Study of the Isobaric Triplet $Mg^{28}-Al^{28}-Si^{28}$†

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The nuclide Mg^{28} has been produced by betatron irradiation and cyclotron bombardments in the following reactions: $Si^{30}(\gamma,2p)Mg^{28}$ and $Mg^{26}(\alpha,2p)Mg^{28}$. It is a 21.3±0.2 hour β^- emitter ($E_{max}=0.418\pm0.01$ Mev, log $ft=4.30$). Mg^{28} decays to Al^{28} with which it is in secular equilibrium. Milking experiments indicate that the Al^{28} daughter has a 2.3-min half-life, and confirm the mass assignment of Mg^{28}. Gamma-ray spectra of the $Mg^{28}-Al^{28}$ secular equilibrium mixture indicate gamma rays of the following energies in Mev (intensities in parentheses): 1.769±0.01 (0.98), 1.346±0.01 (0.70), 0.949±0.01 (0.29), 0.400±0.01 (0.31), 0.0319±0.001 (0.96). The 1.769-Mev gamma results from the decay of Al^{28}. Coincidence measurements show that the 1.346-, the 0.949-, and the 0.400-Mev gammas are each in coincidence with the 0.0319-Mev gamma, and that the 0.949- and 0.400-Mev gammas are in coincidence with each other. Delay coincidence measurements between the 1.346-Mev gamma and the 0.0319-Mev gamma indicate that the half-life of the latter is $<2\times10^{-9}$ sec. This information together with the $\alpha^K_{exp}=0.032\pm0.066$ indicates that the 0.0319-Mev gamma is an $M1$ transition as predicted if the ground-state doublet of Al^{28} is a $j-j$ doublet. A complete decay scheme for the isobaric triplet, $Mg^{28}-Al^{28}-Si^{28}$, is proposed. All spins and parities of ground and excited states are assigned. Assuming a mass of 27.985818±0.000043 amu for Si^{28}, the mass of Al^{28} is 27.990809±0.000045 and the mass of Mg^{28} is 27.992738±0.000047. On the basis of an empirical scheme of nuclear systematics the energy available for decay and the half-lives of the following nuclei are discussed: Si^{32}, Ne^{24}, O^{20}. A test for $j-j$ doublets is proposed. This test indicates that the ground state doublets of Al^{28} and P^{32} are true $j-j$ doublets, whereas the first excited state doublet of Al^{28} is not.

I. INTRODUCTION

Mg^{28} is a recently discovered[1,2] isotope with a considerable tracer usefulness because its half-life is so much longer than any other magnesium activity. Since its discovery a number of other studies of its various nuclear properties have been published. In particular, Marquez[3] has studied the beta spectra for the $Mg^{28}-Al^{28}$ isotopic pair. Both were found to have "allowed" shapes. In addition, Jones and Kohman[4] have produced the isotope by bombarding silicon with high-energy protons. Wapstra and Veenendaal[5] have studied the 31-kev gamma ray in an attempt to deduce its multipole order and character. Iwersen, Koski, and Rasetti[6] have produced this isotope in a pile by bombarding a Mg–Li alloy. The reaction is $Mg^{26}(t,p)Mg^{28}$. Finally, a tentative decay scheme for the isotope has been reported.[7]

It has now been possible to obtain relative intensities for all the gamma-ray transitions, definite evidence on the spin and parity change in the 31-kev gamma-ray transition, and a tentative assignment of the spin of all the excited states of Al^{28} arising from the decay of Mg^{28}. It is the purpose of this paper to report on these new experimental data and to give the details of the previous experimental evidence presented.[1,7]

In a chart of the nuclides, the isotopes Si^{32}, Mg^{28}, Ne^{24}, and O^{20} are an alpha particle apart in a sequence immediately below stable S^{36}. Each of these nuclei has two neutrons in excess of stability. At first glance one might believe, in spite of their even-even character, that these nuclei would be short lived, for they all lie further from the line of stability than the short-lived nuclei with one less neutron, Si^{31}, Mg^{27}, Ne^{23}, and O^{19}.

On the other hand, Suess[8] by an analysis of masses in this region of the chart of nuclides, felt there was a distinct possibility that Si^{32} and perhaps Mg^{28} would prove to be stable. A careful radiochemical search for stable Si^{32} has been performed by Turkevich and Tompkins[9] with negative results. However, one is led to the conclusion from the mass data that there is at most a small amount of energy available for transition in the decay. An additional compelling reason for expecting long half-lives is the spin and parity change expected in these decays. Both S^{32} and Si^{32} have spin and parity assignment of 0+. The decay of P^{32}, on the other hand, is known to have a relatively high ft value because of its l-forbidden character. Therefore, one may expect a similarly high ft value and a considerably longer half-life for the l-forbidden Si^{32} decay. The transition between ground states of the isobaric couple $Al^{28}-Si^{28}$ is second forbidden. Therefore, one expects the transition between the ground states of Mg^{28} and Al^{28} to be second forbidden with a correspondingly longer half-life. In a similar manner, one would expect Ne^{24} to have a forbidden transition to the ground state of Na^{24}. Also O^{20} could beta decay to the ground

† This research was partially supported under a contract between The Florida State University and the U. S. Atomic Energy Commission.

[1] R. K. Sheline and N. R. Johnson, Phys. Rev. **89**, 520 (1953).
[2] M. Lindner, Phys. Rev. **89**, 1150 (1953).
[3] L. Marquez, Phys. Rev. **90**, 330 (1953).
[4] J. W. Jones and T. P. Kohman, Phys. Rev. **90**, 495 (1953).
[5] A. H. Wapstra and A. L. Veenendaal, Phys. Rev. **91**, 426 (1953).
[6] Iwersen, Koski, and Rasetti, Phys. Rev. **91**, 1229 (1953).
[7] R. K. Sheline and N. R. Johnson, Phys. Rev. **90**, 325 (1953).
[8] H. Suess (private communication).
[9] A. Turkevich and A. Tompkins, Phys. Rev. **90**, 247 (1953).

state of F^{20} only by an *l*-forbidden transition. On the basis of these considerations, an attempt to produce one or more of these isotopes through cyclotron and betatron bombardments seemed justified. The logical choice to produce an activity long enough lived to be observed after the bombarded sample was air mailed hundreds of miles seemed to lie between Mg^{28} and Si^{32}. It was felt that Si^{32} lay so close to the line of stability that it might be extremely long lived and therefore difficult to observe. Accordingly we decide to look first for Mg^{28}. A betatron bombardment of ordinary elemental silicon was attempted with the University of Chicago betatron. First experiments were done with detecting equipment at the site of the betatron in an attempt to observe a possible short-lived activity. These results were negative, and therefore bombardments of longer duration were attempted both with the betatron at the University of Chicago and with the cyclotron of the University of California.

