1, 2, 3, and 4. Also, while both burst frequency and corrected ionization current display recurrences of variations at intervals of 27 or 28 days, primary pulses in the former (expressed in percent) are about 60 times as great as in the latter, and secondary pulses are about 20 times as great. Also, while both display variations in general phase opposition to those in sunspot area, the pulses in burst frequency (expressed in percent) in this instance are some 11 to 16 times as great as the primary pulses in the ionization current. The corrected ionization current displays a clear-cut relation to magnetic character not displayed by the raw burst-frequency data; it remains to be seen whether correction for barometric variations would bring out a closer relation between burst frequency and magnetic disturbances. Finally, while the barometric coefficient for the frequency of the small bursts is of the same sign as that for the corrected ionization current, it is some 20 times as great, at least for the season when the dependence upon barometric pressure is clearly evident. The indication here provided that the bursts are associated with a soft component calls to mind the fact that Korff[9] found the rate of production of neutrons to be associated with the soft component.

The writer wishes to acknowledge helpful comments by Dr. W. F. G. Swann and the continued cooperation of Dr. V. A. Long and Dr. R. M. Whaley.

[9] S. A. Korff, Phys. Rev. 59, 949 (1941).

PHYSICAL REVIEW VOLUME 72, NUMBER 12 DECEMBER 15, 1947

Gamma-Rays from the Alpha-Particle Bombardment of Na, Mg, Al, Si, P, S

ERNEST POLLARD AND D. E. ALBURGER
Sloane Physics Laboratory, Yale University, New Haven, Connecticut*

(Received September 12, 1947)

Na, Mg, Al, Si, P, S targets have been bombarded by 7.2-Mev helium ions. The emission of gamma-radiation has been observed. Lead absorption coefficients were obtained in all cases. The values lie close to the minimum of the lead absorption curve. In the case of Al, absorption in copper has been measured and, in addition, absorption of Compton recoil electrons by aluminum has been measured by a coincidence method. The results show that a gamma-ray of energy 3.5±0.3 Mev is present. This agrees with a transition from the Q_2 to Q_0 state observed in the $Al^{27}(\alpha p)Si^{30}$ reaction. Unequivocal energy assignments cannot be made for the remaining reactions. However, lead absorption experiments indicate the following probable values: *S*, 1.6±0.3 Mev; Mg, 3.2±0.6 Mev; Na, 2.3±0.3 Mev. The values for elements Si and P cannot be assigned until it is clear whether the absorption is above or below the minimum. Lead absorption coefficients are given. Since the gamma-ray energies are generally higher than the difference between energy levels obtained from other information, it is likely that in these cases direct transitions are preferred to cascade.

1. INTRODUCTION

In the region between sodium and chlorine there has been a considerable amount of experimental work on the nuclear energy levels as revealed by the formation of groups of particles in transmutations[1] or of inelastically scattered protons.[2] Relatively little recent work has been done on the direct observation of radiation due to transitions between levels of excitation produced in the bombardment process. Savel,[3] bombarding with polonium alpha-particles, has observed the presence of gamma-radiation from fluorine, sodium, magnesium, and aluminum, and measured the absorption coefficients in lead. Speh[4] has shown that the energy of the radiation from fluorine bombarded by polonium alpha-

* Assisted by the Office of Naval Research under Contract N6ori-44.

[1] For example, C. J. Brasefield and E. Pollard, Phys. Rev. 50, 296, 890 (1936); A. N. May and R. Vaidyanathan, Proc. Roy. Soc. A155, 519 (1936); O. Haxel, Zeits. f. Physik 90, 373 (1934), and Zeits. f. Tech. Physik 11, 410 (1935), H. L. Schultz, W. L. Davidson, Jr., and L. H. Ott, Phys. Rev. 58, 1043 (1940).

[2] R. H. Dicke and J. Marshall, Phys. Rev. 63, 86 (1943).

[3] P. Savel, Ann. de physique 4, 88 (1935).

[4] K. D. Speh, Phys. Rev. 50, 689 (1936).

TABLE I.

