Gamma-Rays from Deuteron Reactions

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Gamma-rays from Na, Mg, Al, Si, P, S, and PbO_2 targets under cyclotron bombardment by 3.7-Mev deuterons have been measured by coincidence absorption of Compton electrons. With PbO_2, Al, and Mg Compton distributions were also obtained by means of a thin lens magnetic spectrometer. Correlation of several of the measured values can be made with excited states of N^{14}, O^{17}, and Si^{28} as obtained from other information. The predominant gamma-rays have moderately large energy, being 8.8 Mev in one case, indicating a preference for direct transitions from states of high excitation to the ground state of the product nucleus.

I. INTRODUCTION

NUCLEAR energy levels appearing during the bombardment process are revealed by gamma-radiation. In analogy with atomic and molecular spectroscopy, the measurement of gamma-ray energies can give spacings, transition probabilities, and other information pertaining to levels in the nucleus.

Correlation of gamma-ray data with levels obtained by other methods should be possible. This has been done[1] in the bombardment of a few very light elements. However, for product nuclei above nitrogen few gamma-rays have been accurately determined. Some recent work[2,3] along this line has been done in which gamma-ray energies associated with the alpha-particle bombardment of Na, Mg, Al, Si, P, and S, were obtained by absorption in lead and by coincidence absorption of Compton electrons. Agreement was found in several cases with existing information and there was, in addition, some evidence for the presence of selection rules.

During this alpha-particle work a few rough measurements were made at the cyclotron tuning resonance for deuterons and with an aluminum target gamma-rays of moderately high energy were observed. A program of coincidence absorption using the deuteron beam was therefore carried out on the same series of target elements.

In the course of this work a thin lens magnetic spectrometer became available and was adapted to measure energies of gamma-rays from targets under cyclotron bombardment. This was applied to several cases which will be described.

II. EXPERIMENTAL METHODS

The experimental arrangement for coincidence absorption measurements has been described previously.[3] This consists of two thin window beta-ray counters placed on a line with the target. Gamma-rays formed in the target produce Compton electrons in the end wall of the first counter which can traverse both counters and give coincidences. The absorber thickness placed between the counters which just reduces the yield to the random coincidence rate is the maximum Compton electron range and from this the incident gamma-ray energy may be calculated.

Relatively high gamma-ray intensities were available in deuteron bombardment and a means was sought to overcome the large random coincidence rate found with the elementary circuit[4,3] used at first. A double coincidence circuit of medium resolution designed[5] by Professors Schultz and Pollard was convenient for this purpose. This employs two 10-megacycle blocking oscillators triggered by the initial pulse rise. Coincidences formed between the narrow rectified oscillator output pulses make the resolving time essentially independent of counter pulse width. In a test using two Geiger counters at a chosen

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[1] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. **20**, 191 (1948).

[2] E. Pollard and D. E. Alburger, Phys. Rev. **72**, 1196 (1947).

[3] D. E. Alburger, Phys. Rev. **73**, 1014 (1948).

[4] A. B. Martin, Phys. Rev. **72**, 378 (1947).

[5] H. L. Schultz and E. Pollard, Rev. Sci. Inst. **19**, 617 (1948).

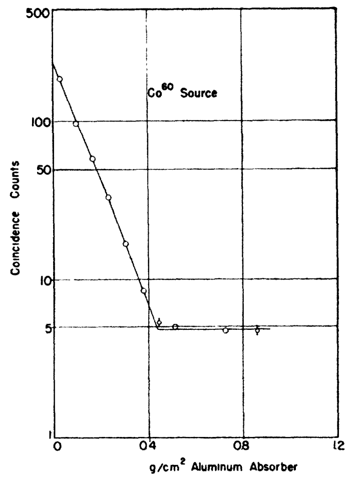

FIG. 1. Coincidence absorption calibration using a Co^{60} source.

counting level, only three random coincidences per minute were recorded in comparison with 100 per minute from the older circuit.

