per gram per sec. produced in the surrounding water by the cosmic radiation.

It will be noted that this figure is slightly higher than that estimated from the balloon data. The reason for this, as has already been pointed out, is that in the balloon flights the bias is set at a sufficiently high value so that only the larger pulses are detected, and, hence, some neutrons are missed. This procedure is necessary in unmanned flights to preclude the inclusion of spurious counts and electrical noise. Hence, our estimates of the number of neutrons should be based on the mountain data and not on the flights carried on to date. For example the number of neutrons estimated by Libby[7] from our data should be somewhat more than doubled.

[7] F. W. Libby, Phys. Rev. 69, 671 (1946).

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Gamma-Rays from Alpha-Particle Reactions*

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Gamma-rays from sodium, magnesium, aluminum, silicon, phosphorus, and sulfur targets under cyclotron bombardment by 7-Mev alpha-particles have been observed. Energies were obtained by measuring the maximum range of Compton-recoil electrons in aluminum, using two beta-ray counters in coincidence. The following gamma-ray energies were found: sodium, 1.85 ± 0.15 Mev and 2.80 ± 0.25 Mev, with an intensity ratio of 6 to 1; magnesium, 1.8 ± 0.2 Mev and 4.3 ± 0.3 Mev, with an intensity ratio of 3 to 1; aluminum, 3.5 ± 0.3 Mev; silicon, 2.3 ± 0.3 Mev; phosphorus, 2.55 ± 0.25 Mev and 4.1 ± 0.4 Mev, with an intensity ratio of 8 to 1; sulfur, 2.4 ± 0.3 Mev. In cases where correlation can be made with energy levels given by the corresponding αp reactions the transition from the second excited state to ground in the product nucleus seems to be favored.

I. INTRODUCTION

THE presence of gamma-radiation in nuclear reactions gives the most direct evidence for the existence of excited states in the product nucleus. In the case of alpha-particle bombardment of the light elements gamma-radiation has been reported,[1] but few reliable energy measurements have been made. This is in contrast to the relatively large amount of consistent data on αp reactions from which energy levels in the final nucleus can be inferred from proton groups. Another approach to the problem is the association of gamma-radiation with particle groups resulting from a nuclear reaction. This has been studied in only a few cases, most recently by Benson who performed[2] proton-gamma coincidence experiments on the $Al^{27}(\alpha p)Si^{30}$ reaction at specific values of proton energy but without

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[1] M. Stanley Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 298 (1937).

[2] Bruce B. Benson, Phys. Rev. 73, 7 (1948).

regard to gamma-ray energy. Coincidences were obtained for protons to the excited states of the Si^{30} nucleus but none were observed for protons to the ground state.

The gamma-ray energy spectrum gives further useful information. If this has been determined, the level separations obtained from proton groups may be compared with independent measurements on quantum transitions in the final nucleus. In addition, the relative gamma-ray intensities may be used to determine transition probabilities and selection rules according to which the product nucleus drops to the ground state. Some work along this line has recently been done.[3] Absorption in lead of gamma-radiation from Na, Mg, Al, Si, P, and S targets under alpha-particle bombardment has been studied and absorption coefficients obtained. The predominant radiations were found to be in a 1.5–5-Mev energy range. Because of the minimum in the lead-absorption curve at 3 Mev, a determination of the energies present in all cases was not possible. However, since the energies were considerably greater than the level separations from other evidence, it seemed that direct transitions were preferred to cascade.

Another gamma-ray measurement technique consists in observing the maximum range of Compton-recoil electrons in aluminum. This method was first described[4] by Bothe and Kolhörster and later applied[5] by Becker and Bothe to the gamma-rays excited in B and Be by alpha-particles. Curran, Dee, and Petržílka used[6] the scheme to measure the gamma-rays resulting from proton capture by Be, B, C, and F. More recently Deutsch has measured[7] the gamma-rays of La^{140}. The method consists in placing two thin-window beta-ray counters on a line with the source so that gamma-rays falling on the end wall of the first counter produce recoil electrons in the forward direction which traverse both counters giving coincidences. By inserting aluminum between the counters the number of coincidences decreases in a roughly logarithmic fashion from a single gamma-ray energy. The thickness of absorber at which counts are reduced to the random coincidence rate gives the maximum range of the electrons. Applying the modified Feather relation[8] for the maximum range of beta-rays in aluminum,