Process	Q values (Mev)
$Na^{23}(\alpha p)Mg^{26}$	1.9; −0.4; −2.1; −3.1
$Mg^{24,25,26}(\alpha p)Al^{27,28,29}$	−1.2; −2.0; −2.9
$Al^{27}(\alpha p)Si^{30}$	2.22; −0.06; −1.44; −2.49
$Si^{28,29,30}(\alpha p)P^{31,32,33}$	−2.4; −3.2; −4.0
$P^{31}(\alpha p)S^{34}$	0.0; −1.2; −2.6; −4.6
$S^{32}(\alpha p)Cl^{35}$	−2.35; −2.85; −3.6
$Al^{27}(pp)Al^{27}$	0; −0.82; −1.90; −2.53; −3.28
$Mg^{24,25,26}(pp)Mg^{24,25,26}$	0; −1.23; −2.58; −3.59

particles has two components, the harder of which is excited only by alpha-particles above 4-Mev energy. The excitation function for gamma-radiation from sodium has been studied by Kovács.[5]

As a result of the observation of proton groups emitted under alpha-particle bombardment, the nuclear energy change (Q) values, given in Table I, have been observed. No study has been made of neutron energies in this region. Some additional information about the general character of levels is available from inelastic scattering and from (dp) reactions.

The present work was carried out with a doubly ionized helium beam of 7.2-Mev energy produced by a cyclotron. Radiation from the six elements Na, Mg, Al, Si, P, S was readily detected and absorption coefficients measured.

2. EXPERIMENTAL METHOD

The bombarding and detecting arrangements can be seen from Fig. 1. The beam is brought out approximately 20 inches from the cyclotron vacuum chamber into a bombardment chamber,

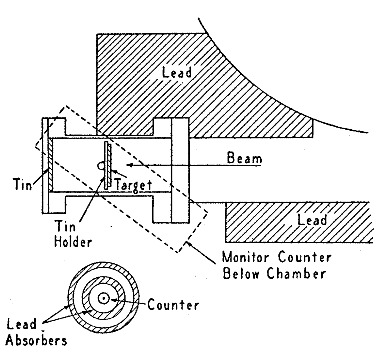

FIG. 1. Experimental arrangement for absorption measurements on gamma-radiation from targets under cyclotron bombardment.

[5] M. Kovács, Phys. Rev. 70, 895 (1946).

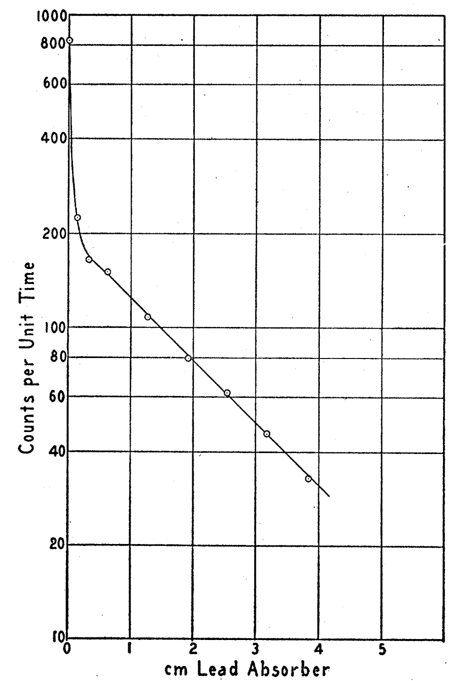

FIG. 2. Absorption of gamma-radiation from thorium-active deposit.

as indicated. Lead shields reduce the "wild" radiation from the dees and walls of the cyclotron. The background counting rate with a pure tin target, which is not transmuted by alpha-particles of 7.2 Mev energy, was found to be $\frac{1}{10}$ to $\frac{1}{2}$ that due to radiation from the six elements bombarded. The targets were thick enough to absorb completely the alpha-particles. These consisted of sheets of the metal itself in the case of aluminum or magnesium, sodium metal fastened on to a tin backing sheet with polystyrene cement, silicon powder fused into a slab and glued to a tin plate with polystyrene cement, red phosphorus stuck by adhesion to a tin plate, and sulfur powder mixed with gold dust (to permit conduction of the beam current) and fused on to a tin plate.