Because of the increased measuring accuracy made possible by higher intensities and improved coincidence counting equipment as compared with previous work[3] using alpha-particles a re-check on the coincidence absorption method became desirable. Co^{60} was available for this purpose. This emits two gamma-rays which have been reported[6] by Deutsch, Elliott, and Roberts to have energies of 1.10 Mev and 1.30 Mev. More recent values given[7] by Jensen, Laslett, and Pratt are 1.16 Mev and 1.32 Mev. Using the same geometry and counting level as in the cyclotron experimental data of Part III the curve in Fig. 1 was obtained. This has an extrapolated maximum range of 0.440 g/cm² of aluminum, although the point at 0.446 g/cm² is probably slightly above the random coincidence rate. From the Feather relation,[8]

$$R(\text{g/cm}^2\text{Al}) = 0.543E(\text{Mev}) - 0.160,$$

a maximum gamma-ray energy of 1.31 ± 0.02 Mev may be calculated using the 0.440 g/cm² range to obtain the electron energy and adding the correct value for the back-scattered quantum. The agreement seems to indicate that this formula is more suitable in the present application than the modified Feather relation published[9] by Bleuler and Zünti.

Additional measurements were made with a thin lens magnetic spectrometer of conventional design[10] adapted as shown in Fig. 2 to observe gamma-rays from cyclotron targets. The beam is deflected through an extension tube and strikes the target which is mounted on the spectrometer radiator for large solid angle in the production of secondary electrons. The tin baffle restricts the beam to a limited portion of the target. A vacuum connection through holes in the spectrometer end plate eliminates foils from the path of the beam which might otherwise result in undesirable gamma-radiation. The energy distribution of electrons from the radiator is measured in the usual fashion. Spaced iron shielding rings are provided to reduce the defocusing effect of the stray cyclotron magnetic field without appreciably affecting the characteristics of the lens. A more complete description of this shielding method is given[11] elsewhere.

To facilitate cyclotron tuning the beam current is read directly from the insulated target-radiator holder by means of a galvanometer. Because of low currents and fluctuations in intensity it was

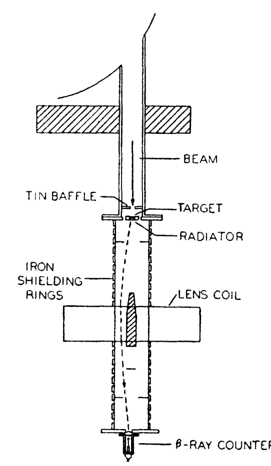

FIG. 2. Experimental arrangement for measuring energies of gamma-rays from targets under cyclotron bombardment. A thin-lens spectrometer has been adapted to obtain secondary electron distributions.

[6] M. Deutsch, L. G. Elliott, and A. Roberts, Phys. Rev. 68, 193 (1945).
[7] E. N. Jensen, L. J. Laslett, and W. W. Pratt, Phys. Rev. 73, 529 (1948).
[8] N. Feather, Proc. Camb. Phil. Soc. 34, 599 (1938).
[9] E. Bleuler and W. Zünti, Helv. Phys. Acta. 19, 137 (1946).
[10] M. Deutsch, L. G. Elliott, and R. D. Evans, Rev. Sci. Inst. 15, 178 (1944).
[11] D. E. Alburger, Rev. Sci. Inst. 19, 474 (1948).

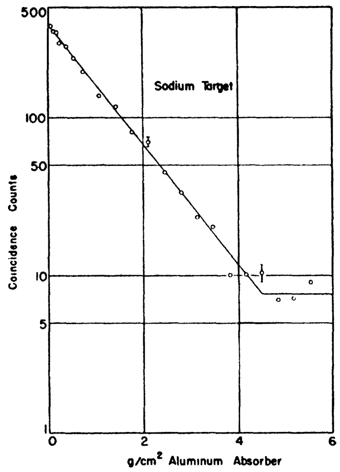

FIG. 3. Coincidence absorption of Compton electrons due to gamma-rays from sodium under deuteron bombardment.

