Gamma Rays from the 1.83-Mev Resonance in the Reaction $Mg^{24}(p,\gamma)Al^{25}$

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The $Mg^{24}(p,\gamma)Al^{25}$ reaction has been studied in the range of proton energies from 1.66 Mev to 2.02 Mev. A new resonance at 1.833 ± 0.007 Mev was observed which corresponds to an excited state of 4.047 ± 0.010 Mev in Al^{25}. The new excited state was observed to decay by the emission of 4.01 ± 0.04, 2.43 ± 0.04, and 1.62 ± 0.03 Mev gamma rays. The last two gamma rays were observed to be in coincidence and the intensity ratio of the first two gamma rays was found to be 60 ± 10:40 ± 10. The experimental value of $\omega\gamma=(J+\frac{1}{2})\Gamma_p\Gamma_\gamma/\Gamma$, for the ground state transition was found to be 3×10^{-3} ev and an upper limit of 10 kev was estimated for Γ the total width of the resonance. Angular distribution measurements have shown that the angular momentum of the new state is either 5/2 or 9/2 with the latter value favored. On the basis of the observed dipole-quadrupole admixtures found for the gamma rays the parity of the new state is probably even. A discussion is given of the place of the new state in the rotational-like bands of Al^{25}.

INTRODUCTION

THE collective model, applied to the low-lying states of Al^{25},[1] indicates that there should be excited states appearing as resonances in the vicinity of 2-Mev proton energy in the reaction $Mg^{24}(p,\gamma)Al^{25}$ which have hitherto been overlooked. These are the 9/2+ and 7/2+ states which are members of bands based on the first-excited state and the fifth-excited state respectively. Since the discovery of further members of the bands already located in Al^{25} would be of considerable interest the work reported in this paper was undertaken.

In two previous papers[2,3] a study was reported of the gamma radiation from a number of resonances in the reactions $Mg^{24}(p,\gamma)Al^{25}$ and $Mg^{24}(pp',\gamma)Mg^{24}$. In the first paper no resonances in the region of proton energies from 1.66 Mev to 2.01 Mev were observed though it was clear from the published yield curve that weak resonances could easily have been overlooked. The second paper contained a detailed study of the 1.66-Mev resonance.

In the region between 1.66 Mev and 2.01 Mev no resonances for the elastic scattering of protons by Mg^{24} have been observed.[4] However because the expected 7/2+ and 9/2+ resonances would be g-wave resonances their small elastic proton width would make their observation by elastic scattering very difficult. The discovery[2] of what is almost certainly a g-wave resonance in the reaction $Mg^{24}(p,\gamma)Al^{25}$ at 1.20 Mev illustrates the suitability of the capture gamma-ray method for the study of resonances of very small particle width. The thick target yield of gamma rays from a capture reaction is proportional to $\Gamma_p\Gamma_\gamma/\Gamma$.[5] The yield is therefore independent of the particle width, Γ_p, provided Γ_p is greater than the gamma-ray width, Γ_γ. The total width, Γ, is assumed to be equal to $\Gamma_p+\Gamma_\gamma$. With present techniques resonances for which $\Gamma_p\Gamma_\gamma/\Gamma>10^{-3}$ ev can be observed so that provided both Γ_p and Γ_γ are greater than approximately 10^{-3} ev the resonance should be readily observed. The single particle limit for the g-wave proton width at 1.80-Mev bombarding energy on Mg^{24} is approximately 200 ev[6] so that even if the reduced width for the g-wave resonance were one ten thousandth of the single particle value, that is $\Gamma_p\sim20\times10^{-3}$ ev, the resonance should be readily observed. A search was therefore made for weak resonances in the reaction $Mg^{24}(p,\gamma)Al^{25}$ in the region of bombarding energies between the resonances at 1.66 Mev to 2.01 Mev. The search was terminated at 2.02 Mev because the increasing background made the observation of weak capture resonances increasingly difficult.

EXPERIMENTAL PROCEDURE AND RESULTS

The apparatus employed was identical in most respects to that described previously.[2,3] As in the previous measurements two 5-inch diameter by 4-inch long NaI(Tl) crystals were used together with a "fast-slow" coincidence arrangement which had a resolving time τ of about 25 millimicroseconds.

The principal difficulty in locating resonances in the vicinity of 2 Mev lies in the presence of impurities such as fluorine and nitrogen in the target material and backing. These give gamma rays from the exothermic (p,α) reactions which usually have much larger cross sections than the cross sections for the emission of capture gamma rays from the target material. Consequently it was decided to search for new resonances in the $Mg^{24}(p,\gamma)Al^{25}$ reaction by observing only gamma rays that were in coincidence with other gamma rays. This procedure eliminates much of the background since the gamma rays from the (p,α) reactions with the

[1] Litherland, McManus, Paul, Bromley, and Gove, Can. J. Phys. **36**, 378 (1958).
[2] Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102**, 208 (1956).
[3] Gove, Litherland, Almqvist, and Bromley, Phys. Rev. **111**, 608 (1958).
[4] Mooring, Koester, Goldberg, Saxon, and Kaufmann, Phys. Rev. **84**, 703 (1951).
[5] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).
[6] H. E. Gove, Atomic Energy of Canada Limited, Chalk River Project, PD-287, 1957 (unpublished).

