Gamma Rays from the Proton Bombardment of Mg^{24}

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(Received March 24, 1958)

Further measurements on the $Mg^{24}(p,\gamma)Al^{25}$ reaction at the 1.66-Mev resonance have revealed a new level in Al^{25} at an excitation energy of 2.739 ± 0.010 Mev. The level decays to the ground state, the second excited state at 0.95 Mev, and the fourth excited state at 1.81 Mev in the intensity ratios $(8\pm6):(63\pm10):(29\pm14)$. This new level should correspond to a resonance at 0.47 Mev in the laboratory system. A careful search for the resonance failed to show it and an upper limit on its value of $\omega(\Gamma_p\Gamma_\gamma/\Gamma)$ is 0.6×10^{-3} ev. Revised gamma-ray branching ratios for the decay of the level corresponding to the 1.66-Mev resonance have been established. The excitation energies of the first and second excited states in Al^{25} have been measured as 0.461 ± 0.004 and 0.949 ± 0.003 Mev, respectively. The Q value for the $Mg^{24}(p,\gamma)Al^{25}$ reaction is found to be 2.287 ± 0.006 Mev. The existence of the previously reported level at 1.61 Mev in Al^{25} is confirmed as is the fact that the proton width of the 0.418-Mev resonance in the $Mg^{24}(p,\gamma)$ reaction is substantially greater than the gamma-ray width.

INTRODUCTION

In a previous paper[1] a fairly extensive series of measurements on the reaction $Mg^{24}(p,\gamma)Al^{25}$ and $Mg^{24}(pp'\gamma)Mg^{24}$ were reported. The results at one resonance (1.66 Mev) at which no coincidence measurements were made were rather ambiguous. It was pointed out[1] that although an observed gamma ray of energy 2.07 Mev had the correct energy to correspond to a primary transition to the 1.81-Mev level it did not have sufficient intensity to account for all the 1.81- and 1.36-Mev gamma rays observed in the direct spectrum. The possibility that a hitherto unobserved state was being fed was suggested. The work reported here was undertaken primarily to elucidate this point. A preliminary account of some of these experimental results has been presented previously.[2]

The results of the previous work[1] have been interpreted[3] in terms of the rotational collective model of Bohr and Mottelson.[4] None of the rotational bands required in this interpretation, however, contained more than three levels.[1] Higher members of the bands should exist; for example, the fourth member of the $K=\frac{1}{2}$ band based on the first excited state of Al^{25} at 0.45 Mev should occur near an excitation energy of 2.89 Mev and have spin and parity $\frac{7}{2}+$. Such a level might be fed with appreciable probability by gamma-ray de-excitation of the $\frac{5}{2}+$ level at 3.88 Mev.

APPARATUS

The apparatus employed was identical in most respects to that described previously.[1] The main difference was the use of an 80-channel Sunvic pulse amplitude analyzer of the Hutchinson-Scarrott[5] design for recording most of the gamma-ray spectra. Later in the experiment a 100-channel Chalk River transistorized "kick-sorter" became available.[6] The latter has a much smaller dead time and, in addition, has an automatic decimal print-out system.

As before,[1] enriched Mg^{24} targets obtained from the Atomic Energy Research Establishment, Harwell, were used. The target thickness was about 5 kev for 1.66-Mev protons.

One other feature of the electronics, representing a modification of that previously employed and one which proved quite useful, allowed the "self-gated" spectrum to be measured directly. The output signals from the preamplifiers on each crystal were fed into two linear amplifiers in parallel. The output of one amplifier went to a single-channel analyzer whose upper and lower biases could be set independently. The output of the other amplifier was connected to the input of a pedestal free voltage gate circuit. In a coincidence experiment the discriminator biases were set to include a portion of the spectrum from one of the scintillation spectrometers and the single-channel analyzer output opened the gate allowing pulses from the linear amplifier of the other scintillation spectrometer to be recorded in the 80-channel pulse-height analyzer. In order to be certain what portion of the direct spectrum was included within the discriminator biases the procedure was to open the gate, through which the linear amplifier output on one spectrometer passed, with the single-channel analyzer associated with the other linear amplifier on the same spectrometer. This was done first with the discriminator biases opened wide to record the direct spectrum, and then with them closed to include that portion of the spectrum required for the coincidence experiment. This technique was also employed recently in measurements involving coincidences between proton groups and gamma rays.[7]

[1] Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102**, 208 (1956).
[2] Bromley, Gove, Litherland, and Almqvist, Bull. Am. Phys. Soc. Ser. II, **2**, 178 (1957).
[3] Litherland, McManus, Paul, Bromley, and Gove, Can. J. Phys. **36**, 378 (1958).
[4] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[5] G. W. Hutchinson and G. G. Scarrott, Phil. Mag. **42**, 792 (1951).
[6] Designed by F. S. Goulding, Atomic Energy of Canada Limited, Chalk River, Ontario.
[7] Bromley, Almqvist, Gove, Litherland, Paul, and Ferguson, Phys. Rev. **105**, 957 (1957).