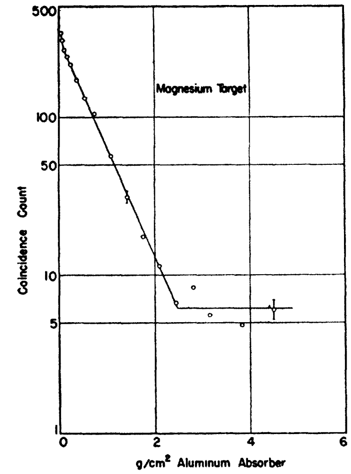

FIG. 4. Coincidence absorption, gamma-rays from $Mg+D^2$.

found most suitable to integrate the beam with a monitor gamma-ray counter (not shown) placed near the target and to refer the yield from the spectrometer at each point to a fixed number of monitor counts. Calibration of the spectrometer was taken from the Compton distribution of Co^{60} gamma-rays. A value of 97 gauss-cm per ampere was obtained.

III. EXPERIMENTAL RESULTS

Coincidence absorption curves for gamma-rays resulting from the deuteron bombardment of Na, Mg, Al, Si, P, and S, are shown in Figs. 3–8. In all cases the separation between counter bases was $1\frac{1}{2}$ inches and coincidences have been referred to 16,000 counts in the first counter. Beam currents of the order of 0.005 microampere were sufficient to operate at the desired counting level.

The curve for sodium in Fig. 3 is nearly linear with an end point at 4.5 g/cm² corresponding to an 8.8 ± 0.6-Mev gamma-ray. An estimate of the cross section for this reaction compared with the formation of Na^{24} could be made. The run was restricted to three hours in order to prevent the build-up of excessive radioactivity and during this time the first or monitor counter recorded a total of 1.7×10^6 counts (about 160/sec.). At the end of bombardment and with the cyclotron turned off, the net rate in the same counter due to 2.8 Mev Na^{24} gamma-rays was about 8.0 per second. From a calculation using a decay constant 1.3×10^{-5} sec.$^{-1}$, this corresponds to the formation of 0.6×10^6 Na^{24} nuclei—not allowing for solid angle and absolute counter efficiency. To compare this yield with the 1.7×10^6 reactions resulting in 8.8-Mev gamma-rays, a factor of about 3 must be introduced because of the increase of counter efficiency with gamma-ray energy.[12] On the same basis 1.8×10^6 Na^{24} nuclei have therefore been formed. The cross sections for these two processes are thus about equal. However, it is unlikely that the 8.8-Mev gamma-ray is produced during the formation of Na^{24},

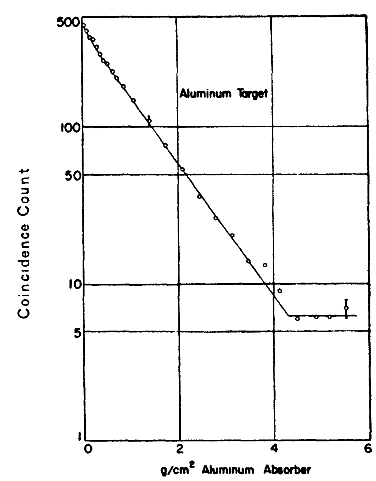

FIG. 5. Coincidence absorption, gamma-rays from $Al+D^2$.

[12] Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta 19, 77 (1946).

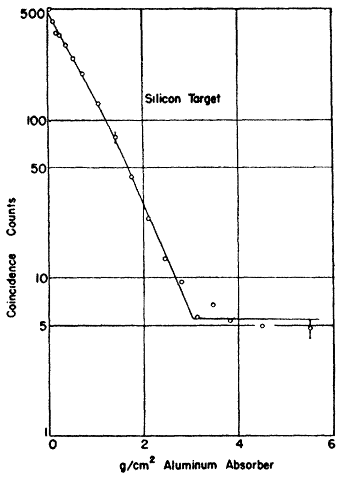

FIG. 6. Coincidence absorption, gamma-rays from $Si+D^2$.