The counter used for absorption was a Herbach-Rademan type GLC-11. The counts were referred to a standard absorption by a monitor proportional counter set to count gamma-rays. The procedure was to count simultaneously on the monitor and the absorption counter, until a fixed number of monitor counts was recorded. In this way errors in beam integration were

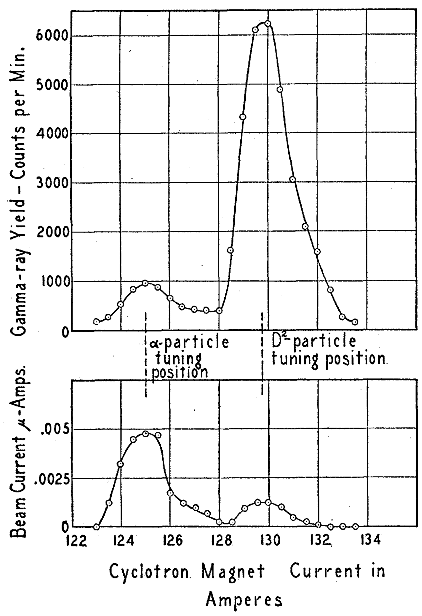

FIG. 3. Cyclotron beam current and gamma-ray yield from an Al target as a function of cyclotron magnet current.

eliminated. The data were very reproducible, the absorptions on each run being repeated several times with fluctuations of the order of those expected from a Poisson distribution. In each case a background absorption curve with a tin target was taken and deducted. The absorbers were cylindrical, with lead shields placed over the top and bottom to absorb scattered radiation. The distance from target to counter was five inches. In order to check the way in which the geometry affected the absorption coefficient, runs were taken with thorium active deposit and Na^{24}. The thorium active deposit results are shown in Fig. 2. The absorption coefficients correspond to soft components plus a single hard component of energy 2.62 Mev. The straight line gives a coefficient in agreement with the theoretical value for this energy. An additional run was taken with annihilation radiation which gave the absorption coefficient 1.73 per cm corresponding to 0.49 Mev, which again checks the validity of the method.

A second method of energy study was used in the case of aluminum. Two beta-ray counters, with thin windows, were placed facing each other on a line with the cyclotron target. A lead radiator ($\frac{1}{8}$-inch thickness) was located in the nearer counter to provide recoil electrons from the incident gamma-radiation. Aluminum sheet absorbers were then placed between the two thin windows, and the number of coincidence counts recorded for a standard number registered by the nearer counter. By determining at what absorption the coincidences fall to background, the energy of the gamma-ray is calculated by use of the absorption formula for an electron of energy E Mev: Range (g/cm² Al) $= 0.571E - 0.161$ and adding a correction (up to 0.25 Mev) for the energy retained by the gamma-quantum in a Compton recoil.

The cyclotron differs from a radioactive source in that deuterons and molecular hydrogen may be present. The coincidence experiments with an aluminum target were performed several days after change from deuterium to helium. It was found possible to separate the He^{++} beam from the H_2^+ and D^+ by adjustment of the magnetic field. To be certain that H_2^+ or D^+ contamination was not responsible for the results, an Al target was bombarded and counts observed with variation of the cyclotron magnetic field. The results

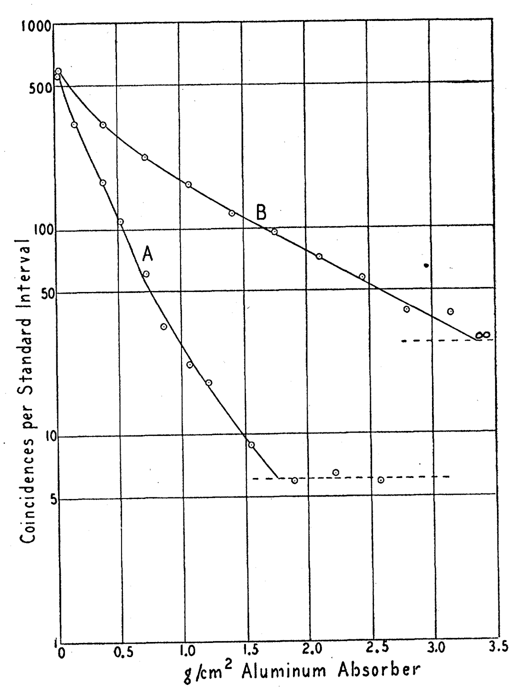

FIG. 4. Coincidence counting of recoil electrons produced by gamma-rays from an aluminum target. A, cyclotron tuned to He^{++} maximum; B, cyclotron tuned to D^+ maximum.

