remainder of the data. Figure 9 shows two plots of the cross section as a function of energy, one for 60° in the c.m. system and one for 90°. There is no indication of an energy level in the He^6 compound nucleus over the small energy interval which is covered here.

Frank and Gammel[12] have made a phase-shift analysis of the data taken at incident triton energies of 1.800 and 2.013 Mev. They find that a ^1S phase shift corresponding to that resulting from scattering by a hard sphere of radius $a=2.35\times10^{-13}$ cm fits the data. This is consistent with the assumption of a strongly attractive interaction between the two free tritons (unbound by 12.25 Mev relative to the ^1S state of He^6).

[12] R. M. Frank and J. F. Gammel, Phys. Rev. **100**, 973(A) (1955).

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Gamma Rays from Excited Levels in Al^{25}

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To measure the energy of γ rays following resonances in the $Mg^{24}(p,\gamma)Al^{25}$ reaction, thin targets of natural magnesium have been bombarded with protons. The radiation of the resonances at 222, 418, and 825 kev proton energy have been investigated, and the γ-ray spectra have been observed with a single NaI(Tl) crystal scintillation counter and a Hutchinson and Scarrott pulse height analyzer. Several γ rays are identified in the spectra, corresponding to transitions from excited levels in Al^{25} at 3.08±0.03, 2.69±0.02, 2.50±0.06, 1.80±0.02, 0.95±0.08, and 0.45±0.06 Mev energy.

From estimates of the γ-ray intensities the following spin assignments are given: For the 2.69-Mev level in Al^{25}, $\frac{3}{2}+$; for the 2.50-Mev level, $\frac{1}{2}\pm$; for the 1.80-Mev level, $\frac{3}{2}-$; and for the 0.95-Mev level, $\frac{3}{2}+$.

No γ rays were found to accompany the 7-second positron activity from Al^{25}. A measurement of the radiation from the annihilation of the positrons is included.

INTRODUCTION

THE spectra of the γ radiation from levels in nuclei excited by bombardment of protons are fairly easily obtained by the help of a scintillation counter and a multichannel pulse-height analyzer. When a single-crystal scintillation counter with good energy resolution is used, and the decay scheme of the excited level is not too complicated, an interpretation of the energy spectrum of the γ rays is possible. The use of a pulse-height analyzer with many channels makes a measurement of the complete γ spectrum possible, without knowing the absolute yield of the reaction under investigation.

In the present work the γ yield of the reaction

$$\begin{array}{llll} Mg^{24}+p\rightarrow Al^{25*}+h\nu\rightarrow Al^{25}+h\nu & & & \\ \quad\searrow & & \searrow 7.6\text{ sec} & \\ \qquad Al^{25}+h\nu\rightarrow & & \quad\searrow & \\ & & \qquad Mg^{25}+\beta^+ & \end{array}$$

was investigated.[1] This reaction was chosen because the excitation energy of the compound nucleus is low, and as there are only a few bound levels in Al^{25} below the first levels reached in proton bombardment, a not too complicated γ spectrum can be expected.

EXPERIMENTAL

A γ spectrometer of fairly good resolution has recently been completed at our Laboratory. The spectrometer consists of a single $1\frac{1}{2}$-inch NaI(Tl) crystal with a DuMont 6292 photomultiplier, and a 120-channel pulse-height analyzer of the Hutchinson and Scarrott design.[2] A single photopeak of a γ ray with an energy near 2 Mev is measured by the spectrometer with a half-width of 5%.

Thin targets of natural magnesium were bombarded in our Van de Graaff generators, and the resonances were well resolved. The yield from the following resonances[3–5] assigned to the capture of a proton in Mg^{24} was investigated.

E_p(lab) in kev	Excitation energy of Al^{25} in Mev	Reference
222	2.50	3
418±0.5	2.69	4
824.9±0.4	3.08	5

Most of our runs were shorter than half an hour, as during this time a sufficient number of counts was obtained to give a statistical accuracy of around 5% or better for the height of the peaks in the high-energy region of the spectra.