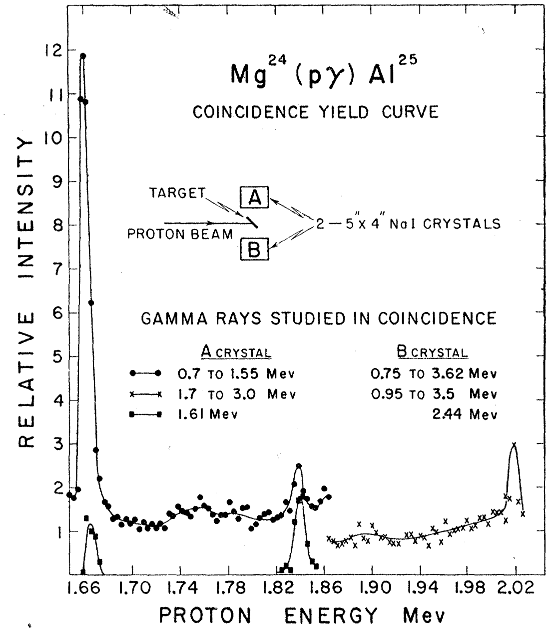

FIG. 1. The yield of gamma rays from the reaction $Mg^{24}(p,\gamma)Al^{25}$. The gamma rays were studied in coincidence using two large sodium iodide crystals as shown in the inset. The various ranges of gamma-ray pulse heights studied in coincidence are also shown.

principal contaminants are not in coincidence with other gamma rays.

The new resonance was first located by means of the coincidence yield curves shown in Fig. 1. For these measurements the two large sodium iodide crystals were placed at 90° to the proton beam with their front faces approximately 2 inches from the target. The target was a layer of metallic Mg^{24} evaporated onto a 0.02-inch tantalum backing. This target and subsequent targets used in the experiment were obtained from the Atomic Energy Research Establishment, Harwell, England. Initially the range of gamma-ray pulse heights studied in coincidence was chosen to include all likely gamma-ray cascades in Al^{25}. The yield curve from 1.66 Mev to 2.02 Mev was studied in this way and the resonance shown in Fig. 1 at approximately 1.83 Mev discovered.

The proton energy of the new resonance was measured relative to the two prominent resonances in the same reaction at 1.655 and 2.007 Mev.[7] The value obtained was 1.833±0.007 Mev. To obtain this value the total width, Γ, of the new resonance was assumed to be much less than the observed width of about 10 kev. The observed width is almost certainly due to target thickness but it constitutes an experimental upper limit of 10 kev to the total width of the resonance.

The background below and above the proton energy of the new resonance was not studied in this experiment. Past experience however indicates that the background, which consists of genuine coincidences, is from high

[7] L. J. Koester, Phys. Rev. **85**, 643 (1952).

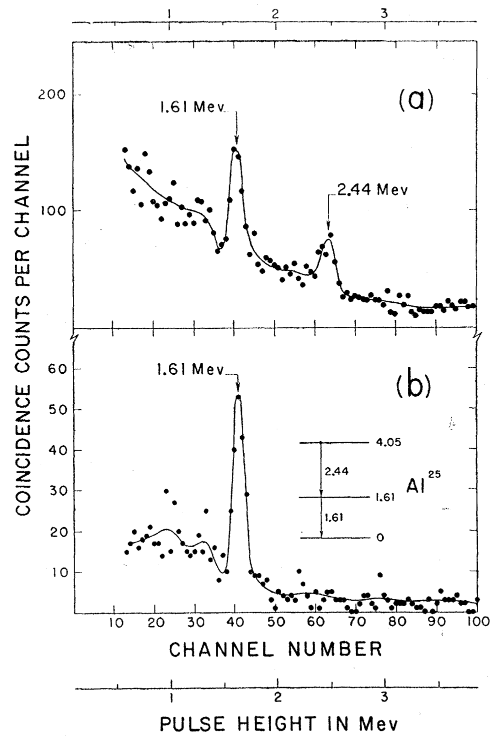

FIG. 2. Coincidence pulse spectra taken at the 1.83-Mev resonance. (a) all gamma-ray pulses in coincidence with gamma-ray pulses in the energy range from 0.75 to 3.62 Mev. (b) All gamma-ray pulses in coincidence with a narrow gate set on the total absorption peak of the 2.44-Mev gamma ray. The inset shows the assumed sequence of the 2.44-Mev and 1.61-Mev gamma rays.

Q-value contaminants in the Mg^{24} target and the tantalum backing.

The gamma-ray coincidence pulse spectrum from crystal A observed at the new resonance is shown in Fig. 2(a). In this case the range of pulses from crystal B studied in coincidence was the same as the range used for the yield curve of Fig. 1. In this particular case the points are shown as solid circles. Two gamma rays of approximately 1.61 and 2.44 Mev appear clearly in the coincidence spectrum. The averages of the measured energies of these two gamma rays from several coincidence spectra and the direct gamma-ray spectra discussed below were 1.62±0.03 and 2.43±0.04 Mev. The sum of these energies, 4.05±0.05 Mev, agrees very well with the value of 4.047±0.010 Mev obtained from the measured energy of the resonance, 1.833±0.007 Mev, and the measured Q-value, 2.287±0.006 Mev, of the $Mg^{24}(p,\gamma)Al^{25}$ reaction.[3] This agreement supports the assignment of these gamma rays to a cascade in Al^{25}.

The order of the 1.62±0.03 and 2.43±0.04 Mev gamma rays cannot be established from the measurements reported in this paper. The available evidence[2,3,8]

[8] P. M. Endt and C. M. Braams, Revs. Modern Phys. **29**, 683 (1957).