are shown in Fig. 3. It can be seen that the yield due to D^+ and H_2^+ drops to zero before the He^{++} yield is at a maximum. As a further proof, absorption curves for the secondary electrons were plotted by the coincidence method at the He^{++} maximum value and at the D^+ value, as shown in Fig. 4. In the He^{++} case, curve A, the end point corresponds to 3.5 Mev while in the D^+ case, curve B, it is 6.8 Mev. Finally, a curve was taken with the cyclotron tuned on the low field side of the He^{++} resonance which agreed exactly with the curve taken at the peak. Had any D^+ contamination been present its effect would have been greatly reduced by this procedure. The fact that no change occurred argues against the presence of D^+. We therefore consider that deuterium or molecular hydrogen contamination of the beam is insufficient to affect our results.

3. EXPERIMENTAL RESULTS

The element aluminum was most carefully studied. Special attention was paid to this element because it has been worked on carefully by various types of natural-source bombardment and has recently been investigated in this laboratory by Benson.[6] The results of lead absorption measurements are shown in Fig. 5. The absorption was carried out to 4 cm with cylindrical absorbers and out to 8 cm with additional flat, lead plates. The majority of the radiation is in a single component with an absorption coefficient $\tau = 0.436 \pm 0.015$. There is a slight indication of a lower energy group which might be associated with the 2.5-minute position activity of P^{30}.

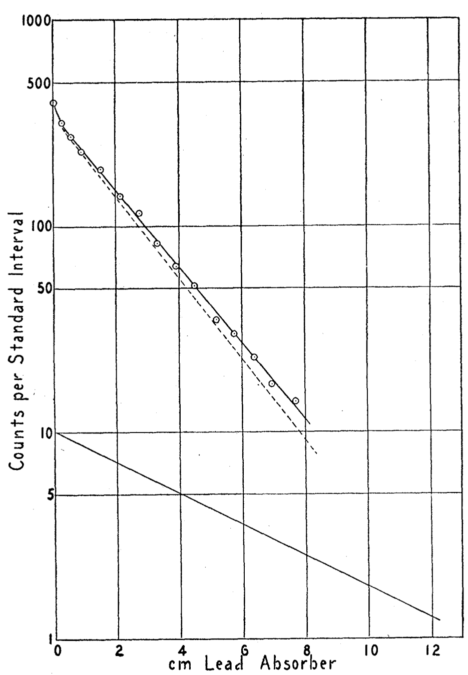

FIG. 5. Absorption of gamma-radiation from Al under alpha-particle bombardment showing the maximum possible neutron yield correction.

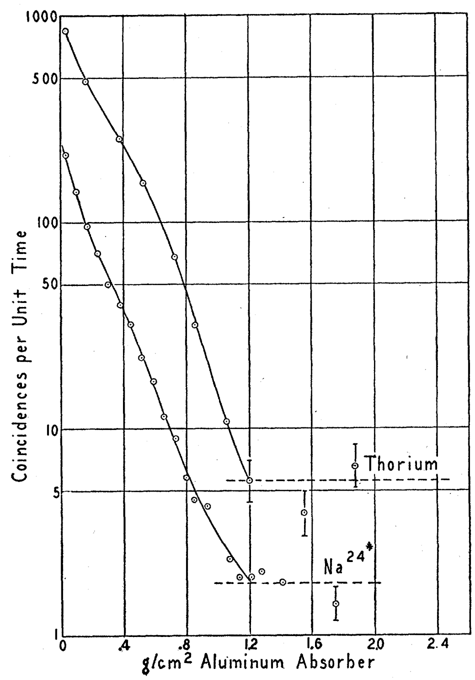

FIG. 6. Coincidence counting of recoil electrons produced by gamma-rays from thorium-active deposit and Na^{24}.