The spectra obtained are shown in Figs. 1, 2, and 3. For comparison a spectrum of the radiation from a Na^{24} source is given in Fig. 4, taken with the same counting equipment as the other spectra. The γ rays from a Zn^{65} (1.12-Mev energy), a Co^{60} (1.17 and 1.33 Mev), and

[1] Churchill, Jones, and Hunt, Nature **172**, 460 (1953).

[2] G. W. Hutchinson and G. G. Scarrott, Phil. Mag. **42**, 792 (1951).

[3] Grotdal, Lönsjö, Tangen, and Bergström, Phys. Rev. **77**, 296 (1950).

[4] S. E. Hunt and W. M. Jones, Phys. Rev. **89**, 1283 (1953).

[5] Recent measurement in this Laboratory (unpublished).

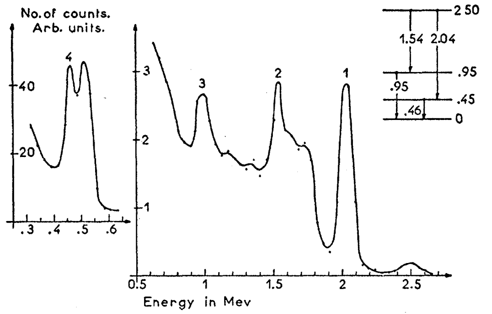

FIG. 1. γ spectrum of the yield from the 222-kev resonance and decay scheme for the 2.50-Mev level.

a ThC″ (2.62 Mev) source were used to calibrate the spectrometer.

PREVIOUS INVESTIGATIONS

The elastic scattering of protons from Mg^{24} in the range from 0.4 to 3.95 Mev has been thoroughly investigated by Mooring *et al.*[6] The resonance at 418 kev was not observed. Koester[7] interprets their data, and assigns the spin and parity $\frac{3}{2}-$ to the level giving rise to a resonance at 825 kev.

Goldberg[8] measured the energy and angular distribution of the neutrons in the reaction $Mg^{24}(d,n)Al^{25}$, and found groups corresponding to the levels of Al^{25} given in Table I. Two other levels of energies 1.94 and 2.92 Mev were also reported, but owing to the low statistical accuracy of their measurement, these levels were marked with a question in Goldberg's report. His spin assignments are also given in Table I.

The γ rays following the 222-kev resonance have been measured.[9] Craig *et al.*[10] report a γ ray of energy 2.03 ± 0.03 Mev with an isotropic distribution to the incident beam, and a γ ray of energy 0.47 ± 0.02 Mev.

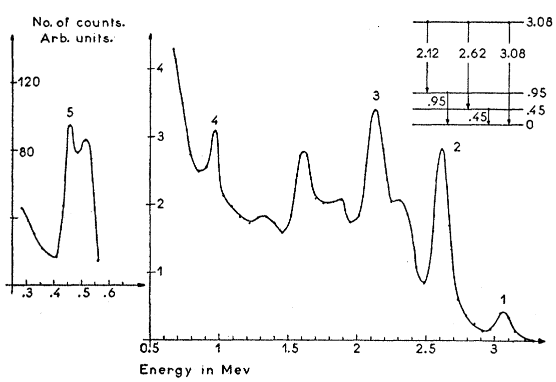

FIG. 2. γ spectrum of the yield from the 825-kev resonance and decay scheme for the 3.08-Mev level.

[6] Mooring, Koester, Goldberg, Saxon, and Kaufmann, Phys. Rev. **84**, 703 (1951).
[7] L. J. Koester, Phys. Rev. **85**, 643 (1952).
[8] E. Goldberg, Phys. Rev. **89**, 760 (1953).
[9] H. Casson, Phys. Rev. **89**, 809 (1953).
[10] Craig, Cross, and Jarvis, Phys. Rev. **96**, 825(A) (1954).

The isotropic distribution is reported consistent with the following spins for the resonant level: $\frac{1}{2}\pm$, $\frac{3}{2}+$.