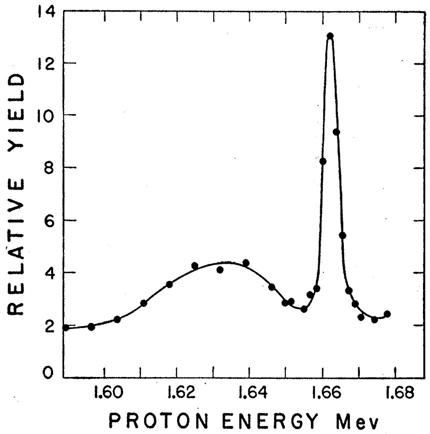

FIG. 1. Yield of 2.93-Mev gamma rays. The two resonances at approximately 1.62 and 1.66 Mev corresponding to levels in Al^{25} at 3.85 and 3.88 Mev are shown.

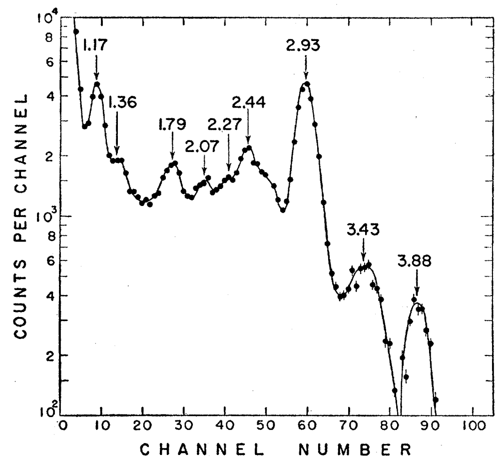

FIG. 2. Direct spectrum of gamma rays measured at the 1.66-Mev resonance at 90° to the incident beam. Measurements made on the resonance and just below it are subtracted to obtain the result shown here.

In most of the coincidence measurements the two 5-in. diameter by 4-in. long NaI(Tl) crystals were located at 90° on each side of the beam and their front faces were placed as close to the target as possible (about two inches) in order to increase their efficiency. A preliminary attempt to measure a coincidence angular correlation with the crystals at about six inches from the target indicated that the counting rate was too low to obtain meaningful results in a reasonable time.

A "fast-slow" coincidence arrangement[8] was used for one of the coincidence measurements towards the end of the experiment. This system had a resolving time of about 50 mμsec. Otherwise the coincidence resolving time was about two microseconds.

RESULTS

Direct and Coincidence Gamma-Ray Spectra Measurements

The yield of 2.93-Mev gamma rays was measured as a function of proton energies between 1.59 and 1.69 Mev. The results are presented in Fig. 1 where the broad resonance at 1.62 Mev and the narrow 1.66-Mev resonance are shown. The direct gamma-ray spectrum was measured at 90° to the beam on, and just below the 1.66-Mev resonance for the same number of protons reaching the target. The measurement made on the resonance took slightly less time than that off, and counting was continued with the beam current reduced to zero until the times were equal. In this way background from sources other than the accelerator was compensated for. The subtracted pulse-height spectrum obtained from the difference of these two measurements is shown in Fig. 2. The only gamma ray not observed previously[1] was that at 2.27 Mev.