II. BOMBARDMENTS, CHEMICAL SEPARATION PROCEDURES, AND HALF-LIFE

In order to look for a very short-lived activity for Mg^{28}, a sample of elemental silicon in granular form was counted in place immediately after turning off the betatron beam. This sample in cylindrical form was mounted directly in the beam of the betatron in such a way that the axis of the cylinder was the axis of the beam. A Geiger tube shielded with 6 inches of lead was placed parallel to it, and 2 inches from the beam center. The betatron and Geiger tube were controlled by a motor-driven timing switch, and a brush recorder was used to record counts. The entire apparatus has previously been described.[10] In this way it was possible to irradiate samples for 3 seconds and then count them within milliseconds after the beam was turned off for a period of 5 seconds. If a Mg^{28} activity in the region from 0.02 second to several minutes were to be produced in this bombardment, it should have been observed. Only the region from 2 to 9 minutes and the region of 5 to 7 seconds are obscured by other known activities to be expected in the silicon betatron bombardment. Using a "rabbit" to transport the silicon sample quickly after irradiation and using the traditional Geiger tube counting setup, the longer half-life region from 9 minutes to 5 hours was explored. The region of 2.6 hours was obscured by the Si^{31} activity. The results from both of these experiments were negative. Therefore it was assumed that the half-life of Mg^{28} did not fall in the region 0.02 second to 5 hours, with the possible exception of those regions obscured by other activities produced in the bombardment.

With this evidence in mind a long betatron bombardment of silicon was undertaken. The expected nuclear reaction was $Si^{30}(\gamma,2p)Mg^{28}$. A sample of elemental granular silicon containing total impurities of less than 0.01 percent was obtained from the Institute of Metals

[10] R. K. Sheline, Phys. Rev. 87, 557 (1952).

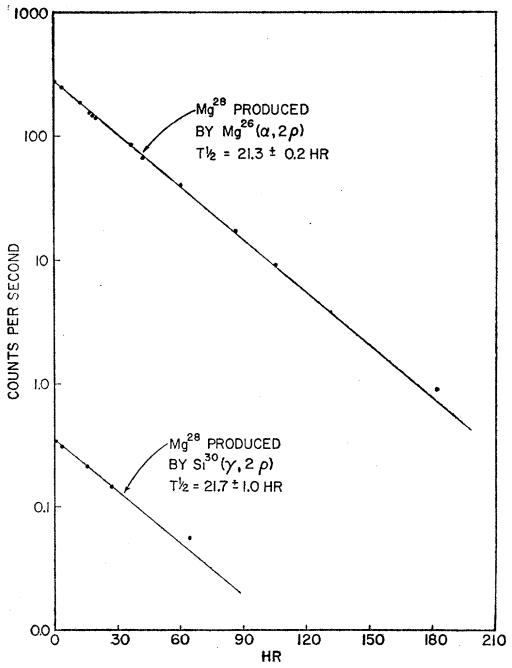

FIG. 1. Mg^{28} half-life determinations from betatron and cyclotron bombardments.

of the University of Chicago. It was irradiated for 8 hours in the gamma spectrum of the 100-Mev University of Chicago betatron. After dissolving the sample in hot concentrated sodium hydroxide, 15 mg of carrier magnesium chloride was added. Neutralization with HCl precipitated silicic acid. The slurry was then evaporated to dryness and warm distilled water added. The SiO_2 was filtered and the filtrate buffered with ammonium chloride and made slightly ammoniacal. The addition of 1 gram of primary ammonium phosphate precipitated magnesium ammonium phosphate. This precipitation was repeated twice to insure high purity. After transferring the precipitate to a planchet and drying, it was counted in a Geiger-Mueller counter. Counts were taken through only 3 half-lives due to the low specific activity. The resulting decay showed a single half-life of 21.7 ± 1.0 hours (Fig. 1).

After this initial success, it seemed advisable to attempt a cross bombardment to confirm the observation of this new activity. The cross bombardment chosen was $Mg^{26}(\alpha,2p)Mg^{28}$.

A disk of magnesium of ordinary isotopic composition 1 and $\frac{5}{16}$ inches in diameter and 0.1 inch thick was bombarded for ten hours in an external beam of 39-Mev alpha particles of the University of California 60-inch cyclotron. The beam covered a one-inch by one-half-inch rectangular area on the disk and penetrated to a depth of $\sim$0.0373 inch. Except for the area of beam penetration, the disk was coated with Krylon plastic spray. By means of a carefully timed procedure, approximately 0.013 inch of the active

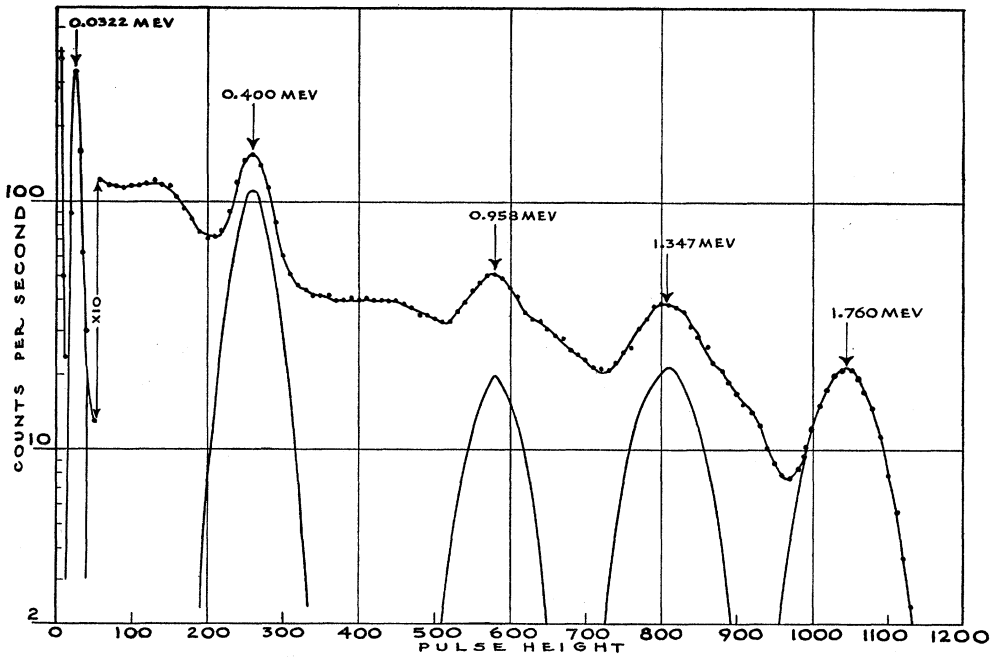

FIG. 2. Typical gamma-ray spectrum of Mg^{28} in secular equilibrium with Al^{28}.

portion was dissolved in 30 ml of 1:10 HCl. In this manner a higher specific activity was obtained. Four milligrams of NaCl were added to the solution as holdback carrier. After buffering the solution with NH_4Cl and making it ammoniacal, the magnesium was precipitated as magnesium ammonium phosphate by the addition of 15 ml of 1 molar primary ammonium phosphate. This precipitation was repeated four times to assure a minimum of impurity. Several samples were transferred to planchets, dried, and counted in Geiger-Mueller counters. The half-life for this bombardment was 21.3±0.2 hours over a decay curve covering 8.6 half-lives. The experimental data are shown in Fig. 1.