The Al^{25} ground-state spin of $5/2+$ seems well established.[8,11]

SPECTRA

Intensities

When a decay scheme consistent with our observed spectrum had been established, the areas under the photopeaks associated with the different γ rays were estimated. These areas were corrected in the following manner:

(1) First, correction was made for the absorption mechanism in the NaI crystal by the help of the experimental peak-to-total curve given by Bell.[12] This curve was roughly extrapolated to higher energies with the help of a measurement on the spectrum of the 2.76-Mev γ ray from a Na^{24} source. Our curve is given in Fig. 5. We believe that the discontinuity of Bell's curve near 0.5 Mev is due to the use of a positron emitter to

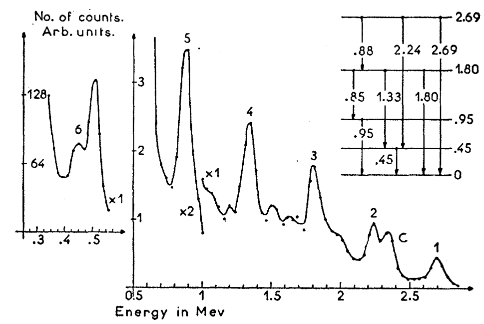

FIG. 3. γ spectrum of the yield from the 418-kev resonance and decay scheme of the 2.69-Mev level.

establish the point at 0.51 Mev. It might be difficult to find the exact peak-to-total ratio from the complex spectrum of positron annihilation radiation.[13]

(2) Secondly, the areas were corrected for the variation of counter efficiency with energy. The values given by Bell[14] could be used for our crystal in the energy region under consideration when increased by 8%. This was found by independent calculations for our counter at a few energies. Bell's data had to be multiplied by the finite solid angle of the counter as seen from the target.

(3) We next corrected for the variation with γ-ray energy of the absorption in the target backing and holder.

[11] M. G. Mayer, Phys. Rev. **78**, 16 (1950).
[12] P. R. Bell in K. Siegbahn, *Beta- and Gamma-ray Spectroscopy* (North-Holland Publishing Company, Amsterdam, 1955), Chap. V, Fig. 6.
[13] Gerhart, Carlson, and Sherr, Phys. Rev. **94**, 917 (1954).
[14] P. R. Bell, in *Beta- and Gamma-ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), p. 154.

Angular variation of the γ-ray intensities was not considered.

As in the extrapolated yield method,[9] the areas of the photopeaks in most cases still have to be estimated by extrapolation. Consequently, some arbitrariness seems unavoidable with a single-crystal arrangement.

The results of the intensity estimates are given in Table II together with the measured energies of the identified γ rays. The intensities are measured in relation to a pronounced γ ray in each spectrum. The energies are given from an estimate of the peak location. The higher possible error in the low-energy part of the spectra stems from the existence of the positron peak and a lower peak-to-background ratio.

Sources of Error

Decay of the Al^{25} Ground State

This decay by positron emission might lead to excited states of Mg^{25}.[15] γ rays from these levels might give errors in the spectra attributed to the decay of excited levels in Al^{25}. A spectrum of the γ rays from the positron emission is given in Fig. 6. A background was measured to include radiation from possible activities with longer half-lives. The activities built up in the two runs are not directly comparable, but a background of sufficient accuracy for the present purpose is obtained.

TABLE I. Energies and spins of excited levels in Al^{25} found by investigating the γ rays from the $Mg^{24}(p,\gamma)Al^{25}$ reaction at resonant energies 222, 418, and 825 kev. For comparison the results of Goldberg[8] are given.

This work $Mg^{24}(p,x)Al^{25}$ Mev level energy	Spin	Goldberg $Mg^{24}(d,n)Al^{25}$ Mev level energy	Spin
3.08±0.03	(3/2−)[a]	3.09±0.06	
2.69±0.02	3/2+	2.70±0.05	
2.50±0.06	1/2+, 1/2−	2.51±0.05	
1.80±0.02	3/2−	1.81±0.04	
0.95±0.08	3/2+	0.95±0.03	3/2+, 5/2+
0.45±0.06		0.45±0.03	1/2+
		0	5/2+

[a] Our spectrum agrees with this assignment by Koester.[7]

A high-energy tail follows the 0.51-Mev peak. The peak arises from the annihilation of positrons at rest, and the tail is well accounted for by the annihilation of positrons in flight and by bremsstrahlung. This was shown by a calculation following Bethe[16] and Gerhart *et al.*[13]

Any possible radiation from the lowest excited level of Mg^{25}, with an energy of 0.58 Mev,[17] is difficult to find, owing to the small distance in energy from the annihilation peak at 0.51 Mev. But an amount of more than 1% of the 0.51-Mev peak would have shown up as a bulge on the side of this peak. Contributions from high-energy γ rays must be even smaller. We therefore conclude that the only error introduced in the Al^{25} spectra from this source is due to the annihilation radiation.