The absorption coefficient is quite low and there exists the possibility that neutrons are present in the radiation, adding a component of low absorption coefficient. By carrying the absorption out to 8 cm, it was hoped that a slight curvature might show the presence of such a neutron component. Using a neutron absorption coefficient of 0.17 cm^{-1}, it is possible to estimate the *maximum possible* correction which could be applied. The dotted line shows the slope contained by deducting a neutron yield of 1/40 the gamma-count. A higher neutron yield gives a convex absorption curve which is without meaning. The "corrected" value is $\tau = 0.455\ cm^{-1}$.

[6] B. B. Benson (in course of publication).

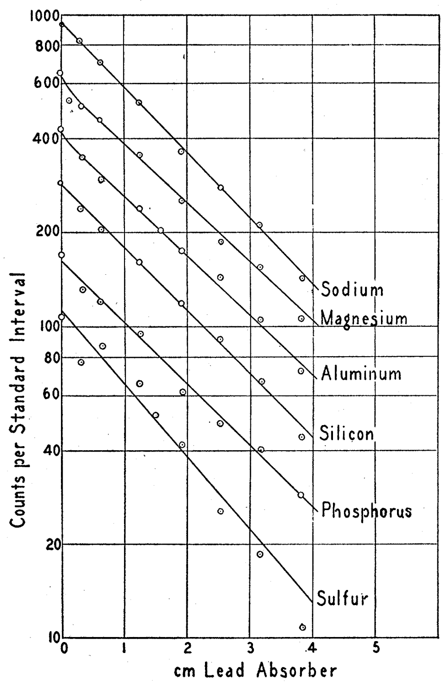

FIG. 7. Absorption of gamma-radiation from Na, Mg, Al, Si, P, and S under alpha-particle bombardment.

To determine to which side of the lead absorption minimum this coefficient corresponds, the absorption in copper was measured. The value obtained corresponds to a single absorption coefficient $\tau = 0.28$ cm^{-1}, which fits a gamma-ray energy of close to the minimum absorption value of 5 Mev for copper. The limits of error are quite high but the measurement proves that the gamma-ray energy is on the high side of the lead absorption minimum. The best value of the maximum gamma-ray energy present was obtained from the coincidence counting of Compton recoil electrons. The absorption of these in aluminum is shown in curve A of Fig. 4. The end point occurs at 1.72 g/cm^2 which gives a maximum energy of 3.5 ± 0.3 Mev. This in good agreement with the uncorrected lead absorption data which give an absorption coefficient of 0.444 ± 0.017 or an energy between 2.7 and 3.7 Mev.

In order to justify the method of coincidence counting, runs were taken with thorium-active deposit and Na^{24} sources. The end points obtained are 2.62 Mev and 2.65 Mev, which agree satisfactorily with 2.62 Mev and 2.76 Mev, respectively. The curves are shown in Fig. 6. In the case of sodium it is known that two components of energy 1.38 Mev and 2.76 Mev are present in equal abundance. While there is some difference between the sodium curve and the single-component thorium curve, it is slight. It is therefore felt that nothing can be said about the presence of components of lower than maximum energy unless the yield is at least three times higher than the maximum energy component. The results for aluminum can be summarized as follows: At least 30 percent of the total radiation is of energy 3.5 ± 0.3 Mev. There is evidence of a weak component of much lower energy, probably less than 0.5 Mev.

The elements Na, Mg, Si, P, S were studied by lead gamma-ray absorption only with results including aluminum as shown in Fig. 7. It can be seen that with the possible exception of magnesium and aluminum, the radiation is predominantly of one absorption coefficient. The values, together with possible energies, are given in Table II which includes estimates of the yield based on a yield of 10 from aluminum. Total counts recorded at zero absorption are also given.