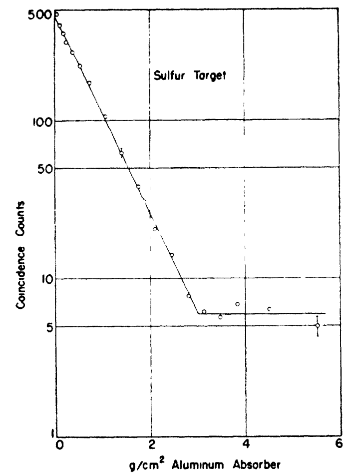

FIG. 8. Coincidence absorption, gamma-rays from $S+D^2$.

since the Q-value for this reaction is less than 5 Mev.

Figure 4 for magnesium has an end point at 2.5 g/cm² Al, giving a gamma-ray energy of 5.1 ± 0.3 Mev. A slight increase in yield below 0.2 g/cm² Al indicates a weak gamma-ray of less than 0.9 Mev.

The aluminum target yield in Fig. 5 shows a predominant gamma-ray energy of 8.5 ± 0.5 Mev from the 4.3-g/cm² Al maximum electron range. A slight break occurs at 0.55-g/cm² Al as seen more clearly with a straight edge, and corresponds to a gamma-ray energy of 1.5 ± 0.2 Mev.

Curves for Si, P, and S given in Figs. 6, 7, and 8 show end points of 3.1, 3.1, and 3.0 g/cm² Al. The first two are from 6.2 ± 0.3-Mev gamma-rays and the third from a 6.0 ± 0.3-Mev gamma-ray.

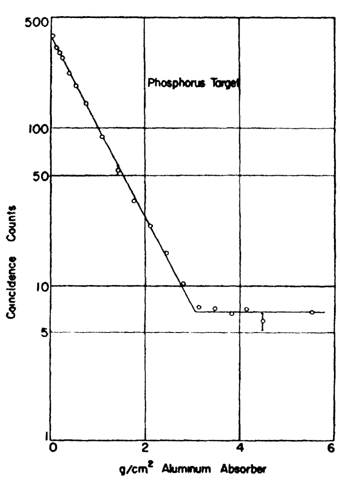

FIG. 7. Coincidence absorption, gamma-rays from $P+D^2$

For an initial test of the spectrometer method described in Part II, cases were considered which might yield simple gamma-ray spectra within the 4-Mev measuring range of the instrument. The $O^{16}(dp)O^{17}$ reaction has been studied recently by Pollard and Davison[13] and by Heydenburg and Inglis.[14] Proton groups to the ground state and first excited state of the O^{17} nucleus at 0.87 Mev have been found. In the absence of other excited states or competing processes, a single gamma-ray energy could be expected.

The Compton electron distribution found with a PbO_2 target mounted on a thick copper radiator is shown in Fig. 9. Because of high background from the main cyclotron chamber and low intensity from the target, a net yield of only 17 percent at the maximum was obtained—giving the statistics indicated at 32.5 amperes. Considerably more shielding was used than shown in Fig. 2. A dashed line has been drawn in Fig. 9 to separate out poorly resolved variations above 40 amperes. The gamma-ray producing the main peak with the inflection point indicated is 0.90 ±0.05 Mev and is thus in agreement with the first excited state of O^{17}. With the present data it is not felt that any significance can be attached to the region of the curve above 40 amperes.

[13] E. Pollard and P. W. Davison, Phys. Rev. **72**, 736 (1947).

[14] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948).

To further study this spectrum coincidence absorption measurements were made on the same target. The combined data for several runs is shown in Fig. 10. Two ranges seem to be present at 0.23 g/cm^2 Al and at 1.92 g/cm^2 Al which correspond to 0.90±0.15 Mev and 4.0±0.3 Mev gamma-rays, respectively. There may also be a component of 2.1±0.3 Mev at 0.85 g/cm^2 Al.