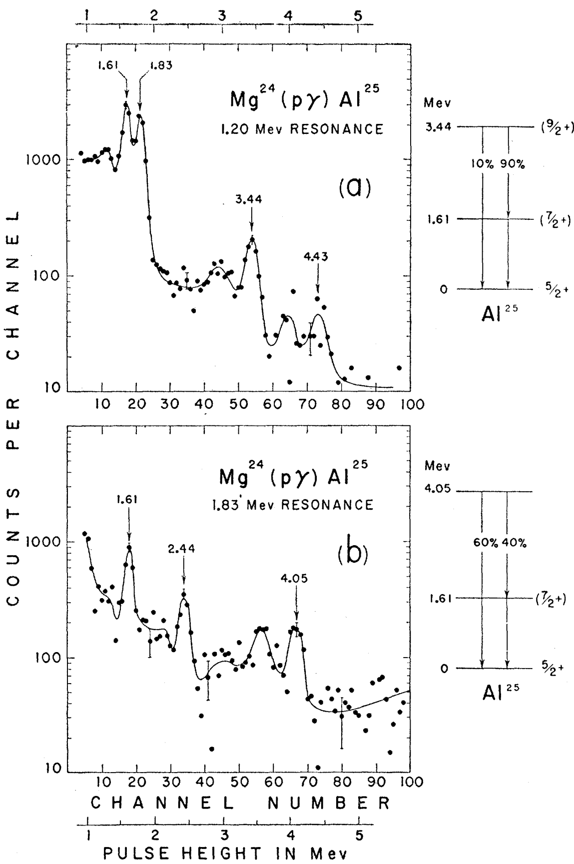

FIG. 3. (a) The gamma-ray pulse spectrum, at 90° to the beam, taken at the 1.20-Mev resonance in the reaction $Mg^{24}(p,\gamma)Al^{25}$. The measured[2] branching ratios are shown on the right. (b) The gamma-ray pulse spectrum, at 90° to the beam, taken at the 1.83-Mev resonance in the reaction $Mg^{24}(p,\gamma)Al^{25}$. The measured branching ratios are shown on the right.

however strongly favors the existence of a state in Mg^{25} and Al^{25} at about 1.61-Mev excitation and provides no evidence for a state near 2.43 Mev which decays principally to the ground state. In this paper therefore, the 2.43 ± 0.04 Mev gamma ray will be assumed to be the 2.44-Mev primary transition to an excited state at 1.61 Mev in Al^{25}.

To demonstrate more clearly the existence of the new resonance the range of pulse heights studied in coincidence was narrowed considerably. The ranges used are shown in Fig. 1 together with the yield curve observed near the resonances at 1.66 and 1.83 Mev. The points on the yield curve in this case are shown as solid squares. The 1.83-Mev resonance appears quite clearly and appears under these conditions stronger than the 1.66-Mev resonance. This is due to the very weak cascading from the 1.66-Mev resonance in this range of gamma-ray energies.[3] The gamma-ray pulse spectrum in one of the large crystals, taken with a narrow gate set to include pulses from the main peak of the 2.44-Mev gamma ray, is shown in Fig. 2(b). The 1.61-Mev gamma ray appears very clearly in the coincidence pulse spectrum.

The ground state transition from the 1.83-Mev resonance was first located by taking spectra on and just below the resonance and subtracting them. Unfortunately the tantalum backing contained sufficient nitrogen for the 4.43-Mev gamma rays from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction to almost obscure the 4.05-Mev ground-state gamma ray from $Mg^{24}(p,\gamma)Al^{25}$. A detailed study of the new resonance therefore had to await the arrival of targets of Mg^{24} deposited upon tungsten which was found to be comparatively nitrogen free. The background from the new targets was principally fluorine in the target material and the 2.61-Mev and 1.46-Mev gamma rays from the room background. However since there were usually about twice as many counts on the resonance compared with the counts off the resonance, it was possible to obtain reliable spectra. Fig. 3(b) shows the difference spectrum taken at the 1.83-Mev resonance and Fig. 3(a) shows a difference spectrum taken at the lower resonance at 1.20 Mev in the same reaction. Both pulse spectra were taken with the same geometrical arrangement of counters, with the same target and for the same number of microcoulombs of protons and consequently were used, with corrections for angular correlation effects to obtain the ratio of the quantities $\omega\gamma=(J+\frac{1}{2})\Gamma_p\Gamma_\gamma/\Gamma$ for each resonance. The ground state gamma ray from the 1.83-Mev resonance appears quite clearly in the spectrum together with the 1.61- and 2.44-Mev gamma rays found previously in the coincidence spectra. The measured energy of the ground-state gamma ray from several spectra was 4.01 ± 0.04 Mev. This is in approximate agreement with the value of 4.047 ± 0.010 Mev which was derived earlier for the energy of the excited state in Al^{25}. In this paper the 4.01 ± 0.04 Mev gamma ray will be assumed to be the 4.05-Mev ground-state gamma ray from the 1.83-Mev resonance. The gamma-ray branching ratios, corrected by using the NaI efficiency curve given by Gove and Litherland[9] and the measured angular correlation coefficients discussed below, are also illustrated in the figure. In Fig. 3(a) the 4.43-Mev gamma ray from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction is also present because of the close proximity of the 1.210-Mev resonance in that reaction.

The angular correlations with respect to the proton beam of the 4.05-Mev ground-state transition and the 2.44-Mev gamma ray, were obtained by taking a pulse spectrum on and just below the resonance at each angle to the proton beam. The Chalk River 100-channel transistorized "kicksorter" was used for these measurements.[10] The spectra taken at each angle were monitored at 90° to the beam by measuring simultaneously the spectrum on and below the resonance with a 30-channel

[9] H. E. Gove and A. E. Litherland, Phys. Rev. **113**, 1078 (1959).
[10] Designed by F. S. Goulding, Atomic Energy of Canada Limited, Chalk River, Ontario.