Jones and Kohman[4] have reported a half-life of 22.1±0.3 hours which differs significantly from our value. In additional bombardments we have repeated our half-life measurements, and find that 21.3±0.2 hours represents accurately all of our determinations. These additional bombardments were also used to study methods of producing the highest possible specific activity utilizing an isotopic target. Through the use of a 5-hour internal beam bombardment, it was possible to produce an initial magnesium activity of approximately 3.5×10^6 counts per minute per milligram of magnesium utilizing the technique of dissolving the active part of the target only. In summary, these experiments indicated the existence of a new 21.3-hour magnesium activity.

III. GAMMA-RAY SPECTRA, ABSORPTION MEASUREMENTS, AND MASS NUMBER ASSIGNMENT

Gamma-ray spectra of this new magnesium isotope were obtained using a sweep-type differential and integral discriminator similar to the one described by

TABLE I. Gamma-ray energies and intensities of Mg^{28} and Al^{28} in secular equilibrium with each other. These data are obtained from small crystal ($1\frac{1}{2}$ in.—1 in.) spectra only.

			Energies in Mev		
Gamma rays	γ_1	γ_2	γ_3	γ_4	γ_5
Run 1	~0.03[a]	0.40 ±0.02	0.95 ±0.02	1.35 ±0.02	1.78 ±0.02
Run 2	0.0316±0.001	0.40 ±0.01	0.940±0.01	1.340±0.01	1.766±0.01
Run 3	0.0322±0.001	0.40 ±0.01	0.958±0.01	1.347±0.01	1.760±0.01
Average	0.0319±0.001	0.40 ±0.01	0.949±0.01	1.346±0.01	1.769±0.01
			Intensities[b]		
Gamma rays	γ_1	γ_2	γ_3	γ_4	γ_5[c]
Run 1	Undetermined	0.30 ±0.03	0.28 ±0.03	0.71 ±0.05	1.00 ±0.05
Run 2	0.962 ±0.05	0.319±0.03	0.292±0.03	0.681±0.05	0.964±0.05
Average	0.962 ±0.05	0.309±0.03	0.286±0.03	0.696±0.05	0.982±0.05

[a] Not used in computing average.
[b] Intensity measurements were not determined in Run 3.
[c] Intensity measurements based on 17.0 percent of the 1.78-Mev gamma ray in the photopeak.

Fairstein.[11] In later bombardments the 20-channel pulse analyzer of Kelley, Bell, and Goss[12] was used to obtain the gamma-ray spectra. A typical gamma-ray spectrum is shown in Fig. 2. Several different determinations of the gamma rays, together with their energies and relative intensities, are listed in Table I. The relative intensities were obtained by correcting the areas in the photopeaks to account for the Compton distributions and by correcting for the geometry and efficiencies of the sodium iodide crystal. In addition, a correction was made for the absorption of the 30-kev gamma ray in the aluminum of the equipment. Jones and Kohman[4] found evidence for several gamma rays with energies extending to at least 2.5 Mev. A very careful search was made for these higher-energy gamma rays and we are able to say that gamma rays of energy greater than 2 Mev have an intensity less than one one-thousandth that of the 1.78-Mev gamma ray listed in Table I. The existence of these additional gamma rays in the spectra of Jones and Kohman may indicate contamination of their sample with a corresponding discrepancy in half-life.

Absorption measurements on the new magnesium activity shown in Fig. 3 indicate 2 betas, one of approximately 3 Mev, and the other of 0.40 ± 0.06 Mev. The actual absorption measurements on the 0.40-Mev beta do not in themselves indicate as large an experimental error as that noted. However, the inaccuracy resulting from subtracting the 3-Mev beta determines the high error. Both the 1.78-Mev gamma listed in Table I, and the approximately 3-Mev β^- observed in the absorption measurements agree almost perfectly with the nuclear data available for Al^{28}. Any Al^{28} produced in the initial bombardment would not be present in the Mg^{28} for two reasons. Its half-life is so short (2.3 min) that it would be dead at the time these separations were run. Also the chemical separation described in Sec. II would have separated it from the magnesium. Accordingly it is assumed that if Al^{28} is present it grows in as the daughter from the parent Mg^{28}. Such a supposition is easy to test through "milking" experiments.

A sample of the active magnesium ammonium phosphate was dissolved in HCl. This solution was made strongly basic with NaOH, causing the precipitation of $Mg(OH)_2$. The precipitate was dissolved in HCl and $AlCl_3$ carrier was added. After buffering with NH_4Cl the solution was made ammoniacal, resulting in the precipitation of aluminum hydroxide. The aluminum hydroxide was centrifuged, washed with a solution of NH_4Cl and NH_4OH, and centrifuged again. The procedure beginning with the dissolving of $Mg(OH)_2$ was carried out in a lusteroid tube. The tube was cut away just above the surface of the precipitate and the section containing the sample was mounted and

[11] E. Fairstein, Rev. Sci. Instr. **22**, 76 (1951).
[12] Kelley, Bell, and Goss, Oak Ridge National Laboratory Report ORNL-1278, December 20, 1951 (unpublished), p. 27.

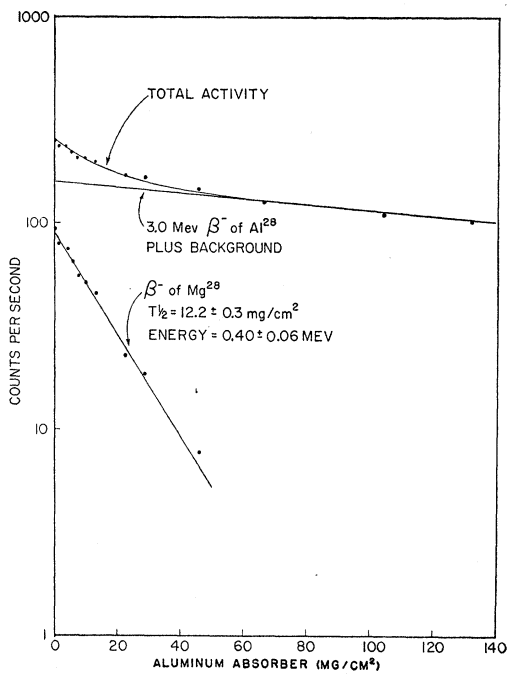

FIG. 3. Low-energy region of absorption curve of Mg^{28} and Al^{28} in secular equilibrium.

placed in a Geiger-Mueller counter. Four minutes elapsed from the time of the first precipitation of the $Al(OH)_3$ until the first count was taken. The decay curve shown in Fig. 4 consists of a 2.3-minute activity which drops off after 6 half-lives into a 21.3-hour background attributed to adsorbed Mg^{28}.