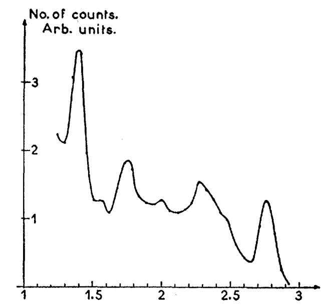

FIG. 4. γ spectrum of the radiation from a Na^{24} source.

Cascades

Two γ rays with energies E_1 and E_2 following each other in cascade faster than the resolution time of the counting equipment, will give rise to real coincidences in the counting crystal. If the intensity of the cascade is high, a measurable coincidence peak of energy E_1+E_2 will appear in the spectrum. The number N_c of counts in this peak can be found in relation to the number of counts N_{ph} in the photopeak of one of the γ rays in the cascade.

If there is only one route by which the lowest excited level can decay, then $N_c=Ng_1k_1g_2k_2$. N is the total number of photons in one of the two γ rays leaving the target, g is an energy dependent factor correcting for counter efficiency, solid angle and absorption, k is the peak-to-total ratio as given by Fig. 5 and gk gives the absolute probability of finding a γ ray counted in the appropriate photopeak. That is, $N_{ph}=Ngk$ and $N_c/N_{ph1}=g_2k_2$; g and k are found as mentioned before.

Thus the coincidence peak to be expected from a cascade can be found. Incidentally, an absolute peak-to-total calibration can also be found using cascades. This ratio is given by gk, and consequently can be meas-

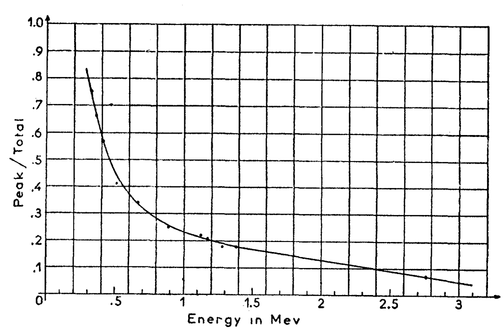

FIG. 5. Experimental peak to total ratio for a $1\frac{1}{2}$-inch crystal of NaI(Tl). The data for the region up to 1.4 Mev are taken from Bell.[12]

[15] Hunt, Jones, and Churchill, Proc. Phys. Soc. (London) **67A**, 479 (1954).
[16] H. A. Bethe, Proc. Roy. Soc. (London) **150**, 129 (1935).
[17] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

TABLE II. γ rays from resonance reactions in $Mg^{24}(p,\gamma)Al^{25}$. Intensities given for each spectrum relative to a pronounced γ ray. All energies in Mev.

Resonance	0.222 (2.50 max energy) Peak No.	E_γ	Intensity	0.418 (2.69 max energy) Peak No.	E_γ	Intensity	0.825 (3.08 max energy) Peak No.	E_γ	Intensity
	1	2.04±0.03	1.0	1	2.69±0.02	1.0	1	3.08±0.03	0.4
	2	1.54±0.05	0.1	2	2.24±0.02	1.1	2	2.62±0.02	1.0
	3	0.95±0.07		3	1.80±0.02	0.5	3	2.12±0.03	<0.2 >0.06
	4	0.46±0.05		4	1.33±0.03	0.8	4	0.95±0.03	
							5	0.45±0.04	
				5	0.88±0.03 0.95 0.85	3.3			
				6	0.45±0.05				

ured if radioactive sources of suitable properties can be found.