TABLE I. Analysis of the angular correlations of the 2.44-Mev and 4.05-Mev gamma rays from the 1.83-Mev resonance. The even-order Legendre polynomial coefficients were obtained by the method of least squares and are given together with their standard deviations (S.D.).

Gamma-ray energy in Mev	a_2/a_0	S.D.	a_4/a_0	S.D.
2.44	+0.40	0.05	−0.01	0.05
4.05	+0.45	0.05	−0.25	0.06

"kicksorter". The front faces of the two large NaI(Tl) crystals were 5.4 inches from the target. The results of these measurements are shown in Fig. 4 together with the results of a least-squares calculation of the Legendre Polynomial coefficients. Table I gives the results of the least-squares fit to the data together with the standard deviations. An analysis of the angular correlation of the 1.61-Mev radiation was not attempted because of the large background in the vicinity of that gamma-ray energy.

The quantity $\omega\Gamma_p\Gamma_\gamma/\Gamma$ for the ground-state transition at the 1.83-Mev resonance was determined by comparison with the 1.66-Mev and 1.20-Mev resonances in the same reaction. The value obtained was 3×10^{-3} ev. This low value for $\omega\gamma$ indicates why the 1.83-Mev resonance was difficult to observe. An estimate was also made of the quantity $\Gamma_\gamma/\Gamma_{p'}$ by searching for the 1.37-Mev gamma ray from inelastic scattering in the pulse spectra. The gamma ray was not observed and a lower limit of 6 was obtained for $\Gamma_\gamma/\Gamma_{p'}$.

DISCUSSION

Experimental Properties of the 4.05-Mev State

The angular correlation coefficients of the ground-state gamma ray given in Table I permit the definite angular momentum assignment of 5/2 or 9/2 to the 1.83-Mev resonance.[11] An angular momentum of 3/2 is ruled out because of the observation of a finite a_4 coefficient and 7/2 is eliminated because the theoretical a_4 term, shown in Fig. 5, has opposite sign to that observed. The coefficients for the other various angular momentum possibilities discussed in this paper are also shown in Fig. 5 and in Table II. These correlation coefficients were calculated from the tables of Sharp *et al.*[12] In each case the coefficients are shown as a function of x, which is the amplitude of the electric

[11] To compare the experimental angular correlation coefficients given in Table I with theory it is necessary to apply a correction for the effect of the finite angular spread of the detector. This correction can be estimated from the tables of H. E. Gove and A. R. Rutledge [Chalk River Laboratory Report CRP-755, 1958 (unpublished)]. Since only the upper portion of the pulse spectrum was used to obtain the angular correlation the correction given by Gove and Rutledge is an upper limit. However the conclusions reached in this paper are not affected by this uncertainty.

[12] Sharp, Kennedy, Sears, and Hoyle, Chalk River Laboratory Report CRT-556, 1953 (unpublished).

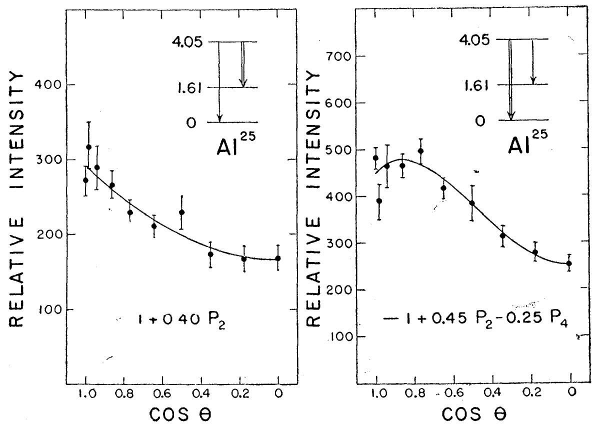

FIG. 4. The angular correlations with respect to the proton beam of the 2.44-Mev gamma rays and the 4.05-Mev gamma rays. The curves are the result of least squares fits to the experimental data. The Legendre polynomial coefficients shown on the figure are also given together with their errors in Table I.

quadrupole radiation divided by the amplitude of the magnetic dipole radiation. The theoretical correlation coefficients for a resonance of angular momentum 9/2 decaying by quadrupole radiation to a state of angular momentum 5/2 are given in Table II. The choice between the assignments of 5/2 or 9/2 to the 1.83-Mev resonance cannot be made with certainty on the basis of the present data because for an appropriate quadrupole to dipole mixing ratio for the 5/2 assignment the experimental correlation can be fitted equally well. This ambiguity can be readily seen by comparing the coefficients for an assignment of 9/2 to the resonance, given in Table II, with the coefficients given in Fig. 5 for an assignment of 5/2. The coefficients for the two alternative angular momenta become very difficult to distinguish experimentally in the region of x equal to approximately $+1.6$.[13] Table II however shows that there is good agreement between the measured correlation of the ground-state gamma ray and the theoretical value for an angular momentum of 9/2 for the 1.83-Mev resonance. Since there is no adjustable dipole-quadrupole mixing parameter in this case an angular momentum assignment of 9/2 can be considered to be more likely than 5/2. A similar argument can be used for the 1.20-Mev resonance in the same reaction.

By using the experimental coefficients given in Table I and the theoretical coefficients given in Table II and Fig. 5 it is possible to deduce the values of the quadrupole-dipole mixing ratio, x, for the 2.44- and 4.05-Mev gamma rays. Table III lists the values of x for the two alternative angular momenta assignments for the 1.83-Mev resonance. The 1.61-Mev state is assumed to be $7/2+$.[2] The presence of appreciable quadrupole-dipole radiation mixtures for the two

[13] It is possible to decide experimentally between these alternatives. This however, requires a difficult triple correlation measurement or an even more difficult polarization measurement of the ground-state gamma ray at 90° to the beam.