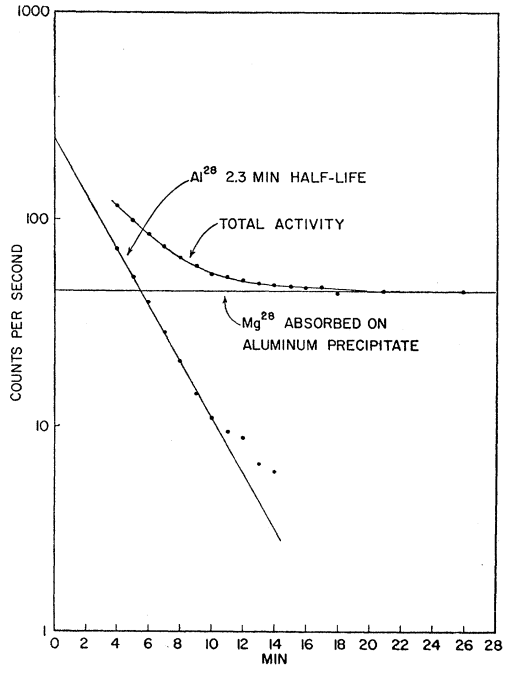

FIG. 4. The decay of the Al^{28} daughter milked from Mg^{28}.

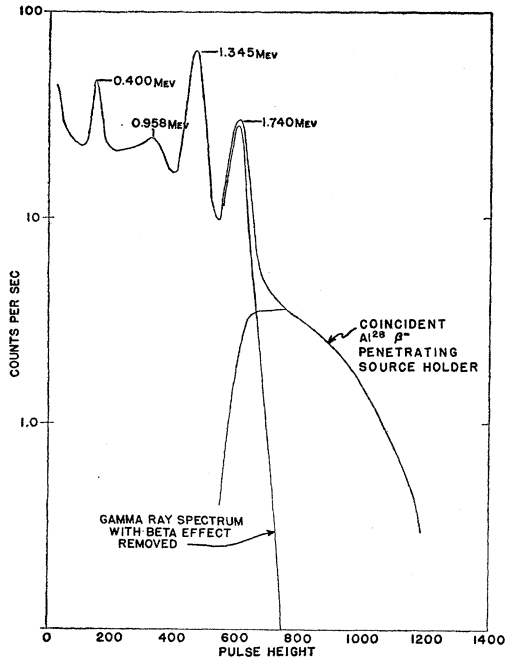

FIG. 5. A large crystal spectrum of Mg^{28} in secular equilibrium with Al^{28} used in coincidence determinations.

The presence of an Al^{28} daughter with a 2.3-minute half-life, approximately 3-Mev β^-, and a 1.78-Mev gamma in secular equilibrium with this new magnesium activity, is extremely strong evidence for its assignment as Mg^{28}.

The additional evidence from cross bombardments and nuclear systematics makes the Mg^{28} mass assignment certain. Marquez[3] has measured the maximum β^- energy of Mg^{28} to be 0.418 ± 0.010 Mev using a double magnetic lens beta-ray spectrometer. We accept his energy measurements for the Mg^{28} and Al^{28} betas rather than those of this study resulting from absorption measurements because of their greater accuracy.* The energies, half-lives, log *ft* values, and degrees of forbiddenness of both Mg^{28} and Al^{28} are shown in Table II.

IV. LARGE CRYSTAL SPECTRA, COINCIDENCE SPECTRA, AND DELAY COINCIDENCE MEASUREMENTS

Gamma-ray spectra were obtained using a $4\frac{3}{4}$-inch thallium activated sodium iodide crystal with a well into which the sample was inserted. One of these spectra is shown in Fig. 5. In such large crystals there is a much greater probability than in small crystals, of observing the coincident sum peaks of gamma rays emitted in coincidence. A comparison of the large crystal spectra and that obtained with a small crystal with the source outside the crystal shows which gamma rays are in coincidence. Figure 5 when compared with Fig. 2 shows quite definitely a decreased intensity of the 0.400- and 0.949-Mev photopeaks together with a corresponding increase in the 1.346-Mev photopeak. The 0.949-Mev gamma line is almost invisible since when a 0.949-Mev gamma ray is detected, the probability that the 0.400-Mev gamma ray (coincident with it) will escape, is quite small. On the other hand, when a 0.400-Mev gamma ray is detected, the probability of escape of the 0.949-Mev gamma is not as small. No line is observed at a pulse height corresponding to 2.7 Mev, showing that the 0.400–0.949 Mev cascade is not in coincidence with the 1.346-Mev gamma ray. The interpretation that the 0.400- and 0.949-Mev gamma rays are in coincidence seems unequivocal. Coincidence information on the 0.0319-Mev gamma ray using large crystal spectra is somewhat more difficult to obtain. Two large crystal spectra were obtained in which the Mg^{28} was surrounded by brass. In this case the majority of the 0.0319-Mev gamma rays did not get into the crystal.

In several other large crystal spectra an aluminum activity holder was used which allowed the majority of the 0.0319-Mev gamma rays to get into the crystal. These spectra are summarized in Table III. γ_2' and γ_4' refer to the energies when the activity is surrounded by aluminum, whereas γ_2 and γ_4 refer to the energies when surrounded by brass. The pertinent pieces of information in Table II are: (a) Both γ_2' and γ_4' have a higher energy than γ_2 and γ_4. (b) This difference in energies between γ_2', γ_4' and γ_2, γ_4 is very close to the energy of γ_1 (0.0319 Mev). (c) Surrounding the sample with either aluminum or brass makes no difference in the energy of γ_5. This information is interpreted as follows: γ_1 is in coincidence with γ_2 and γ_4. Therefore when the activity is surrounded by aluminum through which γ_1 can penetrate, the sum peaks are observed, namely γ_2' and γ_4'. These are slightly higher in energy than when the activity is surrounded by brass through which γ_1 cannot pass. The effect of the metal holder on the activity is not appreciable, as indicated by the fact that the Al^{28} γ_5 is exactly the same in both measurements. The comparison of the aluminum and brass differences of γ_4 and γ_5 indicates again a discrepancy of 0.03 Mev, just the energy of γ_1. Since it has previously been shown that γ_2 and γ_3 are in coincidence, and that

TABLE II. Data on the β^- decays of Mg^{28} and Al^{28}.

Isotope	Energy max of β^- (Mev)	Half-life (min)	log *ft*	Degree of forbiddenness
Mg^{28}	0.418	1278	4.30	Allowed
Al^{28}	2.865	2.3[a]	4.92[a]	Allowed[b]

[a] There is some indication from half-life measurements in milking experiments that Al^{28} has a slightly shorter half-life and correspondingly smaller log *ft* value.

[b] These values are from H. T. Motz and D. E. Alburger, Phys. Rev. 86, 165 (1952).

