzer from the protons scattered by a heavy target backing. Tantalum was chosen for the target backing because its gamma-ray yield under proton bombardment is very small. In this run, the target thickness was chosen about eight times larger than that used in Run 1 so that weak broad resonances would be detected. The resulting increase in the instrumental energy spread allowed a larger energy step between points to be used. The data from this run are shown in Fig. 2, labelled "Gamma-ray yield" and "Alpha-particle yield—full energy group." The gamma-ray yield shown is that recorded by a single Geiger counter. The alpha-particle yield curve was later extended to lower proton energies to overlap the gamma-ray yield curves obtained by previous workers.

Run 3

Although the alpha-particle yield curve showed resonance levels quite well separated, the gamma-ray yield curve showed many more levels which overlap substantially in the high energy region. To get information regarding the origin of this radiation, estimates were made of the gamma-ray energy by coincidence counter absorption measurements[1] on the secondary electrons ejected by the gamma-rays from a lead converter. Absorption curves taken at eight different incident proton energies are shown in Fig. 3, together with the corresponding half-thicknesses of aluminum absorber. At the two lower incident proton energies, the half-thickness corresponds to the order of 10-Mev gamma-ray energy, while for higher incident proton energies, the half-thicknesses correspond to gamma-ray energies of the order of 1 to 2 Mev. The hard gamma-rays observed at the lower proton energies are due to the radiative capture process, but it was believed that some other process, such as inelastic scattering, must be responsible for the soft radiation.

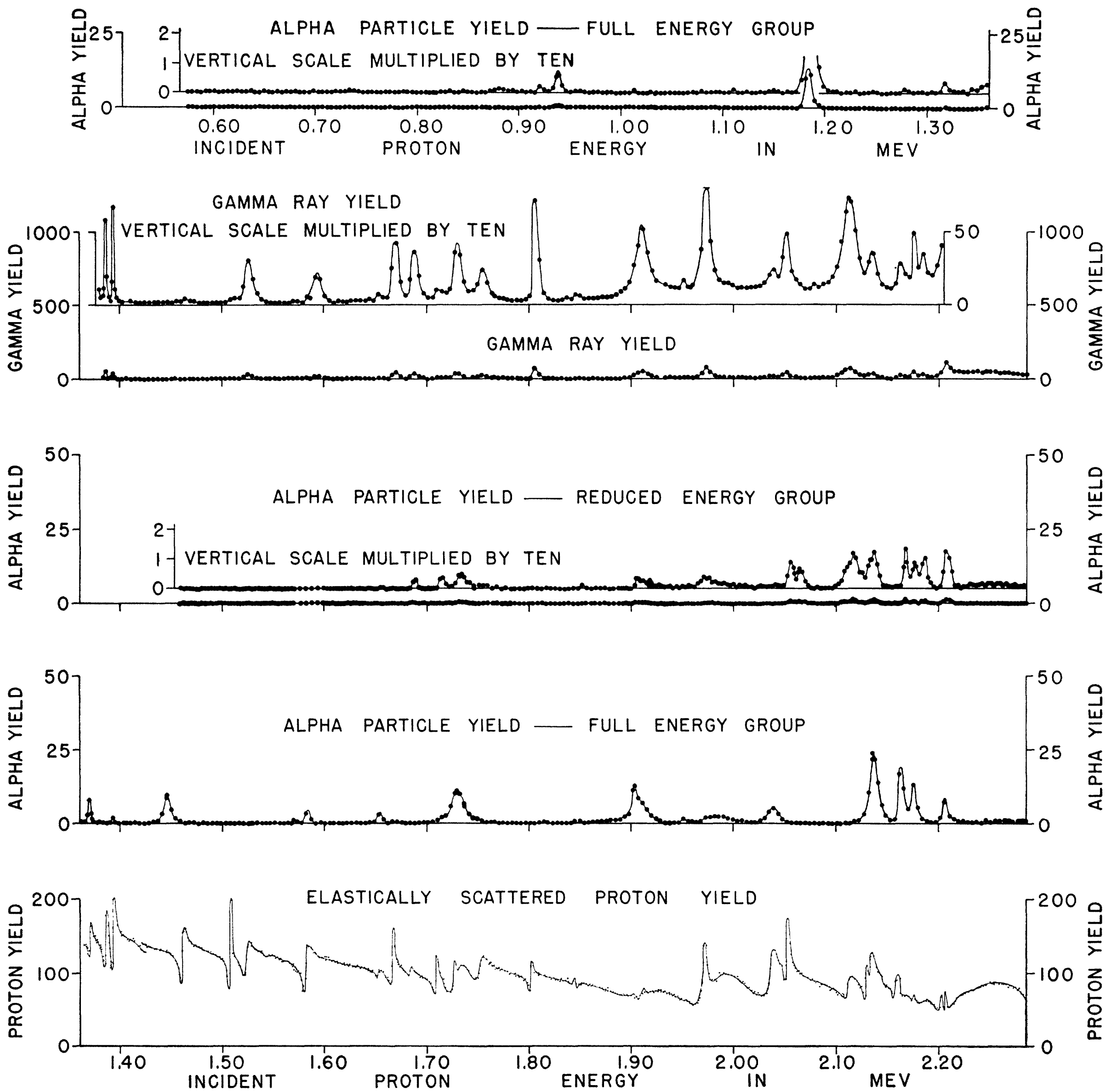
To make possible the detection of inelastically scattered protons, the apparatus was modified so that the proton beam could pass through a thin self-supporting aluminum foil (about 25-kev thick for 3-Mev protons). Momentum analyses of the scattered and disintegration particles were then made at four different incident proton energies, alpha-particles being distinguished from scattered protons by counter pulse-height discrimination. These data are shown in Fig. 4. A reduced energy alpha-particle group appears, as well as several inelastically scattered proton groups. The apparent structure in the full energy alpha-particle group was shown later to be the result of the thickness of the target. From the positions of the peaks, the Q-value for each group was computed. From these the excitation energies of the corresponding states in Al^{27} and Mg^{24} can be obtained. In this work no attempt was made to obtain accurate Q-values. Targets used were relatively thick and the analyzer was adjusted to be as insensitive as possible to magnetic field setting. Values obtained for energy level positions, which are shown in Table I, are sufficiently accurate to show unambiguous correspondence with levels previously observed.