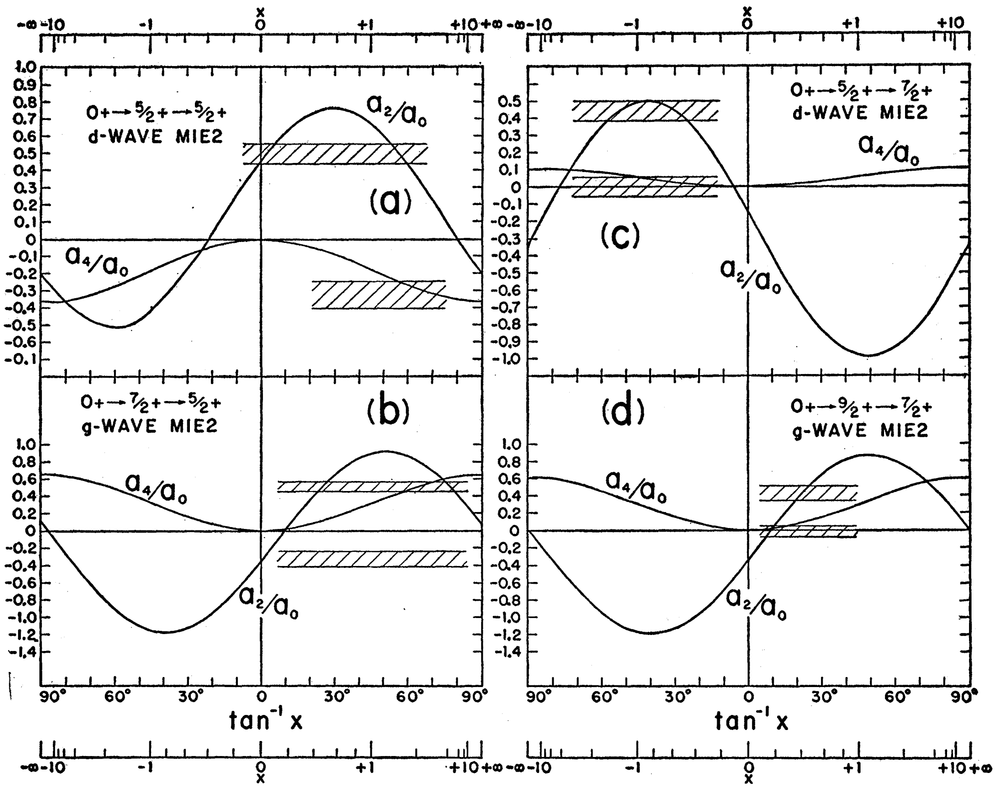

FIG. 5. The theoretical angular correlation coefficients are shown for a number of pairs of angular momenta of the states in Al^{25}. The coefficients are shown as a function of x which is the amplitude of the electric quadrupole radiation divided by the amplitude of the magnetic dipole radiation. In (a) and (b) the experimental values of the coefficients are from Table II. In (c) and (d) the experimental values of the coefficients for the 2.44-Mev radiation from Table I have been increased by the geometrical corrections obtained from Table II. The corrected experimental coefficients are shown as shaded bands.

gamma rays indicates that, for either spin assignment, the 1.83-Mev resonance has probably even parity. This is because only in very special cases, such as self-conjugate nuclei, does magnetic quadrupole radiation compete with electric dipole radiation.[14]

The 1.83-Mev resonance was not observed[4] in the elastic scattering of protons by Mg^{24} which is an indication that the natural width of the resonance is very small. The *d*-wave resonances at 1.66 Mev and 2.01 Mev were however observed by Mooring *et al.*[4] and were shown to have total widths of 0.1 kev and 0.15 kev, respectively.[7] It is therefore quite probable that the resonance at 1.83 Mev has an even smaller total width. Consequently, though it is not possible to deduce the value of Γ_γ from the observed value of $\omega\Gamma_p\Gamma_\gamma/\Gamma$ by assuming that the natural width Γ of the resonance is approximately equal to the proton width Γ_p, it is possible to make the definite statement that $\Gamma_\gamma \geq 6 \times 10^{-4}$ ev for the ground-state gamma ray. The extreme single particle gamma-ray transition widths[15] to the ground state are 4×10^{-3} ev for an electric quadrupole transition and 10^{-4} ev for a magnetic quadrupole transition. The observed lower limit for Γ_γ is therefore consistent with an even parity assignment for the new state at 4.05 Mev but does not conclusively establish the parity.

TABLE II. Comparison of angular correlation of the 4.05-Mev gamma ray with theory.[a,b]

	a_2/a_0	S.D.	a_4/a_0	S.D.
Experiment	0.49	0.06	−0.33	0.08
Theory	0.48		−0.29	

[a] The theoretical coefficients for the case $9/2+ \xrightarrow{-E2} 5/2$ were obtained from Sharp *et al.* (reference 12). The spin and parity of Mg^{24} were assumed to be zero and even.
[b] To correct for the effect of finite angular acceptance of the gamma-ray counters the experimental a_2/a_0 coefficient has been divided by 0.915 and the a_4/a_0 coefficient by 0.765 [H. E. Gove and A. R. Rutledge, Chalk River Laboratory Report CRP-755, 1958 (unpublished)].

[14] Gamba, Malvano, and Radicati, Phys. Rev. **87**, 440 (1952).