Several other targets were tried under deuteron bombardment, aluminum giving the curve in Fig. 11. This spectrum extends beyond the range of the instrument as to be expected from the coincidence absorption data of Fig. 5. The upper portion has been extended back with a dashed line and subtracted from the experimental points resulting in the curve below. The $H\rho$ value at the inflection point yields a gamma-ray energy of 1.72±0.08 Mev, which is a somewhat more accurate determination than the coincidence absorption measurement of Fig. 5. The expected deviation in points is indicated at 45 amperes. A slight variation seems to occur at 110 amperes which could indicate the presence of a 3.0±0.2 Mev gamma-ray.

With magnesium the Compton distribution in Fig. 12 was obtained and is apparently the unresolved composite resulting from several gamma-rays. A maximum energy of 4.9 Mev at about 175 amperes is in essential agreement with the coincidence absorption curve of Fig. 4. Spectrometer curves for the remaining targets were not taken.

IV. DISCUSSION

A summary of the gamma-ray energies measured is given in Table I together with the probable reaction in cases where correlations can be made.

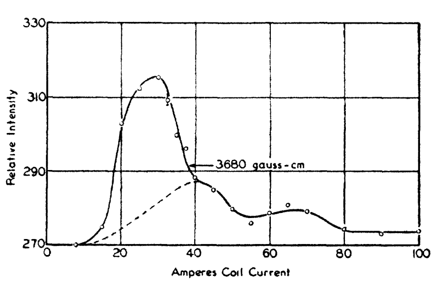

Fig. 9. Compton electron distribution from a thick copper radiator due to gamma-rays from PbO_2+D^2 as measured by the arrangement in Fig. 2.

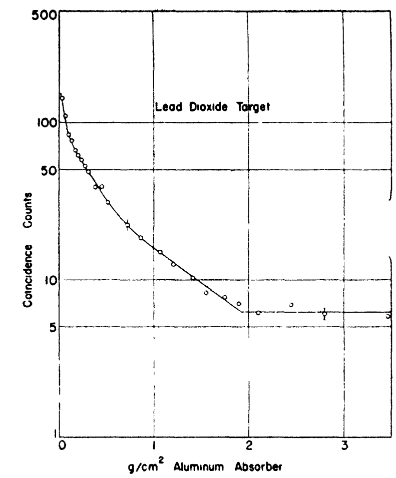

Fig. 10. Coincidence absorption, gamma-rays from PbO_2+D^2. The end point at about 0.23 g/cm^2 Al corresponds to the prominent peak in Fig. 9.

The first excited state of Si^{28} has been found from radioactivity measurements of Bleuler and Zünti[15] and by Barkus[16] to be at 1.8 Mev. This level is further confirmed[17] by Peck using photographic methods to study the $Al^{27}(dn)Si^{28}$ reaction. He obtains a first excited state at 1.7±0.3 Mev and other levels ranging up to 9.7 Mev at the same bombarding energy used in the present work. His levels are consistent with a Q-value[18] of 9.4 Mev for the dn reaction and could also account for the 8.5-Mev gamma-radiation observed here. The 1.72-Mev gamma-ray has therefore been assigned in Table I to Si^{28}.

In the spectrum from PbO_2 the agreement of the 0.90-Mev gamma-ray with the first excited

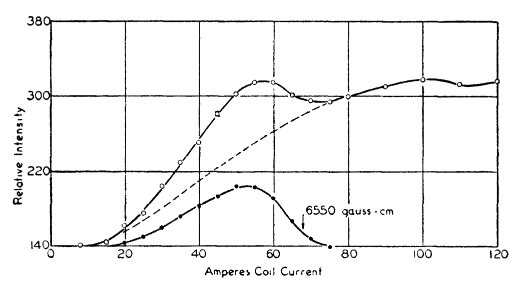

Fig. 11. Compton distribution, gamma-rays from $Al+D^2$. The $6550H\rho$ component agrees with the break at 0.55 g/cm^2 Al in the curve of Fig. 5.

[15] E. Bleuler and W. Zünti, Helv. Phys. Acta **20**, 195 (1947).
[16] W. H. Barkas, Phys. Rev. **72**, 346 (1947).
[17] R. A. Peck, to be published.
[18] Q-values have been calculated from masses given by Mattauch and Flügge, Physik. Zeits. **44**, 181 (1943).