Run 4

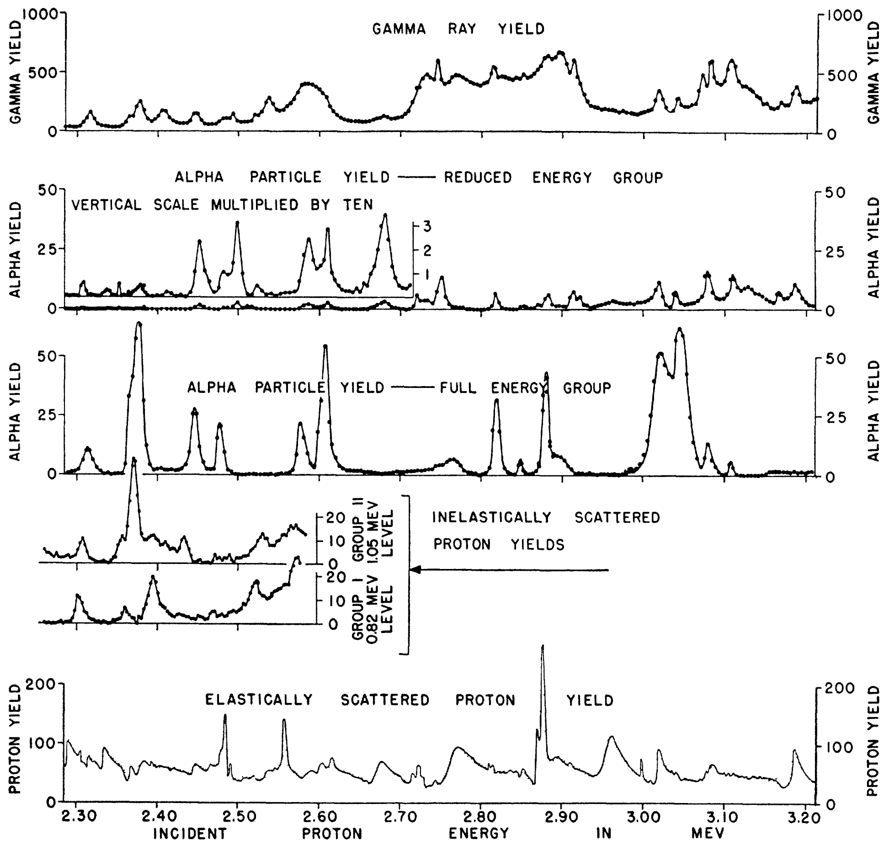
The absorption curves indicated that very little, if any, of the gamma-radiation at the higher proton energies was due to the radiative capture process, but the curves for the two lower proton energies, and the work of Plain *et al.*[1] show virtually no soft radiation. To find where the transition between hard and soft gamma-radiation takes place, and to establish that the soft radiation comes from excited residual nuclei, yield curves were obtained for hard gamma-radiation, the reduced energy alpha-particle group, and the inelastically scattered proton groups which leave the aluminum in the 0.82-Mev and 1.05-Mev excited states. Since scattering from a thick target backing would mask these low energy particle groups, and since self-supporting aluminum foils corresponding to the desired target thickness were unavailable, the aluminum was evaporated onto 1000A nickel foil.[10] The target thickness was about the same as that used in Run 2, and the yields were normalized to the same thickness. The hard gamma-radiation was detected by coincidence counters with 3.5 mm of aluminum absorber between