$$\text{range (g/cm}^2\text{ Al)} = 0.571E\ (\text{Mev}) - 0.161,$$

the electron energy may be calculated. Addition of the back-scattered quantum energy gives the incident gamma-ray energy. The method is good to 5–10 percent accuracy for a single gamma-ray. If two gamma-rays are present it is difficult to single out the softer component unless well separated in energy and three or more times the intensity of the harder component. In such a case a break in the curve will appear at an absorption corresponding to the lower energy gamma-ray.

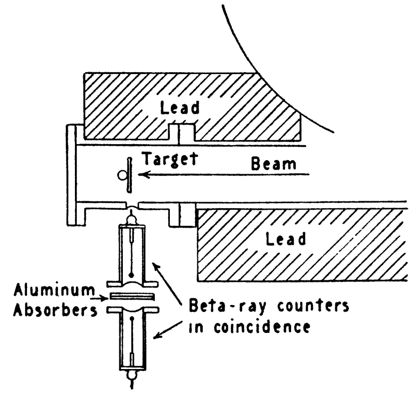

FIG. 1. Experimental arrangement for measuring the maximum range in aluminum of Compton-recoil electrons produced by gamma-rays from targets under cyclotron bombardment.

In the present work this coincidence method has been applied to the gamma-rays resulting from the alpha-particle bombardment of Na, Mg, Al, Si, P, and S and an attempt has been made to correlate the energies obtained with levels of excitation observed in αp studies.

II. EXPERIMENTAL

Figure 1 shows the experimental arrangement. A 7-Mev alpha-particle beam is brought out from the main cyclotron chamber into an external

[3] Ernest Pollard and D. E. Alburger, Phys. Rev. 72, 1196 (1947).
[4] W. Bothe and W. Kolhörster, Zeits. f. Physik 56, 751 (1929).
[5] H. Becker and W. Bothe, Zeits. f. Physik 76, 421 (1932).
[6] S. C. Curran, P. I. Dee, and V. Petržílka, Proc. Roy. Soc. 169, 269 (1938).
[7] M. Deutsch, Manhattan Engineer District, LAMS Report 142, Series c; MDDC Report 237, October, 1944.
[8] E. Bleuler and W. Zünti, Helv. Phys. Acta 19, 137 (1946).

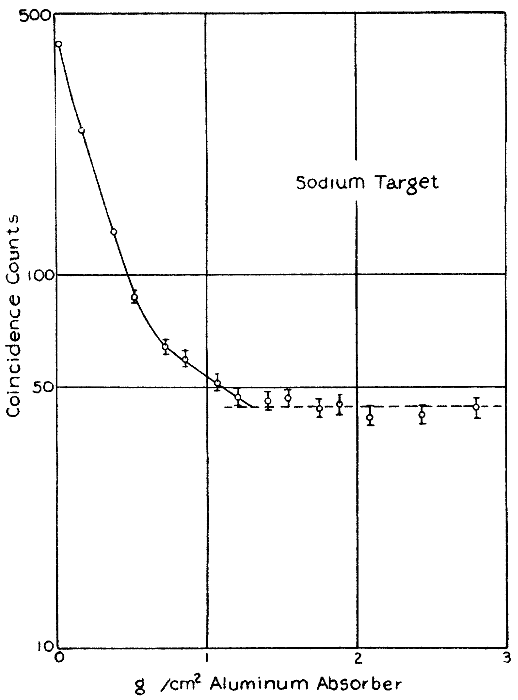

FIG. 2. Absorption of Compton-recoil electrons produced by gamma-rays from a sodium target under alpha-particle bombardment, indicating the presence of two gamma-ray energies.