Since the gamma-ray spectrum at this resonance is clearly quite complex, a series of coincidence measurements was made by setting a voltage gate to accept a narrow band of pulse heights in various regions of the direct spectrum from one detector and measuring the pulse-height spectra in coincidence with these in the second detector. Some of the results are shown in Fig. 3. In each case the direct spectrum and the narrow band of pulse heights selected is shown on the upper part and the corresponding coincidence spectrum on the lower part of each drawing. The total number of protons striking the target was not the same for each of the coincidence spectra shown in Fig. 3, the relative amounts being in the ratio of 1:1:1.5:2:1:1.1 in order of decreasing energy of the gate setting [(a), (b), (c), (d), (e), and (f), respectively, in Fig. 3]. The qualitative results of these coincidence measurements are interpreted as follows (reference to Fig. 11 may be helpful). Figures 3(a) and 3(b) show that the 2.93- and 0.95-Mev gamma rays are in coincidence and that the 1.16-Mev gamma ray is in coincidence with one of energy between 2.93 and 2.44 Mev. Figure 3(c) indicates that the 2.27-Mev gamma ray (shown in Fig. 2) is in coincidence with a 1.61-Mev gamma ray. In the previous work[1] the 1.61-Mev gamma ray was observed only at the 1.20-Mev resonance (corresponding to a level in Al^{25} at 3.44 Mev) where it was shown to be in coincidence with a 1.83-Mev gamma ray. From those data it was not possible to say whether these two gamma rays resulted from a cascade through a level at 1.83 or through one at 1.61 Mev in Al^{25} although the latter was assumed. The results shown in Fig. 3(c) demonstrate that the level involved is likely at 1.61 Mev as do those of Fig. 3(d).[9] In the latter case the 1.61-Mev gamma ray is

[8] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

[9] Results of a recent investigation of another new level in Al^{25} provide additional confirmation of an excited state in Al^{25} at 1.61 Mev [Litherland, Gove, and Ferguson, Bull. Am. Phys. Soc. Ser. II, **3**, 37 (1958)].

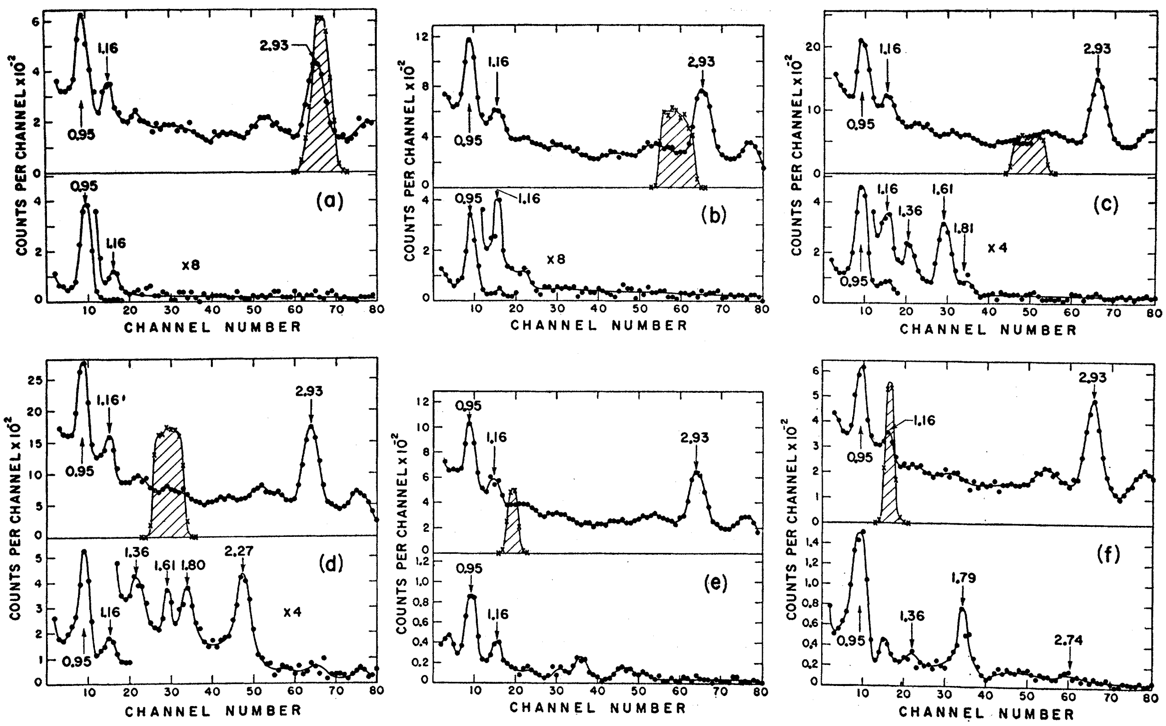

FIG. 3. A series of coincidence spectra measured at the 1.66-Mev resonance. In each case the direct spectrum measured in one spectrometer is shown together with the section of the direct spectrum used in the coincidence circuit gate (shown shaded) in the upper half of each figure, while the corresponding coincidence spectrum measured in the second spectrometer is shown in the lower half.