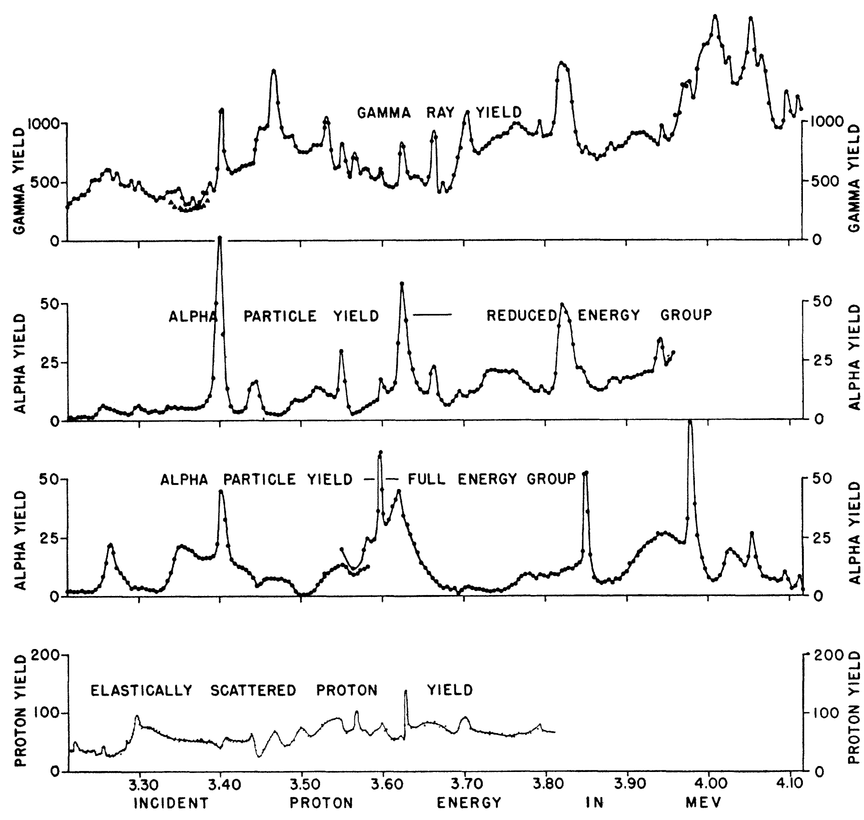
[10] S. Bashkin and G. Goldhaber, Rev. Sci. Instr. 22, 112 (1951). This technique was developed after the first parts of the present experiment were completed.

FIG. 2. Reaction yield curves from thin aluminum targets bombarded by protons. The charged particle yields were taken at an angle of 164° with respect to the incident proton beam. The solid angle of observation was 0.0028 steradian. The gamma-ray yields are those recorded by a single Geiger counter located about a centimeter from the target. Elastically scattered proton yields were taken with a target about 750 ev thick for 3-Mev protons. Full energy alpha-particle and gamma-ray yields were taken with a target about 6 kev thick for 3-Mev protons. Reduced energy alpha-particle and inelastically scattered proton yields were taken with a target about 7 kev thick for 3-Mev protons and normalized to a target 6 kev thick. Accurate comparison of yields cannot be made because of the possibility of different angular distributions and the variation of peak yields with the ratio of target thickness to resonance width. Yield values are the number of counts, divided by 64, recorded for 48 microcoulombs of incident protons. The low energy extension of the full energy alpha-particle yield curve was taken to overlap the gamma-ray yield curves taken by previous workers. The gamma-radiation at proton energies above 2 Mev is mainly from excited Al^{27} and Mg^{24} residual nuclei. Note that, with few exceptions, for each resonance shown on the yield curves for absorption processes, there is a resonance in the elastic proton scattering. Note also that while the resonances in general are broader for the higher proton energies, very sharp resonances are found up to the highest energies reached.