bombardment chamber. Targets are attached to a tin holder and consist of Na, Mg, and Al metals, fused silicon, red phosphorus, and sulfur fused with gold dust for beam current conduction. To minimize absorption of gamma-radiation from the target by the wall of the bombardment chamber a foil window has been provided. Two thin-window beta-ray counters are placed outside the bombardment chamber on a line with the target. These are shielded by lead blocks located so as to reduce stray radiation from the main cyclotron chamber. As previously described, Compton-recoil electrons are produced by gamma-rays from the target falling on the brass end and side walls of the first counter. Some of these pass through both counters, resulting in time-coincident pulses. Separate inputs connect the two counters to a double-coincidence recording circuit. The first counter input circuit also operates a scaling and recording circuit. The number of counts registered by this circuit is independent of the absorber placed between the counters and may therefore be used to integrate

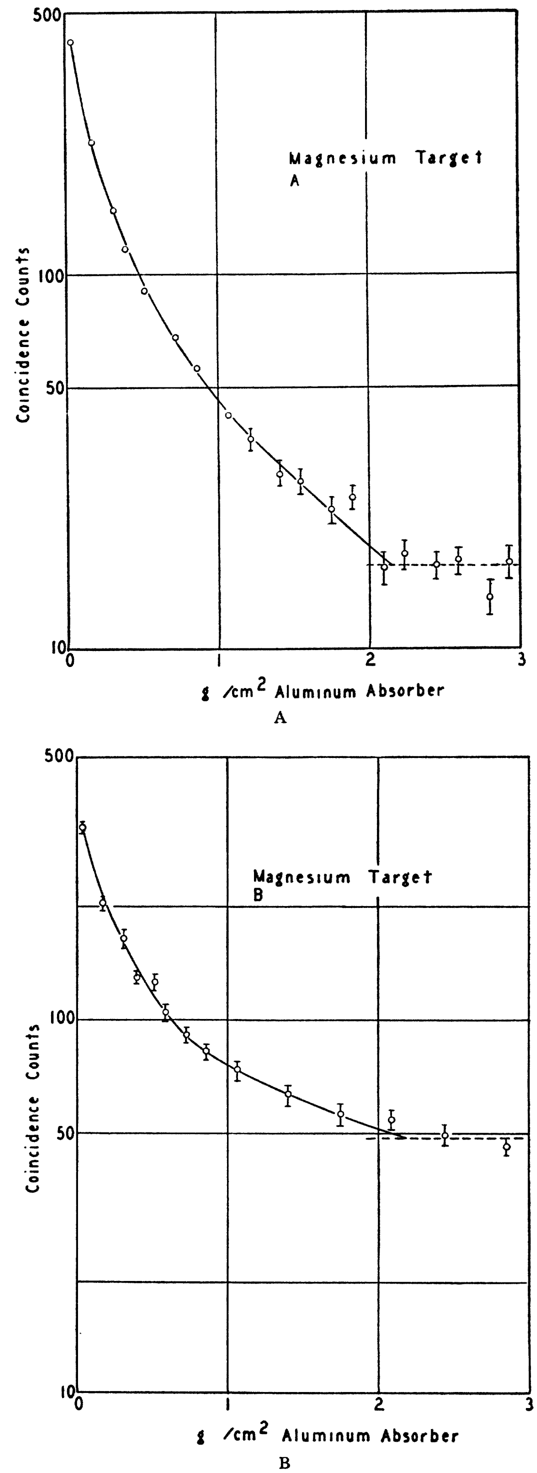

FIG. 3. Absorption curves for a magnesium target: A—counter bases $\frac{3}{4}$ inch apart; B—improved geometry with counter bases 2 inches apart, showing more clearly the presence of a second gamma-ray.

the beam. Thus, at each value of absorption coincidences are observed for a fixed number recorded by the first counter.

As a check on the method for the particular geometry and absorbers used, runs were made with sodium (24) and thorium active deposit sources. In each case the maximum range obtained corresponded to the known highest energy gamma-ray within the experimental limits of error.