* *Note added in proof.*—Since this article was submitted for publication a more accurate measurement of the maximum energy of the Mg^{28} beta ray has been obtained by Olsen and O'Kelley, Phys. Rev. 93, 1125 (1954). They report $E_{max}=0.459\pm0.002$, log $ft=4.45$. This difference in energy in no way affects the conclusions reached in this article. However it puts the ground state of Mg^{28} 6.484 Mev above the ground state of Si^{28} with a consequent change of the mass of Mg^{28} to 27.992782 ± 0.000046.

γ_1 and γ_2 are in coincidence, a coincidence may be inferred between γ_1 and γ_3.

As a check on the coincidences between the 0.0319-Mev gamma ray and the 0.40- and 0.949-Mev gamma rays, a coincidence spectrum was obtained. One counter of the coincidence setup was set so as to accept only the 0.0319-Mev gamma rays. The other detector was used to monitor the region from 0.2 to 1.0 Mev. The spectrum so obtained is shown in Fig. 6.

It is noteworthy that it is almost identical with the ordinary spectrum from 0.2 to 1.0 Mev. This coincidence spectrum indicates definitely that the 0.0319-gamma ray is in coincidence both with the 0.400- and 0.949-Mev gamma rays. In the case of the 0.949-Mev gamma ray, this could only be inferred indirectly from the large crystal work.

The 0.0319-Mev gamma ray results from an excited state of Al^{28} which is so near the ground state that there is a distinct possibility that it might be metastable. Accordingly, delay coincidence measurements were made utilizing a delay coincidence scintillation spectrometer previously described.[13] In this case the delay coincidence scintillation spectrometer employed sodium-iodide thallium activated crystals with Type 5819 multiplier tubes as detectors. Coincidence measurements between the 1.346-Mev gamma ray and the 0.0319-Mev ray were made. In Fig. 7 (curve 2) the number of coincidences is plotted as a function of delay time for a sample of Mg^{28}. The slope of curve 2 indicates a half-life $\leq 2.27\times10^{-9}$ sec. Without a change in the apparatus, a resolution curve for prompt coincidences was obtained between the 1.28-Mev gamma ray of Na^{22}, and the 0.032-Mev electron pulses from the Compton distribution of positron annihilation with which the 1.28-Mev gamma is in prompt coincidence.

The half-life so observed is slightly shorter than in the case of Mg^{28}. (See Fig. 7, curve 1.) However, the difference is so small that it is possible to say that the half-life of the 0.0319-Mev excited state of Al^{28} is less than 2×10^{-9} sec. Although no metastable state of measurable half-life was observed in these experiments definite existence of the coincidence between the 1.35-Mev gamma and the 0.032-Mev gamma is indicated.

TABLE III. Gamma-ray energies in Mev as determined from large crystal spectra in which the activities were surrounded by aluminum or brass.

Activity surrounded by aluminum	Energy in Mev			
	γ_2'[a]	γ_4'[a]	γ_5'	$\gamma_5'-\gamma_4'$
Run 1	0.400	1.345	1.740	0.395
Run 2	0.401	1.356	1.755	0.399
Run 3	···	1.350	1.750	0.400
Run 4	···	1.350	1.735	0.385
Average	0.4005	1.350	1.745	0.392
Activity surrounded by brass	Energy in Mev			
	γ_2	γ_4	γ_5	$\gamma_5-\gamma_4$
Run 5	0.375	1.315	1.745	0.430
Run 6	0.390	1.325	1.745	0.420
Average	0.382	1.320	1.745	0.425

[a] The primes on gamma rays 2 and 4 indicate that the sample was surrounded by aluminum rather than brass; $\gamma_2'=(\gamma_2+\gamma_1)$, $\gamma_4'=(\gamma_4+\gamma_1)$.

[13] F. K. McGowan, Phys. Rev. **79**, 404 (1950).

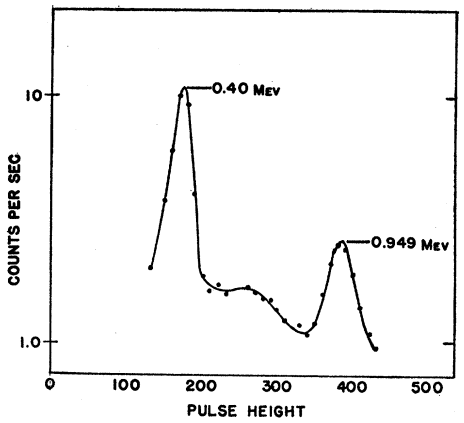

FIG. 6. A coincidence spectrum of Mg^{28} in secular equilibrium with Al^{28}, with one counter of the coincidence set so as to accept only the 0.0319-Mev gamma rays, while the other detector is used to monitor the region of 0.2 to 1.0 Mev.

V. DECAY SCHEME OF Mg^{28} AND THE MASSES OF Al^{28} AND Mg^{28}

The decay scheme for Mg^{28} must involve an energy level scheme in Al^{28} which will permit the following: (1) coincidences between the 1.346, 0.949, 0.400-Mev gammas, and the 0.0319-Mev gamma; (2) a coincidence between the 0.949-Mev gamma and 0.400-Mev gamma; (3) no coincidences between either the 0.949-Mev or the 0.400-Mev gammas and the 1.346-Mev gamma; (4) very similar intensities in the 0.944- and 0.400-Mev gammas; (5) an intensity for the 0.0319-Mev gamma which is approximately equal to the sum of the intensity of the 1.346-Mev gamma and either the 0.949- or the 0.400-Mev gammas; (6) a single Mg^{28} beta ray. Such a decay scheme is shown in Fig. 8(a). The level scheme for Al^{28} is almost identical with that derived by Enge, Buechner, and Sperduto[14] from a magnetic analysis of the $Al^{27}(d,p)Al^{28}$ reaction. There is one important exception. They report a level at 1.015 Mev for which we find no evidence in the decay of Mg^{28}. Because of its large intensity in the $Al^{27}(d,p)Al^{28}$ work, there can be little doubt of its existence. However, after a careful search for this level with enough resolution to observe it, we must conclude that it is not populated in the Mg^{28} decay.

In order to assign spins and parities to the various states of Al^{28}, it is first advisable to establish the nature of the 0.0319-Mev gamma transition. A delay coincidence measurement of the half-life of the 0.0319-Mev state indicates that it is less than 2×10^{-9} sec. From this measurement one may immediately conclude that

[14] Enge, Buechner, and Sperduto, Phys. Rev. **88**, 963 (1952).