the Geiger tubes. The reduced energy alpha-particle yield and the hard gamma-yield were taken together. The inelastic scattering yield curves were taken over a limited region only, because in the region covered, combined with the reduced energy alpha-yield curve, they satisfactorily accounted for the gamma-ray yield. The data from this run are shown in Fig. 2, labelled "Alpha-particle yield—reduced energy group," and "Inelastically scattered proton yields." The hard gamma-ray yield is not shown, because it was not detected above 1.8 Mev, except for one slight indication at 2.72 Mev. The coincidence counter efficiency was


GAMMA YIELD
GAMMA RAY YIELD
ALPHA PARTICLE YIELD —— REDUCED ENERGY GROUP
VERTICAL SCALE MULTIPLIED BY TEN
ALPHA YIELD
ALPHA PARTICLE YIELD —— FULL ENERGY GROUP
GROUP II 1.05 MEV LEVEL
GROUP I 0.82 MEV LEVEL
INELASTICALLY SCATTERED PROTON YIELDS
PROTON YIELD
ELASTICALLY SCATTERED PROTON YIELD
2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10 3.20
INCIDENT PROTON ENERGY IN MEV


GAMMA YIELD
GAMMA RAY YIELD
ALPHA YIELD
ALPHA PARTICLE YIELD —— REDUCED ENERGY GROUP
ALPHA PARTICLE YIELD —— FULL ENERGY GROUP
PROTON YIELD
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INCIDENT PROTON ENERGY IN MEV

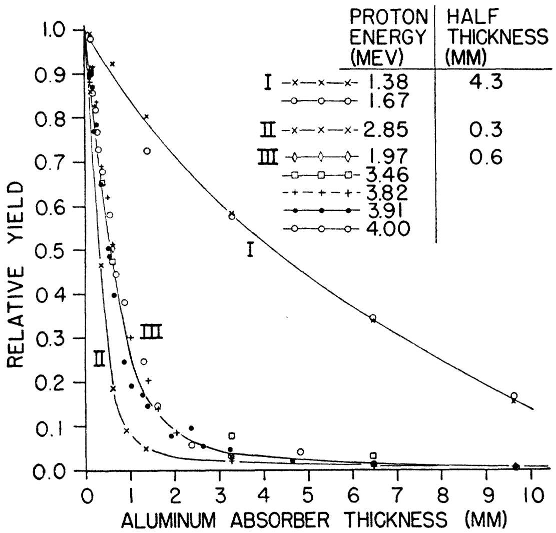

FIG. 3. Absorption curves for electrons ejected from a lead converter by gamma-rays from aluminum targets bombarded by protons. The corresponding gamma-ray energies are about 10 Mev for the two lower proton energies, and 1 to 2 Mev for the higher proton energies.

such that if 10 percent, or in most cases less, of the radiation were hard, it would have been detected.

IV. DISCUSSION

In the energy region covered, all reactions resulting from the proton bombardment of aluminum are resonance processes. The resonance levels are broad enough to overlap appreciably at the highest proton bombarding energies, but there is no continuum evident. While the gamma-ray yield curve seems to indicate a continuum, it must be remembered that it is in effect the sum of a number of separate yield curves. This indicates that the compound nucleus picture is valid for discussion of the reactions resulting from the bombardment of aluminum by protons in this energy range. With few exceptions, for every resonance shown on the yield curves for gamma-rays, alpha-particles (both full and reduced energy), and inelastic scattering, there is resonance elastic scattering. This is to be expected, for any state of the compound nucleus formed by proton capture must be capable of decay by emission of a proton with the full energy available. There is, however, less correlation among the yield curves for the alpha-particles and inelastic scattering. Evidently there are wide variations in the partial widths for modes of decay of the compound nucleus from resonance to resonance. An accurate comparison of the partial widths for the different reactions cannot be made because observations were made at only one angle, and because of the variation of the peak yield with the ratio of target thickness to resonance width. The resonances in the lower energy regions are narrow, but at higher proton bombarding energies broad levels appear mixed with narrow levels.