III. EXPERIMENTAL RESULTS

Sodium

Figure 2 shows one of two careful runs on sodium targets made after a series of preliminary experiments. Coincidence counts per 8000 registered by the first counter have been plotted logarithmically against aluminum-absorber thickness expressed in grams per square centimeter. The value at each absorber thickness is the average of a number of points taken so as to smooth out non-random as well as statistical variations. Expected deviations were calculated from total numbers of counts and are indicated by vertical lines. Two ranges at 0.76 g/cm^2 and 1.29 g/cm^2 can be resolved from the curve. Application of the Feather relation as previously described shows that the observed end points correspond to 1.85±0.15-Mev and 2.80±0.25-Mev gamma-rays. Extrapolating the higher energy component portion of the curve back to zero absorption and deducting the background gives a soft-to-hard component yield ratio of approximately 6 to 1. No correction has been made for the variation of counter efficiency with gamma-ray energy. There is slight evidence for a gamma-ray of even higher energy.

Magnesium

Curve *A* of Fig. 3 was obtained with the counter bases separated by a $\frac{3}{4}$-inch spacer ordinarily used. This shows an end point at 2.15 g/cm^2 produced by a gamma-ray of 4.3±0.3-Mev energy and considerable curvature below 1 g/cm^2. An improvement in geometry by increasing the counter separation to 2 inches resulted in curve *B* of Fig. 3. A more definite break has appeared at 0.75 g/cm^2 corresponding to a 1.8±0.2-Mev gamma-ray. A ratio of soft-to-hard gamma-ray intensities of approximately 3 to 1 is obtained from either curve.

Aluminum

A single electron group with an end point at 1.72 g/cm^2 was obtained, as shown in Fig. 4. This corresponds to a 3.5±0.3-Mev gamma-ray. Slight indication of a curvature near the observed end point suggests a second gamma-ray of lower energy.

Silicon

Figure 5 shows one of several runs made on silicon yielding a maximum electron range of 1.02 g/cm^2 with slight evidence for a higher energy component. The gamma-ray observed has an energy of 2.3±0.3 Mev.

Phosphorus

The curve in Fig. 6 was obtained with the usual $\frac{3}{4}$-inch counter separation. The two end points have the values 1.17 g/cm^2 and 2.05 g/cm^2 and correspond to 2.55±0.25-Mev and

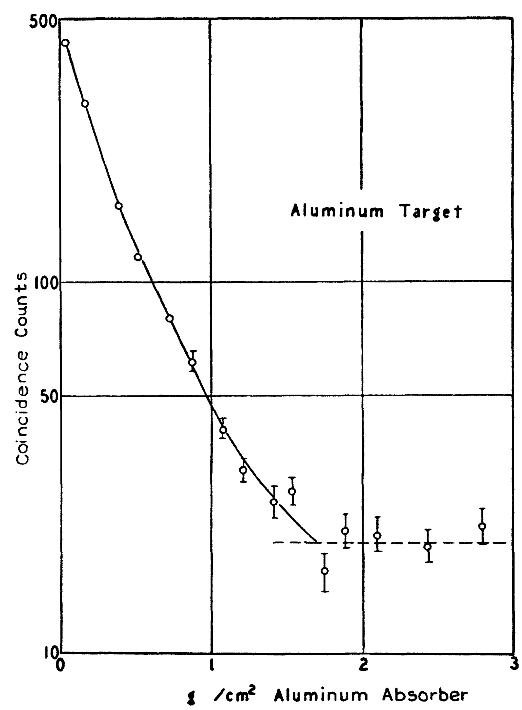

FIG. 4. Aluminum target absorption curve indicating a single gamma-ray energy.

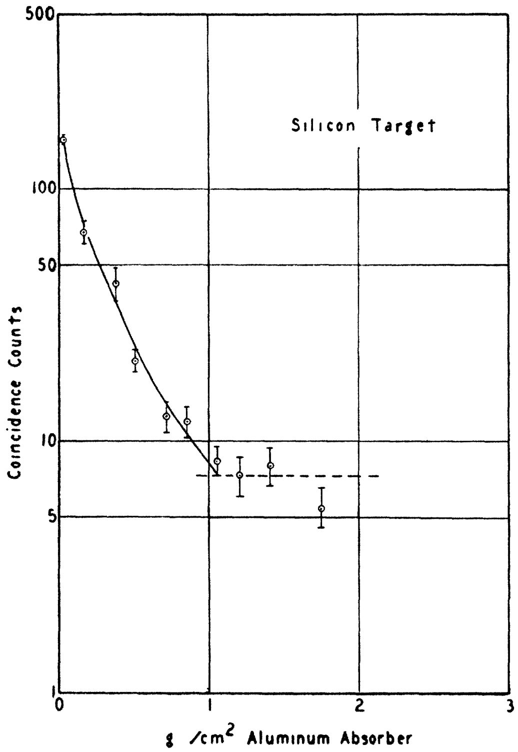

FIG. 5. Absorption of recoil electrons produced by gamma-rays from a silicon target.