γ Radiation from Resonances in Carbon

The peak C in the spectrum from the 418-kev (Fig. 3) resonance can be attributed to the 456-kev resonance in C^{12}. The excitation energy of the corresponding level in N^{13} is 2.37 Mev.[18] With a soot target a yield from this resonance was observed at a bombarding energy corresponding to the 418-kev resonance in Mg^{24}. In the γ spectrum of this yield a pronounced peak at 2.34 Mev was observed. The peak moved to 2.37 Mev when the energy of the bombarding protons was raised to above 450 kev. The movement was slight, but quite evident.

Constant Background

Peaks were observed in the constant background corresponding to the 2.62-Mev radiation from ThC″ and the 1.46-Mev radiation from the decay of K^{40}.[17] The radiation probably comes from the walls and floor of our generator hall. One inch of lead was sufficient to bring the background down to a moderate level.

Different Spectra

222-kev Resonance Spectrum (Fig. 1)

The level at 2.50 Mev is chiefly de-excited via the 0.45-Mev level, giving the strong γ rays of 2.04- and 0.46-Mev energy. The peak at 2.50 corresponds to the energy of a γ ray to the ground state. This peak can be accounted for by coincidences between the 2.04- and 0.46-Mev γ rays to within 1% of the peak at 2.04 Mev. The transition to the ground state must, if it exists, be weak.

The photopeak of the 2.04-Mev γ ray is followed in the usual manner by a "one-quantum annihilation" peak and a "pair" peak at energies near 1.53 and 1.02 Mev. The peculiar sharpness of the 1.54-Mev peak and the broadening of the 1.02-Mev peak down to 0.9 Mev can be explained by assuming a transition from the 2.50-Mev level to the level at 0.95 Mev. A very rough estimate for the intensity of this transition is given in Table II.

825-kev Resonance Spectrum (Fig. 2)

The picture from the previous spectrum is repeated. The de-excitation of the 3.08-Mev level via the 0.45-Mev level is evident, giving γ rays of energies 2.62 and 0.45 Mev. The transition to the 0.95-Mev level also is pronounced, giving γ rays of energies 2.12 Mev (energy coincident with the "annihilation" peak of the 2.26-Mev ray) and 0.95 Mev. The main structural difference from the previous spectrum is the existence of a ground state transition, which gives the 3.08-Mev peak.

418-kev Resonance Spectrum (Fig. 3)

The decay scheme of the 2.69-Mev level obviously is more complicated than the previous two. It can only be explained by the appearance of transitions to the 1.80-Mev level previously reported by Goldberg.[8] Four possible routes exist for the de-excitation of the 2.69-Mev level. A direct transition to the ground state, a 2.24- and a 0.45-Mev transition via the first excited level, a 0.89-Mev transition to the 1.80-Mev level, and a 1.74- and a 0.95-Mev transition via the second excited level are possible. The existence of γ rays corresponding to the three first of these routes is evident from the peaks in the spectrum. The probability for the last route must be very small, as there is no pronounced peak at 1.74 Mev.

For the de-excitation of the 1.80-Mev level the following routes are possible: A 1.80-Mev transition to the ground state, a 1.35- and a 0.45-Mev transition via the first excited level, and a 0.85- and a 0.95-Mev transition via the second excited level. γ rays corresponding to the two first of these routes give rise to pronounced peaks in the spectrum. The high intensity of the 0.88-Mev peak, in relation to the peaks at 1.80 and 1.33 Mev, suggests that the last route also is probable. Separate runs on the 0.88-Mev peak with high resolution show pronounced shoulders on both sides of the peak, which also indicates that γ rays of energies 0.85 and 0.95 Mev may be present.

[18] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

DISCUSSION OF SPINS

2.50-Mev Level

A spin of more than $\frac{1}{2}$ for the 2.50-Mev level would give the energy-favored transition to the ground state (spin $5/2+$) a higher probability than the transition to the first excited state (spin $\frac{1}{2}+$). We adopt the spin of $\frac{1}{2}+$ or $\frac{1}{2}-$ for the 2.50-Mev level.