TABLE I. Energy levels in Al^{27} and Mg^{24}.

Isotope	Levels listed in AEC compilation*	Computed from momentum analyses 14*B*	14*C*	14*D*
	Mev	Mev	Mev	Mev
Al^{27}	+0.84	+0.81	+0.83	···
Al^{27}	+1.07	+1.05	+1.04	···
Al^{27}	+1.48		not observed	
Al^{27}	+1.79		not observed	
Al^{27}	+2.28	···	+2.25	+2.20
Al^{27}	+2.82	···	···	+2.75
Mg^{24}	+1.38	+1.30	+1.35	+1.24

* D. E. Alburger and E. M. Hafner, AEC-549, BNL-T-9.

This investigation was undertaken with the hope that the resonance structure would be sufficiently simple that the partial width, the angular momentum, and the parity might be determined for each level. The excitation curves shown in Fig. 2 were meant to be only a preliminary survey of the energy region. In many cases resonances are well resolved, but the targets were not sufficiently thin to permit determination of their true shape. For example, the apparent overlapping of the three scattering resonances just below 1.40-Mev (Fig. 2, Proton yield) can be attributed almost entirely to the effects of target thickness. Results (not shown) in this energy region, obtained with thinner targets and higher energy resolution, show these levels very well separated with short regions between levels which appear to follow Rutherford yield.

Except for resonance regions, the elastic scattering yield varies inversely with energy squared up to a proton energy of about 2.5 Mev. Estimates from calculated target thickness indicate that the scattering cross sections between resonances are close to Rutherford values up to this energy. However, the data are presented as proton yields rather than differential scattering cross section, since the cross-section values in the neighborhood of the resonances are uncertain because of inadequate resolution.

Considerable effort was spent in trying to assign widths and *J*-values to a few levels that are sufficiently far from neighboring levels so that a one-level Breit-Wigner formula could be used. Each scattering resonance tried could be fitted with a formula of the form

$$Y=|Y_R^{\frac{1}{2}}+Ae^{i\phi}e^{i\delta}\sin\delta|^2,$$

where Y = observed yield, Y_R = Rutherford yield, $A=Y^{\frac{1}{2}}_{max}\pm Y^{\frac{1}{2}}_{min}$, ϕ is an empirically determined angle, and $\tan\delta=-\frac{1}{2}\Gamma/(E-E_R)$, Γ being the total width. Because of the large spin of the ground state of the aluminum nucleus (5/2), and the large number of competing reactions, the formulation of A and ϕ in terms of the usual parameters used in the description of scattering phenomena is ambiguous. In no case could the angular momentum of a level be uniquely assigned.

Extension of this work to include data on the angular distribution of reaction products had been planned, but consideration of the problem now indicated that such data would not, in most cases, lead to unambiguous assignment of angular momentum.