4.1 ± 0.4-Mev gamma-rays with an 8 to 1 intensity ratio.

Sulfur

One of several runs on sulfur is given in Fig. 7 and shows a single electron group. The end point at 1.1 g/cm^2 is produced by a 2.4 ± 0.3-Mev gamma-ray. In the cases of both silicon and sulfur, yields were very low and resolution of any other gamma-rays present was not considered practicable with the beam intensity available.

IV. DISCUSSION

Q-values for αp reactions with the six target elements are compiled in Table I. Addition of the bombarding alpha-particle energy to these quantities gives the observed values of total kinetic energy of the product particles. The most positive Q-value in each case is therefore associated with a minimum mass of the product nucleus and corresponds to the ground state Q_0. More negative values represent successive excited states Q_1, Q_2, etc., and by subtracting these from Q_0 the levels of excitation in Mev are obtained.

TABLE I.

Reaction	Q_0	Q-Values (Mev) Q_1	Q_2	Q^9		Gamma-ray (Mev)	Relative intensity
$Na^{23}(\alpha p)Mg^{26}$	1.44	1.12	−0.30	−1.35	a	1.85	6
						2.80	1
$Mg^{24\ 25\ 26}(\alpha p)Al^{27\ 28\ 29}$	−1.2	−2.0	−2.9		b	1.8	3
						4.3	1
$Al^{27}(\alpha p)Si^{30}$	2.26	−0.02	−1.32	−2.49	c	3.5	
$Si^{28\ 29\ 30}(\alpha p)P^{31,32,33}$	−2.4	−3.2	−4.0		b	2.3	
$P^{31}(\alpha p)S^{34}$	0.00	−1.2	−2.6	−4.6	d	2.55	8
						4.1	1
$S^{32}(\alpha p)Cl^{35}$	−2.35	−2.85	−3.6		e	2.4	

[a] Data recently taken in this laboratory and to be published by R. F. Humphreys and H. T. Motz. Values are tentative pending analysis of proton range corrections.
[b] O. Haxel, Zeits. f. tech. Physik **16**, 410 (1935).
[c] W. E. Duncanson and H. Miller, Proc. Roy. Soc. **146**, 396 (1934) (corrected by Livingston and Bethe).
[d] E. Pollard and C. J. Brasefield, Phys. Rev. **50**, 890 (1936).
[e] C. J. Brasefield and E. Pollard, Phys. Rev. **50**, 296 (1936).

The last two columns in Table I summarize the gamma-ray energies and relative intensities found in the present work. The sodium target values correspond quite well to Q_2 to Q_0 and Q_3 to Q_0 transitions, the former yielding the higher intensity. The lower energy of the two gamma-rays observed from the magnesium target and

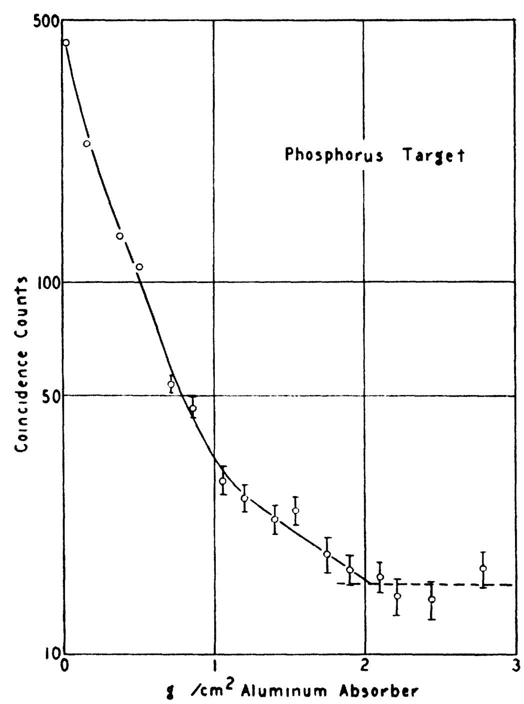

FIG. 6. Absorption curve for a phosphorus target giving clear indication of two gamma-ray energies.