Comparison of the Data with the Collective Model

The application of the collective model to Al^{25} results in the prediction of two states in the vicinity of the new state reported in this paper.[1] These states are the $7/2+, K=1/2$, member of the band of rotational states based upon the 2.51-Mev excited state in Al^{25} and the $9/2+$, $K=1/2$, member of the band based upon the first-excited state of Al^{25} at 0.45 Mev. A summary of the experimental information[3,8] on the gamma-ray branching ratios is given in Fig. 6. The $7/2+$ state cannot correspond to the new state at 4.05 Mev because an angular momentum of 7/2 is eliminated by the measured angular correlation of the ground-state gamma ray. Angular momenta of 5/2 or 9/2 are how-

[15] D. H. Wilkinson, Atomic Energy Research Establishment Report T/R 2492, 1958 (unpublished).

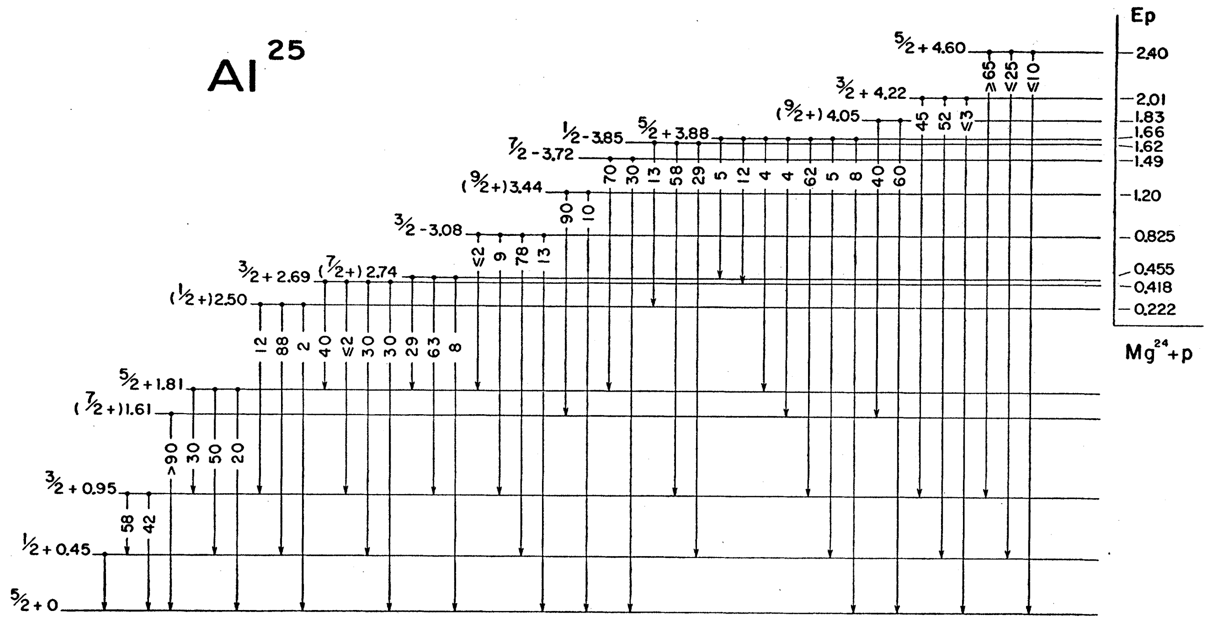

FIG. 6. A summary of the experimental information[3,8] on the gamma-ray branching ratios in Al^{25}. The branching ratios shown on this figure supersede those given in Fig. 1 of reference 1.

ever allowed for the 4.05-Mev state with 9/2 the most favored value as discussed above.

A more recent estimation of the expected position of the $9/2+$, $K=1/2$, state has been made[3] as a result of the discovery of a state at 2.74 Mev in Al^{25}. This state has the expected properties of the $7/2+$, $K=1/2$, member of the band based upon the first excited state of Al^{25}. The $9/2+$, $K=1/2$, state is expected near 3.85-Mev excitation. Though it is possible that the new state at 4.05 Mev is this state, a review of the evidence for or against a $9/2+$, $K=1/2$, state near 3.85 Mev is necessary.

At a proton bombarding energy of 1.62 Mev there appears, in the reaction $Mg^{24}(p,\gamma)Al^{25}$, a pronounced broad resonance.[2] This bombarding energy corresponds to an excitation in Al^{25} of 3.85 Mev. No evidence for a sharp g-wave resonance corresponding to the expected $9/2+$, $K=1/2$, state was observed. The sharp resonance at 1.66 Mev is a d-wave resonance whose properties have been extensively studied.[2,3] However the $9/2+$, $K=1/2$, state would be expected to decay primarily by emitting 2.04-Mev $E2$ radiation to the $5/2+$, $K=1/2$, 1.81-Mev state and by 1.11-Mev $M1$ $E2$ radiation to the $7/2+$, $K=1/2$, 2.74-Mev state. Unfortunately yield curves including those gamma rays in the vicinity of 1.62-Mev proton energy were not taken in the early experiments[2] on the $Mg^{24}(p,\gamma)Al^{25}$ reaction. Moreover it was not confirmed in the early work that the additional very weak cascading at the 1.62-Mev resonance was actually resonant at 1.62 Mev. Two of the very weak gamma rays observed at 1.62-Mev bombarding energy were observed to be in coincidence and to have energies of approximately 1.34 Mev and 2.06 Mev. These gamma rays were interpreted[2] to result from a cascade through the 2.51-Mev state in Al^{25}. However they could also within the considerable experimental uncertainties be the strongest of the gamma rays from a nearby g-wave resonance. The 2.04-Mev primary to the 1.81-Mev state would be followed by a strong 1.36-Mev branch to the 0.95-Mev state in Al^{25}. It would seem therefore that the region near 1.62-Mev bombarding energy should be investigated more thoroughly using very thin targets of Mg^{24} on tungsten to minimize the effect of the broad resonance at 1.62 Mev.