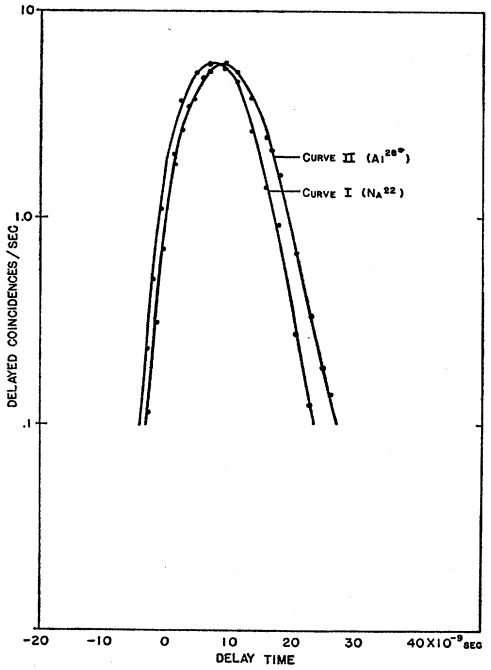

FIG. 7. The number of delayed coincidences as a function of delay time.

it is a dipole transition. Quadrupole or higher pole transitions of this energy would be expected to have much longer half-lives. It is then necessary to choose between $M1$ and $E1$ transitions. One sensitive method of distinguishing between these two transitions would be to observe the internal conversion coefficient. Smith and Anderson[15] have failed to observe internal conversion electrons, putting an upper limit on $\alpha^K_{\text{exp}} \leq 2$. By observing the intensity of the 0.0319-Mev gamma ray relative to the other gamma rays in the Mg^{28} decay, Wapstra and Veenendaal[5] set an $\alpha^K_{\text{exp}} = 0.30 \pm 0.20$, but were not able to draw a definite conclusion as to the nature of the transition. The results presented in Table I together with that part of the decay scheme indicated in Fig. 8(a) determine a value of $\alpha^K_{\text{exp}} = 0.032 \pm 0.066$ for the 0.0319-Mev gamma ray.

Although relativistic K-shell internal conversion coefficients for $E_\gamma < 150$ kev are not yet available, there is a method for obtaining extrapolated values of the coefficients at low energies. The ratio of the relativistic coefficients[16] to the nonrelativistic coefficients[17] is plotted for $E_\gamma \leq 150$ kev, and the ratio is extrapolated to one at zero electron energy.[18] Low-energy K-shell conversion coefficients for electric radiation are obtained by multiplying the nonrelativistic values by a correction factor from the ratio plot. Similarly, for magnetic radiation, extrapolated coefficients are obtained by multiplying the extrapolated coefficient for electric radiation by a correction factor from a plot of β_{l-1}/α_l extrapolated to zero electron energy.

The values obtained for these extrapolations indicate $\alpha_1^K = 0.31$, $\alpha_2^K = 10.8$, $\beta_1^K \lesssim 0.1$. The value for β_1^K is very uncertain because the extrapolated ratio of β_1^K to α_2^K is not known at very low energies. Fortunately the experimental data discriminate clearly against an internal conversion coefficient of 0.31. Therefore by elimination one is led to the conclusion that the 0.0319-Mev-gamma ray is an $M1$ transition. Since the spin and parity of the even-even Mg^{28} nucleus must be 0+, the allowed beta decay to the 1.375-Mev level determines its assignment as either 0+, or 1+. The ground state of Al^{28} with a $(d_{\frac{5}{2}})^{-1}s_{\frac{1}{2}}$ configuration should be 3+ according to the rules of Nordheim.[19] Furthermore, no other assignment for the ground state is completely consistent with the decay to the first excited state of Si^{28}, and with the gamma and beta decay energies and intensities of the Mg^{28} decay. The 0.0319-Mev excited state which goes to the 3+ ground state via an $M1$ transition must be 2+ rather than 4+, since it is populated by the 0+ or 1+ 1.375-Mev level, preferentially in comparison to the ground state. Finally the 0.978-Mev level must be 1−, 2−, or 2+ so that it can compete with the (2+) 0.031-Mev level for gamma rays, yet not be populated by the Mg^{28} beta decay. The various possible combinations of these spin possibilities together with the type of gamma-ray transitions which these combinations of spins determine are indicated in Figs. 8(b), (c), (d), (e), and (f). The measured ratio of the intensity of the 1.346-Mev gamma ray to the 0.400-Mev gamma ray is 2.25. By using the Weisskopf[20] formula it is possible to compute

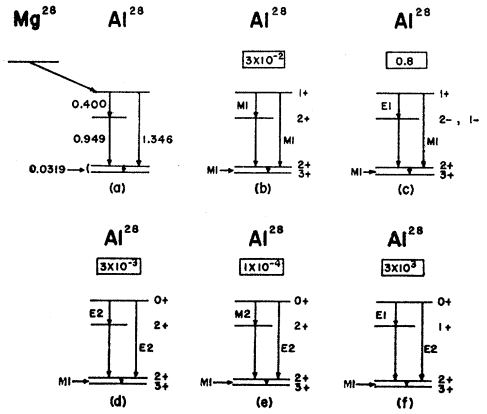

FIG. 8. Various possible assignments of Al^{28} energy levels, spins, and parities. (a) indicates the correct energy level assignment. (b), (c), (d), (e), and (f) indicate various possible spin and parity assignments. The numbers in the boxes above (b), (c), (d), (e), and (f) indicate the ratios of the intensities of the 1.346-Mev gamma to the 0.400-Mev gamma, calculated using the Weisskopf formula for each set of proposed parities and spins.

[15] R. D. Smith and R. A. Anderson, Nature **168**, 429 (1951).
[16] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).
[17] M. H. Hebb and E. Nelson, Phys. Rev. **58**, 486 (1940).
[18] P. Axel and R. F. Goodrich, U. S. Office of Naval Research Report (unpublished).
[19] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).
[20] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

the theoretical ratio of intensities of the 1.346 Mev gamma to the 0.400-Mev gamma for the various combinations of spins. They are indicated in the boxes above the Figs. 8(b), (c), (d), (e), (f). Case (c) comes considerably closer than any of the others to predicting the experimental value. This would probably be a cleancut decision for 2−, or 1− for the 0.978-Mev level except for the experiments of Holt and Marsham.[21]

In their investigation of (d,p) stripping reactions on Al^{27} they observe an angular distribution of the unresolved proton groups going to the 0.0319-Mev and ground-state levels in which $l_n=0$. This indicates $J=2+$ and/or $3+$ for the ground state doublet, which agrees with the results obtained here from the Mg^{28} decay. However, Holt and Marsham[21] obtain an angular distribution of the unresolved proton groups going to the 0.978- and 1.015-Mev levels which could be fitted by a combination of about 10 percent of $l_n=0$ and about 90 percent $l_n=2$. Since the 0.978-Mev level populated in the Mg^{28} decay is produced in much less intensity in the (d,p) stripping reaction than the 1.015-Mev level, according to the work of Enge, Buechner, and Sperduto,[14] it is concluded that the 0.978-Mev level is responsible for the 10 percent $l_n=0$ angular distribution in the experiments of Holt and Marsham. Therefore, the spin and parity of the 0.978-Mev level should be 2+ or 3+. Since the Weisskopf formula is known to err by a large factor at times, and since the 2+ state is the second choice from the calculation of the ratio of gamma-ray intensities (see Fig. 8), the most probable assignment of the 0.978-Mev level is 2+. However, because of the calculations using the Weisskopf formula, an assignment as 2− or 1− is not completely ruled out and is indicated in the parentheses.