included in the gate and the concidence spectrum shows a 2.27-Mev gamma ray. The sum of these two energies is equal to the level excitation of 3.88 Mev in Al^{25} which corresponds to the 1.66-Mev resonance. The 2.27-Mev gamma ray is then the primary to the 1.61-Mev level. Similarly the primary to the 1.81-Mev level of energy 2.07 Mev is included to some extent in the gate shown in Fig. 3(c) which accounts for the 1.36- and 1.81-Mev gamma rays observed. The results shown in Fig. 3(e) are only of interest when compared to those of Fig. 3(f), and indicate that a considerable change occurs in the coincidence spectra when the gate is set to include the 1.16-Mev gamma ray and when it is set to include gamma rays of slightly higher energy. The results shown in Fig. 3(f) demonstrate that a new level in Al^{25}

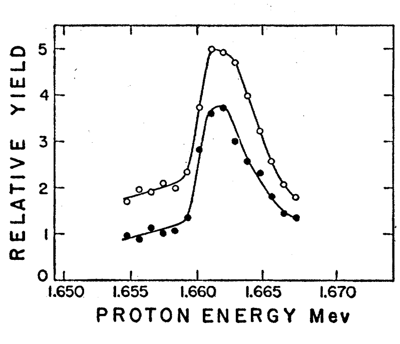

FIG. 4. The curve through the open circles is the yield of gamma rays in the direct spectrum which give rise to pulses corresponding to the energy range from 0.87 to 0.98 Mev, while that through the closed circles is the same for the energy range from 1.08 to 1.21 Mev.

is being fed by gamma rays from the 1.66-Mev resonance. In this case the coincidence spectrum shows principally a gamma ray of energy 1.79 Mev in coincidence with the 1.16-Mev gamma ray. That this 1.79-Mev gamma ray is not due to the ground-state transition from the 1.81-Mev level is clear from the previous results[1] which showed that the 1.81-Mev level decays with greater probability to the first excited state of Al^{25} at 0.45 Mev than to the ground state and hence a 1.36-Mev gamma ray of greater intensity should also be observed. The spectra of Figs. 3(a) and 3(b) indicate that the 1.16-Mev gamma ray is in coincidence with a gamma ray of energy between 2.44 and 2.93 Mev; some evidence for a 2.74-Mev gamma ray appears in Fig. 3(f). These results can only be explained by assuming that the 1.16-Mev gamma ray is a primary feeding a new level in Al^{25} at about 2.74 Mev, which in turn decays predominantly by a cascade through the second excited state at 0.95 Mev.

Since this new level is very close in energy to the well-known level at 2.69 Mev the two primary radiations are not resolved in the direct spectrum at the 1.66-Mev resonance. The fact that the spectrum in coincidence with 1.16-Mev gamma rays, shown in Fig. 3(f), is completely different from that observed[1,10]

[10] J. Varma and W. Jack, Proc. Phys. Soc. (London) 71, 100 (1958).

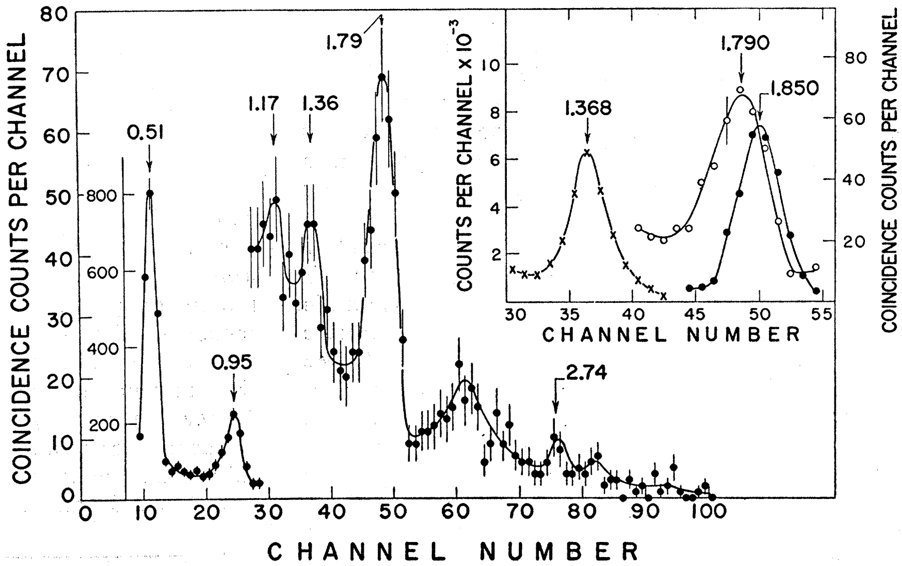

FIG. 5. Spectrum of gamma rays in coincidence with 1.16-Mev gamma rays at the 1.66-Mev resonance. The inset figure shows the region of this spectrum in the vicinity of 1.79 Mev on an expanded scale including, in addition, calibration gamma-ray lines of energy 1.368 and 1.850, respectively.

at the resonance corresponding to the level at 2.69 Mev and that the intensity of the 1.16-Mev gamma ray is too great to be interpreted as leading to the new level alone, shows that the width of the 2.69-Mev level for proton emission is substantially greater than that for gamma emission.