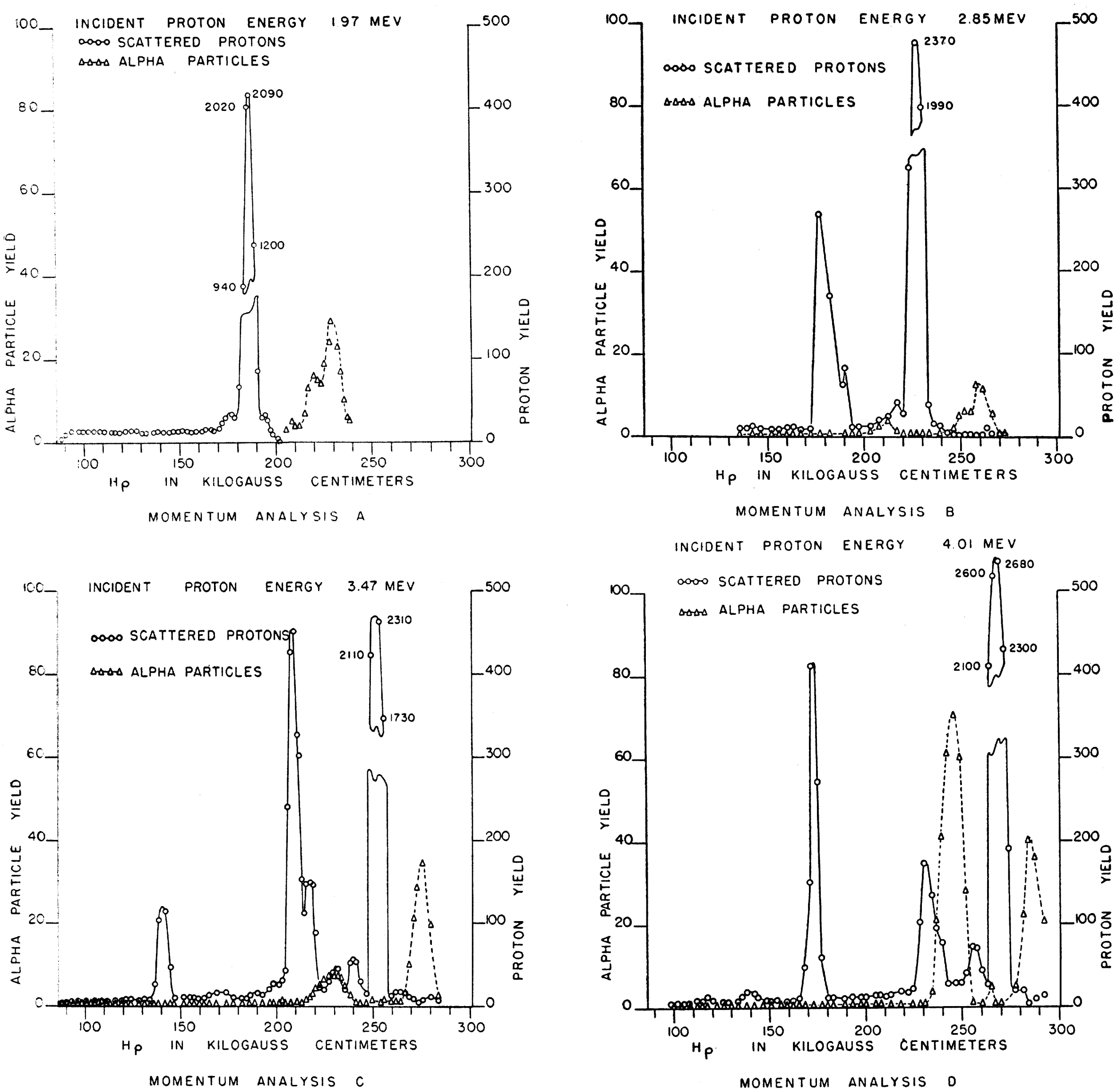

FIG. 4. Momentum distributions of particles from an aluminum target, 25 kev thick for 3-Mev protons, bombarded with protons of four different energies. Four groups of inelastically scattered protons and two alpha-particle groups, corresponding to transitions to the ground state and first excited state of Mg^{24} are evident. The apparent structure of the full energy alpha-particle peak is due to the thickness of the target.

It would appear that the analysis of the angular distribution of the full energy alpha-particles would be particularly revealing, since the spins of the alpha-particles and of the residual Mg^{24} nuclei are both zero. Consequently, the orbital angular momentum of the alpha particles is equal to the J-value of the compound state in Si^{28}. However, according to Eisner and Sachs,[11] the largest power of $\cos\theta$ that can appear in the angular distribution is twice the smaller of the two orbital angular momenta involved—namely, that of the incident proton and of the emitted alpha-particles. For example, if the incident protons are S-protons, the angular distribution of the alpha-particles will be symmetric, regardless of their orbital angular momentum.

Detailed studies of yields with angular distribution measurements might, for certain levels, lead to assignment of angular momentum quantum numbers and parity. However, if such measurements were to be made on a large fraction of the levels observed, the time and effort required would be prohibitive. The work was therefore discontinued.

The authors are indebted to Professors R. G. Herb and R. Rollefson for advice and encouragement throughout the experiment, to M. Cutler and L. J. Koester for their help in taking data, and to G. Goldhaber for the construction of the magnetic balance used for measurement of the magnetic field.

[11] E. Eisner and R. G. Sachs, Phys. Rev. 72, 680 (1947).