The first excited state of Si^{28} would be expected to be 2+.[22] The entire decay scheme for the isobaric triplet $Mg^{28}-Al^{28}-Si^{28}$ is shown in Fig. 9.

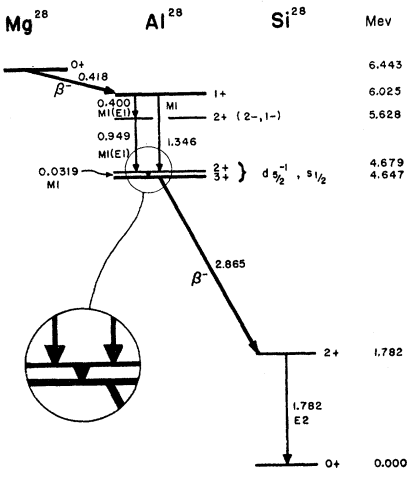

FIG. 9. Decay scheme for the isobaric triplet $Mg^{28}-Al^{28}-Si^{28}$.

[21] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 249 (1953).

[22] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

TABLE IV. Energetic relationship between certain isobaric triplets.

Isobaric triplets	Prediction[a] of first couple energy differences in Mev	Energy differences of first couple as indicated by the Fermi-Weisäcker equation	Prediction of half-lives
$S^{36}-Cl^{36}-A^{36}$	(−0.97)	−3.2	...
$Si^{32}-P^{32}-S^{32}$	+0.12	−2.3	700±500 years
$Mg^{28}-Al^{28}-Si^{28}$	(1.76)	−1.3	(21.3 hours)
$Ne^{24}-Na^{24}-Mg^{24}$	4.4	−0.02	short
$O^{20}-F^{20}-Ne^{20}$	7.4	+1.6	very short

[a] Values in parentheses are known and not predictions.

The masses of Al^{28} and Mg^{28} have been calculated on the basis of the decay scheme shown in Fig. 9. Masses of 27.985810±0.000080,[23] 27.985792±0.000032,[24] and 27.985825±0.000016[25] have been reported for Si^{28}. A weighted mean gives a value of 27.985818±0.000043. Using the weighted mean, an energy transition of 4.647±0.0014 Mev, and 931.152[26] as the conversion factor, gives 27.990809±0.000045 as the mass of Al^{28}. An energy of 1.796±0.014 Mev is involved in the decay of Mg^{28} to the ground state of Al^{28}. From this the mass of Mg^{28} is determined as 27.992738±0.000047.††

VI. DISCUSSION

The search for Mg^{28} was undertaken on the assumption that O^{20}, Ne^{24}, Mg^{28}, and Si^{32}, whose decays are forbidden, might be sufficiently long-lived to serve as tracers. Its discovery has given new impetus to the search for the remaining isotopes of this group.

These unknown activities, together with other known activities and stable isobars, form the isobaric triplets shown in Table IV.

The energy differences between the second couples of the triplets (e.g., $Cl^{36}-A^{36}$, and $P^{32}-S^{32}$), are known, whereas in general the energy differences between the first couples (e.g., $Si^{32}-P^{32}$ and $Ne^{24}-Na^{24}$) are unknown. The energy differences between second couples can be plotted against mass number and then the energy coordinate changed to the energy differences between first couples. Only the decay energy of Mg^{28} and the mass difference between Cl^{36} and S^{36} can be used to define the first-couple energy differences coordinate. However, this is sufficient to predict energy differences for the rest of the first couples as shown in Table IV. It is interesting to note the comparison of the energies predicted using the method described and those predicted by the Fermi-Weisäcker equation. In general, the Fermi-Weisäcker equation predicts too little energy for the first couple by two or more Mev. Except

[23] H. E. Duckworth and R. S. Preston, Phys. Rev. **79**, 402 (1950).

[24] H. Ewald, Z. Naturforsch. **6a**, 293 (1951).

[25] K. Ogata and H. Matsuda, Phys. Rev. **89**, 27 (1953).

[26] J. W. M. Dumond and E. R. Cohen, Phys. Rev. **82**, 555 (1951).

†† See *Note added in proof*, p. 1646.

for $S^{36}-Cl^{36}$ and $O^{20}-F^{20}$, the Fermi-Weisäcker equation also predicts the wrong direction for the decay.

Unfortunately, since nothing is known about the decay scheme, it is not possible to predict half-lives for Ne^{24} and O^{20}. Since both Na^{24} and F^{20} have a number of excited states into which Ne^{24} and O^{20} can decay, it is probable that they will be short-lived in spite of the forbiddenness of their ground-state transitions. It should be stated that the one-particle shell model predicts even greater forbiddenness for the first several transitions from O^{20} to excited states of F^{20} than to the ground state. Therefore, because of the very great usefulness of a long-lived oxygen isotope, it would seem worth while to look for this isotope on the slim possibility that all energetically available transitions are forbidden. Si^{32} has such a small amount of energy available for decay that it must either decay into the ground state or to the 77-kev state of P^{32} described by Van Patter *et al.*[27] If one accepts the explanation of Inglis[28] for this ground-state doublet together with the accepted spin and parity assignment of the P^{32} ground state as $1+$, then the 77-kev excited state should have a spin of $2+$. Such an assignment of the doublet suggests that the Si^{32} decay should go to the ground state of P^{32} rather than to the 77-kev state. Since Si^{32} goes to the P^{32} ground state by a change of a $d_{\frac{3}{2}}$ neutron into an $s_{\frac{1}{2}}$ proton, and P^{32} goes to the ground state of S^{32} by exactly the same type of change, it is probable that the log ft value for these two beta decays would be very nearly the same. Using the log ft value of 7.9 for the P^{32} decay together with the 0.12 Mev of energy predicted for the Si^{32} decay, a half-life of 700 ± 500 years for Si^{32} is calculated. The large error is due to the large uncertainty in the energy.

Attempts to produce Si^{32} by successive (n,γ) reactions in the pile and by the reaction $Si^{30}(\alpha,2p)Si^{32}$ produced very small amounts of a long-lived activity. More recently, Lindner[29] has produced Si^{32} by high-energy proton spallation of chloride. He observed a simple beta decay of 0.10-Mev maximum energy and a 700-year half-life. The very close agreement between his experiments and the calculations presented here seems to justify them in spite of their empirical nature.

The implications of an $M1$ type transition from the 31-kev state to the ground state of Al^{28} are of considerable interest in addition to their worth in helping with spin assignments in the decay scheme.

According to Inglis,[28] the ground-state doublet of Al^{28} arises from neutron-proton $j-j$ coupling. The $d_{\frac{5}{2}}$ proton hole couples with the $s_{\frac{1}{2}}$ neutron. The splitting between the $J=2$ and $J=3$ levels is small because it is caused by a small term in the spin exchange operator. If these one-particle shell model arguments are correct, one would expect the 31.9-kev transition to be a magnetic dipole. The confirmation of this prediction by the experimental results presented here is gratifying.