The existence of an energy-unfavored transition to the 0.95-Mev level can be explained by choosing the spin $\frac{3}{2}+$ for this level from the two values given by Goldberg.[8]

In the further discussion we will justify the assignment of spin $\frac{3}{2}-$ to the level at 1.80 Mev. The apparent nonexistence of γ rays indicating a transition from the 2.50- to the 1.80-Mev level, might be used to give a parity assignment for the 2.50-Mev level. An existing radiation from this transition might on the other hand be too weak to be detected. Therefore an unambiguous parity assignment can not be given.

3.08-Mev Level

Koester's[6] spin assignment for this level, $\frac{3}{2}-$, gives electric dipole radiation for the transitions to lower levels. The present measurements agree well with this assumption. There is a similarity between the spectrum from this level and the γ rays emitted by the 3.405-Mev level[19] in Mg^{25}, a $\frac{3}{2}-$ level in the mirror nucleus of Al^{25}.

2.69- and 1.80-Mev Levels

An assignment of the spins $\frac{1}{2}+$ or $\frac{3}{2}\pm$ to the 1.80-Mev level is possible from the intensities of the observed γ rays from this level. A spin of $\frac{1}{2}-$ would give too low a probability for the transition to the ground state, and higher spins will suppress the relatively strong transition to the first excited level.

The validity of Weisskopf's estimates of transition probabilities, based on the single-particle model,[20] is thoroughly discussed by Kinsey and Bartholomew.[19] Arguments based on these considerations and similar to those given above seem to justify a spin assignment of $\frac{3}{2}$ for the 2.69-Mev level. As the ratio of magnetic dipole to electric quadrupole emission is not too well established, spins of $\frac{1}{2}+$ and $5/2+$ might also be possible.

The transition from the 2.69 to the 1.80-Mev level obviously is parity-favored, and the transitions to the lower levels are parity-unfavored. The only combination of spins mentioned leading to such transitions is a spin of $\frac{3}{2}-$ for the 1.80-Mev level and a spin of even parity for the 2.69-Mev level.

The assignment $\frac{3}{2}+$ is preferred for the 2.69-Mev level. The assignment is in agreement with earlier investigations[8]; it may especially be noted that the assumption of a D level at this energy can explain why a resonance at 418 kev was not found in the elastic scattering experiment of Mooring *et al.*[6] The width of a D level may be too small at this energy to be resolved.

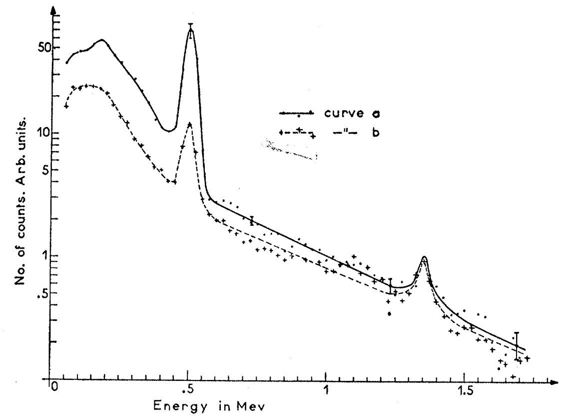

FIG. 6. (a) Radiation from annihilation of positrons in the decay of the Al^{25} ground state. The spectrum was obtained by 20-second bombardment of thin targets with protons of energy corresponding to the 825-kev resonance in Mg^{24}. The proton beam was then shut off and the γ rays counted in 10 sec. This run was repeated 100 times. (b) Background. 20 seconds of bombardment were followed by 10 sec of waiting and 25 sec of counting. 40 runs. The peak at 1.45 Mev is due to radiation from K^{40} in the constant background.

CONCLUSION

In conclusion, the levels and spins found in this investigation are compared with the results of Goldberg[8] in Table I. We have found no evidence of the two dubious levels reported by Goldberg.

It is a pleasure for us to acknowledge the help of T. Holtebekk, R. Jahren, and O. Os with the experimental work. We are also indebted to Professor R. Tangen for support and advice during the investigation, and to J. Sandstad for valuable help with the electronic equipment.

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[19] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **93**, 1260 (1954).

[20] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).