Figure 4 shows the direct yield of pulses corresponding to energies between 0.87 and 0.98 Mev and those between 1.08 and 1.21 Mev. This demonstrates that both the 1.16-Mev and 0.95-Mev gamma rays resonate at the 1.66-Mev resonance and hence the two levels at 2.74 and 2.69 Mev are fed by gamma rays from the $\frac{5}{2}+$ level at 3.88 Mev.

Energy Measurements

In order to establish the excitation energy of this new level in Al^{25} and the laboratory energy of the protons required to excite the resonance corresponding to this level, a series of measurements of gamma-ray energies was undertaken. The measurements described below consisted first of measuring the energy of the transition between the new level and the second excited state, and the transition between the second excited state and the ground state. This gives the excitation energy of the new level, and to determine the proton energy required to excite this level an accurate knowledge of the Q value is necessary. This was obtained by measuring the excitation energy of the level in Al^{25} corresponding to the resonance at 0.825 Mev. In this case the energies of the gamma-ray transitions from this resonance to the first excited state of Al^{25} and from the first excited state to the ground state were measured. No attempt was made to measure the proton energy corresponding to this resonance; the value of 0.825 Mev measured at the University of Wisconsin[11] was assumed. In all cases the energies of calibration gamma rays from radioactive sources were obtained from Nuclear Data Cards.[12]

To obtain the energy of the gamma-ray transition between the new level and the second excited state in Al^{25} the spectrum in coincidence with 1.16-Mev gamma rays was remeasured at the 1.66-Mev resonance. This is shown in Fig. 5 together with a comparison between this gamma ray and the 1.368±0.001 Mev gamma ray from the decay of Na^{24} and the 1.850±0.008 Mev gamma ray from the decay of Y^{88}. This gives a value of 1.790±0.010 Mev for the gamma ray in question.

The energy of the second excited state of Al^{25} was obtained by measuring the energy of the gamma ray in coincidence with the 2.93-Mev gamma ray at the 1.66-Mev resonance. In this case the gamma rays

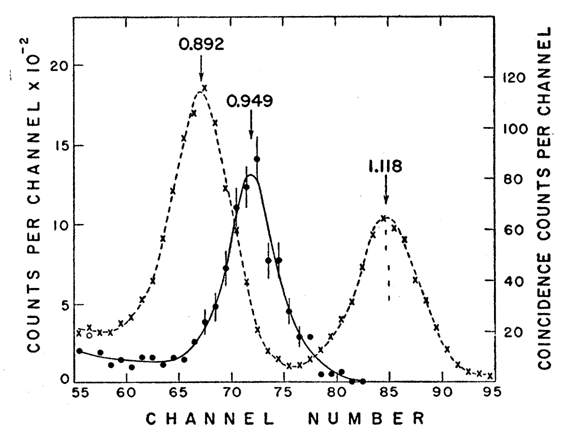

FIG. 6. The curve through the closed circles is the gamma-ray spectrum in coincidence with 2.93-Mev gamma rays measured at the 1.66-Mev resonance, while that through the crosses is the direct spectrum of gamma rays from a Sc^{46} source used for calibration.

[11] Mooring, Koester, Goldberg, Saxon, and Kaufmann, Phys. Rev. **84**, 703 (1951).

[12] *Nuclear Data Cards* (National Research Council, Washington, D. C.).

resulting from the decay of Sc^{46} were used for calibration. This is illustrated in Fig. 6. Using values of 1.118±0.003 and 0.892±0.003 Mev for Sc^{46} an energy of 0.949±0.003 Mev was obtained for the second excited state of Al^{25}. The value previously reported was 0.97±0.03 Mev.[13] From these two measurements the excitation energy of this new level in Al^{25} is 2.739±0.010 Mev.