4. DISCUSSION

Alpha-particle bombardment can cause the following processes:

1. Simple capture.
2. Inelastic scattering, i.e., capture and re-emission of the alpha-particle with reduced energy.
3. Transmutation with emission of a neutron. (α,n) reaction.
4. Transmutation with emission of a proton. (α,p) reaction.

TABLE II. Absorption coefficients and yield of gamma-rays produced by alpha-particle bombardment.

Element	μ-cm^{-1}	Gamma-ray energies (Mev)	Rel. yield	Total counts at zero abs.
Sodium	0.485 ± 0.017	2.3 ± 0.3 (probable) or 5.2 ± 0.5	9.0	12,600
Magnesium	0.448 ± 0.017 >14	3.2 ± 0.6	7.3 0.7	12,400
Aluminum	0.444 ± 0.017 >14	3.6 ± 0.5	10.0 0.5	8,830
Silicon	0.478 ± 0.016	2.4 ± 0.3 (probable) or 4.9 ± 0.5	1.4	5,300
Phosphorus	0.460 ± 0.027	2.7 ± 0.3 or 4.2 ± 0.5 (probable)	2.7	4,340
Sulfur	0.555 ± 0.080	1.6 ± 0.3	1.2	5,040

In principle the radiation observed can be due to any or all of these processes. The relative probabilities can now be discussed.

Simple Capture. If it is assumed that the capture process yields one gamma-quantum only, then the general trend of mass values indicates that passage to a nucleus four mass units greater requires release of 10 Mev or so. This is greater than the observed energies. It is, of course, possible that two or more gamma-quanta are emitted, in which case the reasoning above is invalid.

Inelastic Scattering. This is a process which has been observed in the bombardment of Li by alpha-particles and for a variety of nuclei under proton bombardment. It would appear to be unlikely that a considerable yield of inelastically scattered alpha-particles could emerge through the potential barrier with energies reduced by 3–4 Mev, as required for Mg, Al, and P. This process, therefore, seems improbable.

(α,n) *Process.* For the case of the elements Na^{23}, Al^{27}, and P^{31}, which have a single isotope, there is less energy available for the (α,n) reaction than the (α,p) reaction both because the mass of the neutron is rather greater and because radioactive nuclei, which are in general more massive, are formed. This relative lack of available energy could therefore be expected to discriminate against this process, since the high energy of the observed gamma-rays points to a high probability of excitation to about 4 Mev. For the other three elements, this reasoning is not so valid.

(α,p) *Process.* The existence of excited states produced in the (α,p) process is well known. The Q values given in Table I show that the target elements Na^{23}, Al^{27}, and P^{31} give rise to product nuclei in states of excitation between 4 and 5 Mev above ground. There would appear to be a strong likelihood that for these three elements the gamma-radiation should agree with differences between levels already found by proton group observation. In the case of Mg and Si, there are present three isotopes each. Moreover, the observations made on proton groups in the (α,p) reactions do not indicate very high degrees of excitation. Therefore, one can assume that (α,n) reactions may well be responsible in these cases. Sulfur is very nearly a single isotope. The greatest degree of excitation from S^{32} would be expected from the (α,p) process which is, therefore, most likely to be responsible for the gamma-rays observed.

With these general points in mind we can suggest the following assignments, tentatively.

Sodium: The 2.3-Mev radiation probably corresponds to the first excited state of Mg^{26}. This agrees with the published Q-values as given in Table I.

Magnesium: No assignment can be given. The radiation is definitely of higher energy than expected from any other evidence.

Aluminum: The radiation is associated with the second excited state of Si^{30}. The energy from proton groups is 3.66 Mev while from this work it is 3.5 Mev.

Silicon: No assignment. The energy measured here is higher than expected from Q values for (α,p) reactions.

Phosphorus: Either the second or third excited state of S^{34}.

Sulfur: Second excited state of Cl^{35}.

While these assignments are not complete, one fact nevertheless appears. The gamma-ray yield is predominantly from states of high excitation. This checks with the observation that proton groups have higher population for higher excitation. The fact that the energy of the radiation runs about double the spacing between energy levels observed in other ways, is evidence that direct transitions are favored in a considerable number of cases. This seems to be certain in the case of the radiation from aluminum and probable in every other case but sodium.