There is also the possibility that the missing 9/2, $K=1/2$, state is so close to the sharp resonance at 1.66 Mev that the two cannot be separated with the targets used in the experiments.[2,3] The two resonances would have to be less than five kilovolts apart for this to happen. The low-energy primary at the 1.66-Mev resonance which feeds the $7/2+$, $K=1/2$, 2.74-Mev state in Al^{25} could then be due partly to the de-excitation

TABLE III. The quadrupole-dipole amplitude mixtures of the 4.05-Mev and 2.44-Mev gamma radiations from the 1.83-Mev resonance, for the two alternative angular momentum assignments for the resonance. The values of x were obtained from the experimental and theoretical coefficients listed in Tables I and II and in Fig. 5. J_i, π_i and J_f, π_f refer to the angular momenta and parities of the initial and final states involved in the gamma-ray transition.

Gamma-ray energy Mev	J_i, π_i	J_f, π_f	Quadrupole-dipole mixture x
4.05	9/2+	5/2+	∞
2.44	9/2+	7/2+	0.4 ± 0.05
4.05	5/2+	5/2+	$+1.6\pm0.03$
2.44	5/2+	7/2+	-1.0 ± 0.6

of the 9/2, $K=1/2$, state at about 3.88 Mev. This possibility could be investigated by careful thin target measurements and by angular correlation measurements of the gamma rays.

It is now necessary to consider the possibility that the 4.05-Mev state, which is very probably 9/2+, is the missing member of the band based on the first excited state. By analogy with the lower members of the first $K=1/2$ band in Al^{25} the 9/2+, $K=1/2$, state would be expected to exhibit prominent cascading within the rotational band. This feature is not observed since the prominent gamma-ray transitions from the 4.05-Mev state are to the two lowest $K=5/2$ states. However the gamma-ray decay properties of the state at 4.05 Mev do not by themselves completely eliminate the possibility that it is the missing 9/2+, $K=1/2$, state. The $E2$ transition to the ground state is not K-forbidden on the collective model, and the 14% $E2$ intensity admixture in the 2.44-Mev radiation could reflect the K-forbiddenness of the $M1$ radiation. The most serious discrepancy between the 9/2+, $K=1/2$, assignment and the results of the collective model is provided by the lack of a 1.37-Mev gamma ray from inelastic scattering at the 1.83-Mev resonance. The expected width[1,6] for inelastic scattering at the 9/2+, $K=1/2$, resonance is approximately 0.6 ev if the resonance is at 1.83 Mev. The observed width is less than 10^{-4} ev, provided Γ_p is assumed to be the largest of the partial widths, so that there are indications that the inelastic scattering is forbidden by some selection rule.

It is relevant here to point out the similarities between the two states in Al^{25} at 3.44 Mev and 4.05 Mev. Figure 3 shows a comparison between the pulse spectra taken at the two resonances. It is possible to argue that the 4.05-Mev state is also a candidate for the third member of the band based upon the ground state. There are two arguments against this possibility. The first and possibly weakest argument is that the energy spacing of the states would then be anomalous. The ground state, the 1.61-Mev state and the 3.44-Mev state form a sequence in energy which agrees quite well with the $J(J+1)$ spacing modified by a vibration rotation term similar to that used for other rotational-like bands in the region $A\sim 25$. The second argument is based upon the absence of inelastic scattering at the 1.83-Mev resonance. The inelastic scattering width for the 9/2+, $K=5/2$, state situated at 1.83-Mev bombarding energy can be shown to be 0.3 ev using equation 6 given by Litherland *et al.*[1] and the barrier penetrability tables given by Gove.[6]

The possibility remains that the state at 4.05 Mev is 9/2+ with a K-value of 7/2 or 9/2. The emission of d-wave protons from the 1.83-Mev resonance leaving Mg^{24} in its 2+, $K=0$, first excited state would then be K-forbidden. The gamma ray cascading at the 1.83-Mev resonance is also consistent with a high K-value. However no low-lying even parity states with $K>5/2$ are predicted in Al^{25} by the Nilsson model[1,16] of a single nucleon in a slowly rotating spheroidal potential. Consequently if the 4.05-Mev state is 9/2+ with a K of 7/2 or 9/2 then its parent states in Mg^{24} must be excited states with K-values greater than zero. Similar considerations[1] are necessary to give a satisfactory account of the properties of the 4.22-Mev and 4.60-Mev states in Al^{25}. There are indications that the considerations of Elliott[17] on "collective motion in the nuclear shell model" can yield, in a simple way, a band of states in Al^{25} with $K=7/2$.[18] The absence however of a 7/2+, $K=7/2$, state at lower excitation energy than the 4.05 Mev 9/2+, $K=7/2$, state raises an obvious problem for this interpretation since the 9/2+, $K=7/2$, would be expected to decay by gamma-ray emission to the 7/2+, $K=7/2$, state. The separation of the two states might be expected to be about 1.83 Mev by analogy with the $K=5/2$ band based on the ground state of Al^{25}. It is of course possible that the assumed 2.44-Mev, 1.61-Mev gamma-ray cascade is incorrectly assigned and that a primary of approximately 1.61 Mev feeds a new state in Al^{25} at about 2.44 Mev. Such a state has not been observed by other methods[3,8] and its existence is doubtful. If the 7/2+, $K=7/2$, state were at an excitation energy greater than 3 Mev in Al^{25} then the results of the present experiment could not exclude the possibility that the state is fed by a low-energy primary.