In order to calculate what proton energy would be required to excite the resonance corresponding to this level, a more accurate Q value for the $Mg^{24}(p,\gamma)$ reaction is required than was previously available. To measure the Q value the gamma-ray energies at the 0.825-Mev resonance were examined. Figure 7 shows the high-energy portion of the direct gamma-ray spectrum together with a calibration line from the decay of Tl^{208} (ThC″) of energy 2.61425±0.00005 Mev. From these spectra and a pulse height *versus* channel number curve, obtained using a linear pulse generator, the energy of the transition from the level corresponding to the 0.825-Mev resonance to the first excited state in Al^{25} is found to be 2.618±0.005 Mev. To measure the energy of the first excited state of Al^{25}, the spectrum of gamma rays in coincidence with these 2.618-Mev gamma rays was measured. The result is shown in Fig. 8 together with a calibration line from the decay of Na^{22} of energy 0.51094±0.00007 Mev taken both before and after the coincidence spectrum measurement. Again a linear pulse generator gave the pulse height *versus* channel number variation. From this measurement the energy of the first excited state of Al^{25} is found to be 0.461±0.004 Mev. This is in agreement with a previous determination[13] yielding 0.454±0.005 Mev. Hence the excitation energy of the level in Al^{25} corresponding to the 0.825-Mev resonance is 3.079±0.006 Mev; this is in agreement with the energy of the ground-state gamma ray shown in Fig. 7. The Q value for the reaction $Mg^{24}(p,\gamma)Al^{25}$ is then 2.287±0.006 Mev. This can be compared to the best average value previously quoted[14] of 2.28±0.01$_5$ Mev.

From the measured excitation energy of the new level and the Q value, one obtains for the laboratory proton energy required to excite the resonance corresponding to this new level the value of 0.471±0.013 Mev.

As a rough check on the consistency of these energies the spectrum of gamma rays in coincidence with 1.8-Mev gamma rays was measured at the 1.66-Mev resonance. The results are shown in Fig. 9 together with calibration gamma rays from the decay of Co^{60} of energy 1.3325±0.0003 and 1.1728±0.0005 Mev. From these data the energy of the primary gamma ray leading to the new level from the 1.66-Mev resonance is found to be 1.156±0.010 Mev. If one adds to this the previously measured energy of the gamma transition between the new level and the second excited state and the energy of this second excited state, one obtains for the excitation energy of the level in Al^{25} corresponding to the 1.66-Mev resonance the value 3.895±0.014 Mev. From this and the Q value, one obtains a laboratory energy for this resonance of 1.675±0.017 Mev which is to be compared with 1.66 Mev as measured at Wisconsin.[11]

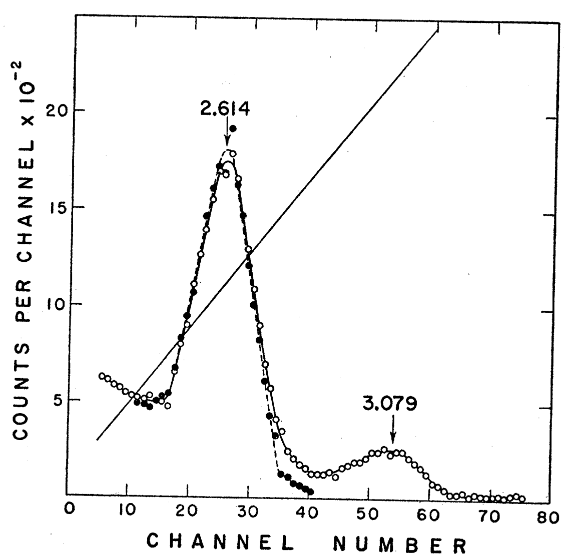

FIG. 7. The curve through the open circles is the high-energy end of the direct spectrum of gamma rays at the 825-kev resonance, while that through the closed circles is a calibration line from ThC″ of energy 2.614 Mev. The straight line is a plot of pulse height *versus* channel number using a pulse generator.

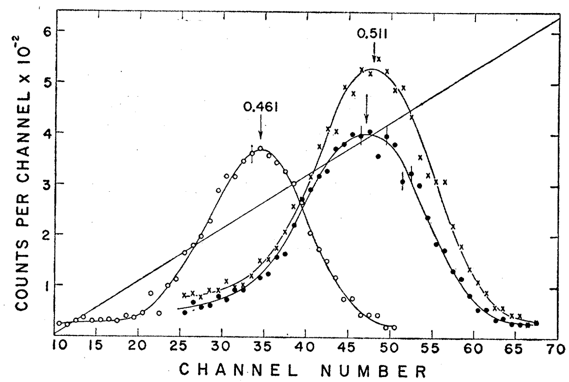

FIG. 8. The curve through the open circles is the spectrum of gamma rays in coincidence with 2.6-Mev gamma rays at the 825-kev resonance, while those through the closed circles and crosses are the direct gamma-ray spectra from Na^{22} in the vicinity of the 0.511-Mev gamma ray measured before and after the coincidence run, respectively. The straight line is a plot of pulse height *versus* channel number using a pulse generator.