In addition, Inglis suggests that the excited state doublet observed by Enge *et al.*[14] may be the result of the excitation of the odd proton from the $d_{\frac{5}{2}}$ orbital to the $d_{\frac{3}{2}}$ orbital. This leaves the spin of the s neutron to be oriented so that two states of $J=1+$ and $2+$ are possibilities. The evidence presented here discriminates strongly against this interpretation. No population of the higher energy level of this doublet is observed from the decay of Mg^{28}. This is very strange if the interpretation of Inglis were correct. There are other indications that the excited state doublet is different from the ground-state doublet. The yield of the proton groups in the excited doublet is in the ratio 4.6 to 38.0, as observed by Enge *et al.*,[14] at 90° and 2.1-Mev bombarding energy. The proton groups going to the ground state and 31.9-kev level were in the ratio 100 to 69. Holt and Marsham[21] observed an angular distribution of the unresolved proton groups going to the excited doublet which can be fitted by a combination of $l_n=0$ and $l_n=2$. This result indicates that one of these two levels has $J=2+$ or $3+$, while the other has $J=0+$, $1+$, $2+$, $3+$, $4+$, or $5+$.

TABLE V. Tests for $j-j$ doublets.

Designation of doublet	Energy of levels in Mev	Spin and parity of levels	Relative[a] intensity of levels	Intensity $\frac{\text{Intensity}}{(2J+1)}$	$j-j$ doublet
Al^{28} ground-state doublet	0.000 0.0319	3+ 2+	100 69	14.3 13.8	Yes
Al^{28} first excited doublet	0.967 1.015	2+(2−,1−) >2	4.6 38.0	0.9(1.5) (5.4,4.2, 3.6)	No
P^{32} ground-state doublet	0.000 0.077	1+ 2+	1.0[b] 1.7[b]	3.3 3.4	Yes

[a] These numbers have meaning only for a given doublet but not for comparisons between doublets.
[b] Intensities for the P^{32} ground-state doublet were determined for 1.8-Mev bombarding deuterons; for 2.0-Mev deuterons the agreement is not quite as good.

VII. A TEST FOR $j-j$ DOUBLETS

Since each component of the $j-j$ doublet is captured into the same configuration, the relative intensities of the doublet should be the same if each intensity is divided by the statistical factor $(2J+1)$. The experimental results of Enge *et al.*,[14] Holt and Marsham,[21] Van Patter *et al.*,[27] together with those of this research provide the data to apply this test to three doublets. In Table V this test is applied to the ground- and first excited-state doublets of Al^{28} and to the ground-state doublet of P^{32}. On the basis of this test, the ground-state doublets of Al^{28} and P^{32} are $j-j$ doublets, whereas the first excited-state doublet of Al^{28} is not. There was a considerable qualitative indication (see Sec. VI) that the ground state of Al^{28} was a $j-j$ doublet, whereas the first excited state was not. The success of this quantitative test in verifying the conclusions about these doublets is not only gratifying but is an indication

[27] Van Patter, Endt, Sperduto, and Buechner, Phys. Rev. **86**, 502 (1952).
[28] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[29] M. Lindner, Phys. Rev. **91**, 642 (1953).

that the test itself is a simple precise way of determining the nature of these doublets.

It is a pleasure to acknowledge the cooperation of the Radiation Laboratory of the University of California, and particularly of G. Bernard Rossi and the crew of the 60-in. cyclotron, in securing the many bombardments essential in this work. We are also grateful to the University of Chicago and the betatron operating crew for a bombardment received from them. Finally, the help of Dr. D. M. Van Patter and Dr. A. E. S. Green in the preparation of this paper is gratefully acknowledged.

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Systematics of Photoproton Reactions*

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The photoproton yields from the elements Ta, Pt, Pb, W, and Au have been determined for betatron bremsstrahlung bombardment at 22-Mev peak energy by the use of zinc sulfide detectors and a 40-μsec betatron pulse duration. The yields, as measured in photoprotons per mole per roentgen, are as follows: Ta, 5.7×10^4; Pt, 2.9×10^4; Pb, 5.8×10^4; W, 5.2×10^4; and Au, 1.9×10^4. These values, along with previous determinations, permit a study of general behavior of photoproton yields for all Z values throughout the periodic table. Comparisons with calculations based on the evaporation model show good agreement with experimental trends up to a Z of 50, after which the measured yields are too high by factors ranging from 10 to 10^4. Calculations based on the direct photoelectric process give better agreement.

INTRODUCTION

In a systematic study of the proton yields from elements bombarded with bremsstrahlung radiation of moderate energy, almost all previous investigations have been limited to elements of either low or medium atomic number.[1–5] With the exception of cerium and bismuth, reported by Toms and Stephens, the elements studied have been confined to the region below a Z of 50. The present paper describes the measurement of photoproton yields from the elements tantalum, tungsten, platinum, gold, and lead. With these additions the systematics of yields as a function of Z is fairly complete except for a gap between a Z of 50 and 73. It now becomes possible to explore the general trend of the results with the proposed mechanisms for photonuclear reactions.

The twenty elements previously reported by this laboratory[1] were studied with betatron bremsstrahlung of 23.5-Mev maximum energy. Diven and Almy used 20.8 Mev, Butler and Almy 22.5 Mev, and Toms and Stephens 22.5 Mev for magnesium and 24 Mev for indium, cerium, and bismuth. The present work employed 22-Mev bremsstrahlung and the photoprotons were directly detected, as previously, with the use of zinc sulfide scintillators.

APPARATUS AND PROCEDURE

The experimental apparatus is essentially the same as that described in detail in reference 1. Briefly, a strongly collimated bremsstrahlung beam of maximum energy 22 Mev strikes the target, consisting of a thin sheet of the element under investigation, placed at an angle of 60 degrees with respect to two identical ZnS scintillators diametrically opposite each other. The detectors are kept fixed at an angle of 90 degrees to the photon beam and subtend an angle of 10 degrees at the target. After passing through the target, the photon beam strikes a 2-g/cm^2 tantalum target contained in a neutron detection assembly, and the number of neutrons from the Ta(γ,n) reaction is used to monitor the bremsstrahlung intensity. Additional monitoring makes use of an ionization chamber and current integrator, which in turn are calibrated in terms of a Victoreen r thimble imbedded in 4 cm of Lucite.

The scintillation pulses from the ZnS screens are detected with the use of 5819 photomultiplier tubes feeding model-100 amplifiers with 1-μsec delay line clipping and into ten-channel integral pulse-height analyzers. For high-Z targets, the combination of low proton yield and large light particle scattering makes discrimination against light particle pileup critical, and with a one-microsecond betatron pulse duration the beam intensity must be reduced prohibitively to achieve sufficient discrimination for the proton pulses. It was this, in fact, which limited the previous study to elements with a Z below 50. By the use of tech-

* Supported in part by the U. S. Air Research and Development Command and the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
[1] A. K. Mann and J. Halpern, Phys. Rev. **82**, 733 (1951).
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[5] M. E. Toms and W. E. Stephens, Phys. Rev. **92**, 362 (1953).