CONCLUSIONS

The new state in Al^{25} at 4.047 ± 0.010 Mev has been shown experimentally to have an angular momentum of 5/2 or 9/2. Arguments have been presented which favor the assignment of 9/2+ to the state. A discussion of the place of the new state in the rotational-like bands of Al^{25} has demonstrated that in spite of the detailed knowledge of 16 states below 4.5-Mev excitation more experimental evidence is needed before the rotational bands of Al^{25} are firmly established. Attempts to find the higher members of the bands already discovered would be of considerable significance especially if it could be shown experimentally that the bands in Al^{25} do terminate at the expected angular momenta. At present such projects seem experimentally unfeasible though the work at the Atomic Energy Institute of the Academy of Sciences of the U.S.S.R. at Moscow[19] indicates that the gamma-ray cascading

[16] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955).

[17] J. P. Elliott, Proc. Roy. Soc. (London) **A245**, 128 and 562 (1958), and private communication.

[18] The low-lying rotational-like bands in Al^{25} are predicted[17] to terminate at quite high values of the angular momentum. Since these angular momenta are in the vicinity of 21/2+ the failure to observe the 9/2+ member of a band cannot be attributed to the termination of the bands unless the theory is inapplicable.

[19] G. N. Flerov, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy*, Geneva, 1958 (United Nations, Geneva, 1958), A/CONF.15/P/2299; and private communication.

of high angular momentum states in the region $A \sim 130$ can be observed by heavy ion reactions. In the region of $A \sim 25$ high angular momenta states should be formed by such reactions as $B^{11}(O^{16},p)Mg^{25}$.

Finally the new state in Al^{25} at 4.047 ± 0.010 Mev corresponds closely in energy to a state in Mg^{25} at 4.052 ± 0.010 Mev. A comparison of these mirror nuclei including all the information available to date has been published.[20]

[20] H. E. Gove and A. E. Litherland, Phys. Rev. **107**, 1458 (1957).

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Precision Measurement of the $Be^9(\gamma,n)$ Cross Section

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Measurements have been made of the photoneutron cross section for Be^9 using γ rays from radioactive sources of Y^{88} (1.85 Mev) and Sb^{124} (1.69 Mev). The values obtained at these two energies are $(6.54 \pm 0.31) \times 10^{-28}$ cm^2 and $(12.62 \pm 0.69) \times 10^{-28}$ cm^2, respectively. The limiting factors in the accuracy of these measurements are the uncertainties in the γ-ray source strength calibration and in the NBS No. 2 Ra-γ-Be neutron source standard, and the lack of precise knowledge concerning the Sb^{124} decay scheme. A new measurement of the γ-ray branching ratios in the Sb^{124} decay has also been made.

I. INTRODUCTION

SEVERAL absolute measurements have been made[1] of the cross section for the $Be^9(\gamma,n)$ reaction using radioactive sources, bremsstrahlung x-rays, and γ rays from proton reactions with the light elements. In general, these measurements have not been of high accuracy; although an uncertainty of only 5% has been reported in one instance,[2] differences of a factor of two between experiments have occurred.[1]

Since a high efficiency, flat response, 4π neutron detector has recently been constructed[3] at the Oak Ridge National Laboratory, it was felt that a remeasurement of the $Be^9(\gamma,n)$ cross section was warranted in order to obtain somewhat higher precision than has been possible in the past.

In order to be able to approach the accuracy with which the world neutron source standards are known ($\pm 2\%$), it was necessary not only to design the experiment with care, but to choose the radioactive γ-ray sources with some caution. The choice of Sb^{124} as one of the sources was dictated by the wide use of Sb-γ-Be neutron sources, even though the Sb^{124} decay scheme is not known as accurately as it is possible to measure the (γ,n) cross section. In addition to the well-known 1.69-Mev γ ray which occurs in about half of the disintegrations,[4] the Sb^{124} decay also includes a 2.09-Mev γ ray which is approximately one-fifth as intense as the 1.69-Mev radiation.[4] The corrections for the branching ratio and for the effect of the higher energy γ ray (both of which have been re-measured with increased accuracy) introduce sizeable uncertainties.

It was therefore necessary to choose another less equivocal radio-isotope in order to realize the precision of which the method is capable. An additional restriction was that the γ-ray energy not be too high, otherwise radiation Compton-scattered within the source would still have sufficient energy to produce a $Be^9(\gamma,n)$ reaction. Such an effect could be quite significant if the $Be^9(\gamma,n)$ cross section indeed rises to the reported[5] value of 0.1 barn at 1.70 Mev.

The isotope Y^{88} was selected as satisfactorily fulfilling these requirements: the dominant γ ray has an energy of 1.85 Mev and the only other radiation with an energy (2.76 Mev) above the $Be^9(\gamma,n)$ threshold at 1.67 Mev has an intensity[6,7] of only 0.5% of the 1.85-Mev γ ray.

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[1] See the summary by F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. (to be published), or that listed in reference 2.

[2] R. D. Edge, Nuclear Phys. **2**, 485 (1956/57). The table in this article which summarizes previous measurements should be used with caution as it contains several inaccuracies.

[3] R. L. Macklin, J. Nuclear Instr. **1**, 335 (1957).

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[5] D. R. Connors and W. C. Miller, Bull. Am. Phys. Soc. Ser. II, **1**, 340 (1956).

[6] Lazar, Eichler, and O'Kelley, Phys. Rev. **101**, 727 (1956).

[7] F. M. Tomnovec, Bull. Am. Phys. Soc. Ser. II, **1**, 391 (1956). There is a misprint in this abstract; the value given as 0.005% should be 0.5%.