Search for the Resonance Corresponding to the New Level

Since the resonance energy corresponding to the new level is established as 471±13 kev, it should be detected

[13] D. S. Craig, Phys. Rev. **101**, 1479 (1956).

[14] D. M. Van Patter and W. Whaling, Revs. Modern Phys. **29**, 757 (1957).

slightly higher in energy than the well-known resonance at 418 kev. Previous work had shown[1] however that carbon contamination on the targets caused the region between 440 and 500 kev in the yield curve to be obscured by the broad $C^{12}(p,\gamma)N^{13}$ resonance at 457 kev. This is demonstrated in Fig. 10(a) in which the direct yield of 0.9-Mev gamma rays from $E_p=380$ to 520 kev is shown. The horizontal bar indicates where the resonance corresponding to the new level should be found.

As a consequence it was necessary to search this region using coincidences between two gamma-ray detectors. A voltage gate on one crystal was set to include pulses corresponding to the total energy peak of about 0.9-Mev gamma rays, while the yield of 0.9-, 1.36-, and 1.8-Mev gamma rays in coincidence with these pulses were measured in the second crystal. These coincidence yield curves are shown in Figs. 10(b), 10(c), and 10(d), respectively. No evidence for a resonance in the expected region is found.

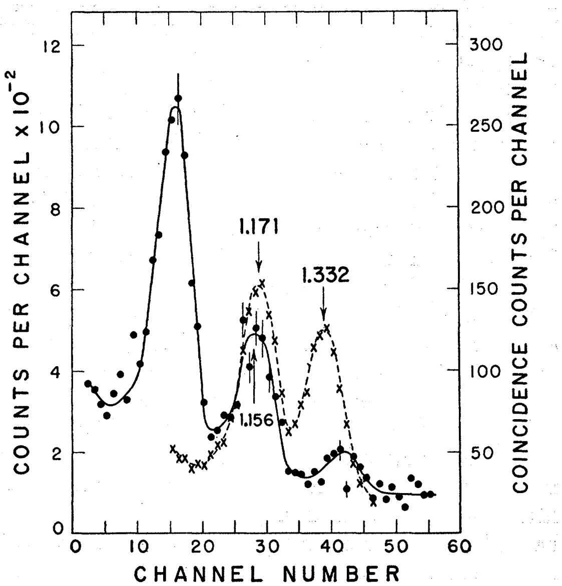

FIG. 9. The curve through the closed circles is part of the spectrum of gamma rays in coincidence with a gate set to include the total absorption peak of gamma rays of approximately 1.8 Mev at the 1.66-Mev resonance, while that through the crosses is a direct calibration spectrum showing the 1.171- and 1.332-Mev gamma rays from Co^{60}.

From the measurements and the known values of $\omega\gamma$ for the 418-kev resonance an upper limit can be set on the value of $\omega\gamma$ for the new level. The 0.89-Mev transition between the level corresponding to the 418-kev resonance and the 1.81-Mev level has a value of $\gamma=\Gamma_p\Gamma_\gamma/\Gamma$ of 6×10^{-3} ev.[1] Since the spin of the 418-kev resonance is $\frac{3}{2}$ the height of this resonance in Fig. 10(c) should be proportional to $\omega\gamma=12\times10^{-3}$ ev. The resonance corresponding to the new level must then have $\omega\gamma\leqslant0.6\times10^{-3}$ ev for the transition to the 1.81-Mev level.