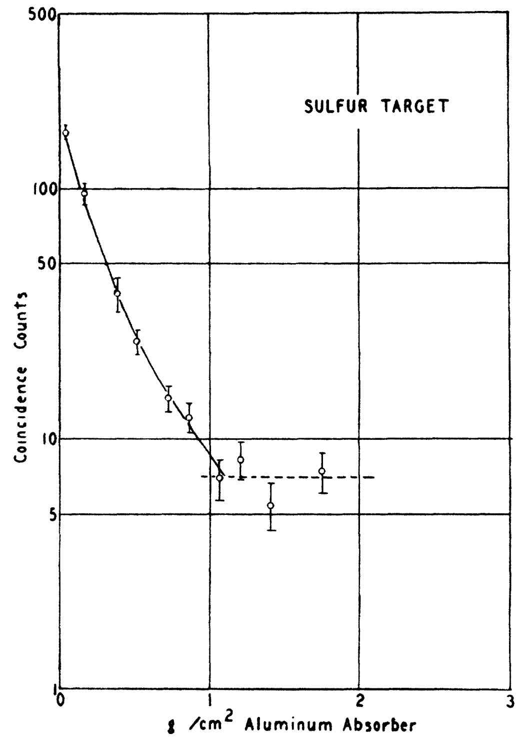

FIG. 7. Absorption of recoil electrons produced by gamma-rays from a sulfur target.

the single gamma-ray from the aluminum target both find correlation with Q_2 to Q_0 transitions. The gamma-rays from both silicon and sulfur targets exceed the highest excitation level observed with proton groups. In the case of phosphorus, good agreement is obtained for the lower energy and more intense gamma-ray with the Q_2 to Q_0 separation while the higher energy component is in fair agreement with the Q_3 to Q_0 transition.

Of the nine gamma-rays observed, six seem to compare favorably with energy level schemes derived from αp reactions. In no case is the lowest energy observed less than the Q_2 to Q_0 separation, although lower energy gamma-rays are undoubtedly present.

A general feature of αp reactions is the more prolific yield of lower energy proton groups. Since these are associated with higher levels of excitation, then such states may be said to be more heavily populated. Thus, more nuclei are left after proton emission in the Q_3 level than in Q_2, while relatively few will be found in the Q_1 and Q_0 levels. Assuming that the gamma-rays observed in the cases of sodium and phosphorus targets are truly produced as a result of αp reactions according to the correlations made above, then the relative intensities and state populations indicate a definite preference for the Q_2 to Q_0 transition. This implies that the more numerous nuclei in the Q_3 state prefer to drop to the ground state by a cascade process of successive Q_3 to Q_2 and Q_2 to Q_0 steps, although some direct transitions do occur. The predominance of Q_2-Q_0 radiation in these cases, as well as from the magnesium and aluminum targets, indicates that the nuclei in the Q_2 level drop directly to the ground state rather than cascade via Q_1.

The remaining gamma-rays from magnesium, silicon, and sulfur targets are due to either higher states of αp excitation or to competing processes. Energy calculations show that the 4.3-Mev and 4.1-Mev components from magnesium and phosphorus targets could well be the result of αn reactions. Other possibilities are inelastic scattering and simple capture. The former is unlikely because of the high potential barrier for emergence of an alpha-particle, while the latter would lead to excited states of more than 10 Mev and might be expected to yield gamma-rays more energetic than those observed. Yields from both silicon and sulfur targets were very low, and it is quite possible that breaks in these curves are being masked by statistical fluctuations. If this were the case the principal yield at zero absorption could be due to gamma-rays corresponding to known level separations while the observed maximum ranges are caused by gamma-rays from competing processes.

It is a pleasure to acknowledge the guidance given in this research by Professor Ernest Pollard.