TABLE I.

Target	Gamma-ray energy (Mev) Coincidence absorption	Spectrometer	Probable reaction
Sodium	8.8 ±0.6		
Magnesium	5.1 ±0.3 <0.9	4.9 max.	
Aluminum	1.5 ±0.2 8.5 ±0.5	1.72±0.08 3.0 ±0.2?	$Al^{27}(dn)Si^{28}$
Silicon	6.2 ±0.3		
Phosphorus	6.2 ±0.3		
Sulfur	6.0 ±0.3		
Lead dioxide	0.90±0.15 2.1 ±0.3? 4.0 ±0.3	0.90±0.05	$O^{16}(dp)O^{17}$ $O^{16}(d\alpha)N^{14}$

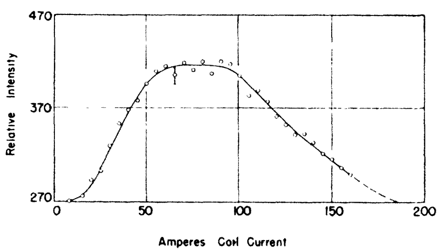

FIG. 12. Compton distribution, Mg+D².

state of O^{17} seems fairly certain. Other levels have not been reported in the *dp* reaction although Burcham and Smith have found[19] excited states of O^{17} at 0.83, 2.95, 3.77, and 4.49 Mev from $F^{19}(d\alpha)O^{17}$. The 4.0-Mev gamma-ray might then be due to the *dp* reaction which has a *Q*-value of 1.95 Mev and could agree with the 3rd or 4th excited states of O^{17}. The *dn* process is ruled out by a −1.7-Mev ground state *Q*-value. The remaining and most likely possibility is the $O^{16}(d\alpha)N^{14}$ reaction having a *Q*-value of 3.13 Mev. The 4.0-Mev gamma-ray would then be in good agreement with the first excited state of N^{14} at 4.0 Mev found[20,3] by Stuhlinger from alpha-particle resonances producing slow neutrons in $B^{11}(\alpha n)N^{14}$. The intermediate and questionable gamma-ray of 2.1 Mev is in rough agreement with radiation of 2.3 Mev observed[21] by Sherr, Muether, and White in the positron decay of O^{14} and might therefore be caused by another level in N^{14}.

The shape of an unresolved coincidence absorption curve depends on the geometry used and the energies and relative intensities present. An estimate of what could be expected with the present arrangement for a single energy may be made from Fig. 1 since the radiation from Co^{60} is roughly monoenergetic. A slight concavity to the coordinates in the logarithmically plotted absorption curve is to be noted. The presence of other gamma-ray components of less than half the energy and of comparable intensity causes a pronounced convexity to the coordinates in the resultant curve as illustrated in Fig. 10 for PbO_2.

This qualitative feature may be applied to the curves for Na, Mg, Al, Si, P, and S, which are nearly linear, excepting for additional yields at low absorption in Mg and Al. Silicon most closely exhibits the shape expected for a single component. The general conclusion to be drawn from these six cases is that at least 30–50 percent of the radiation consists of the highest energy components and that smaller intensities of lower energy gamma-rays are probably present. In view of low lying level spacings of the order of 1 Mev or less obtained by other methods in this region of the periodic table, the predominance of these energies indicates a preference for direct transitions from states of high excitation. The processes producing these gamma-rays will have to be determined from further particle reaction level data, by comparing particle and gamma-ray excitation curves, or by performing coincidence experiments between particles and gamma-rays.

The author wishes to acknowledge the assistance given by Mr. William Bateson, who constructed the thin lens spectrometer used in this work. Many valuable discussions were held with Professor Ernest Pollard whose suggestions were greatly appreciated.

[19] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **A168**, 176 (1938).
[20] Stuhlinger, Zeits. f. Physik **114**, 185 (1939).
[21] R. Sherr, H. R. Muether, and M. G. White, Bull. Am. Phys. Soc. **23**, No. 7, A4 (1948).