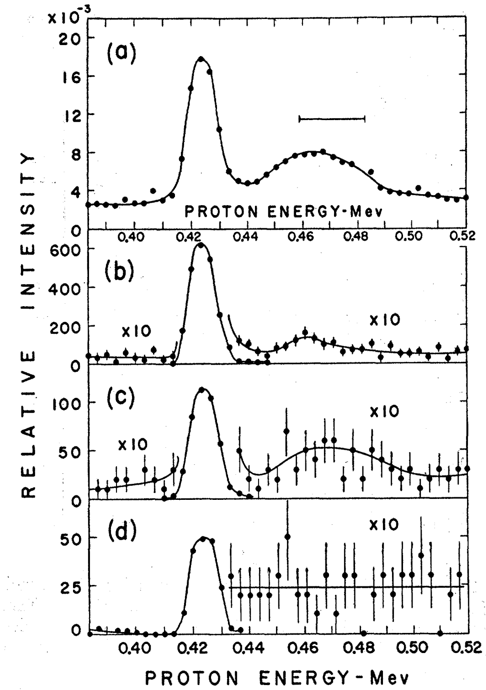

FIG. 10. Attempts to locate the resonance corresponding to the level in Al^{25} at 2.74 Mev. (a) The direct yield of 0.9-Mev gamma rays; (b) the yield of 0.9-Mev gamma rays in coincidence with 0.9-Mev gamma rays; (c) the yield of 1.36-Mev gamma rays in coincidence with 0.9-Mev gamma rays, and (d) the yield of 1.81-Mev gamma rays in coincidence with 0.9-Mev gamma rays. The broad resonance observed in the direct yield curve is the 457-kev resonance in the reaction $C^{12}(p,\gamma)N^{13}$. The horizontal bar indicates where the resonance corresponding to the 2.74-Mev level in Al^{25} should occur.

DISCUSSION

The results of these experiments do not provide unambiguous spin and parity assignments for the new level at 2.74 Mev in Al^{25}. Because it is fed by a relatively low-energy transition from the $\frac{5}{2}+$ level at 3.88 Mev its spin is probably $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. Because its decay by gamma emission does not feed the $\frac{1}{2}+$ first excited state at 0.46-Mev spin assignments of $\frac{5}{2}$ or $\frac{7}{2}$ are most probable. One cannot further select between these on the basis of such arguments. The parity of the level is completely undetermined.

The relative branching ratios of the decay of the 2.74-Mev level can be estimated from the coincidence spectra as illustrated in Figs. 3(f) and 5. Both were measured with the front faces of the NaI crystals about two inches from the target; hence, angular correlation effects are considerably attenuated. The results shown in Fig. 11 are in the ratios $(8\pm6):(63\pm10):(29\pm14)$ to the ground state, the level at 0.95 Mev, and that at 1.81 Mev, respectively.

Relative branching ratios for the 3.89-Mev level are obtained by analyzing the direct spectrum of Fig. 2

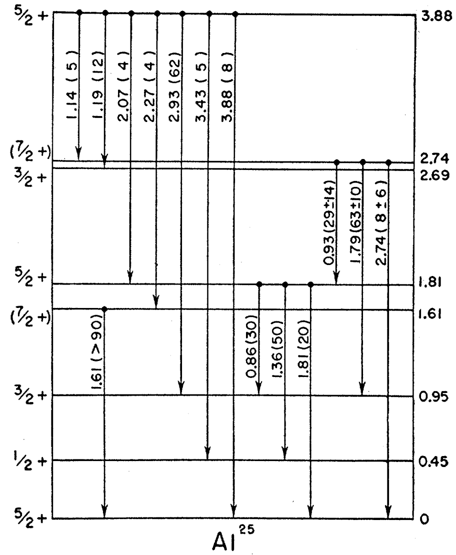

FIG. 11. A simplified energy level diagram for Al^{25} showing the levels involved in the work described in this paper. Excitation energies and spin and parity assignments (bracketed where not certain) are given for each level. Gamma-ray energies and relative branching ratios are given for four of the levels.

into its various components. Again this spectrum was measured with the crystal front face two inches from the target, thus attenuating correlation effects. However, the results given in Fig. 11 are not particularly accurate both because of the complexity of the spectrum and because of the possible existence of large residual direct correlation effects.

The possible interpretation of this level in terms of the collective model is of some interest. For an odd-A nucleus the rotational spectrum for a band with $K=\frac{1}{2}$ is given by[4]

$$E_J=E_0+A[J(J+1)+a(-)^{J+\frac{1}{2}}(J+\tfrac{1}{2})] -B[J(J+1)+a(-)^{J+\frac{1}{2}}(J+\tfrac{1}{2})]^2$$

where

$$A=\frac{\hbar^2}{2I},\quad B=\frac{16A^3}{(\hbar\omega)^2}=16A^3\times\frac{1}{4}\left[\frac{3}{(\hbar\omega_\beta)^2}+\frac{1}{(\hbar\omega_\gamma)^2}\right].$$

Here I is the moment of inertia about an axis perpendicular to the axis of deformation and $\hbar\omega$ is the vibrational energy assuming beta and gamma vibrations are equal. Applying this formula to the three levels previously assumed to lie at excitations of 0.45, 0.95, and 1.81 Mev, interpreted[1] as $J=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ members of a $K=\frac{1}{2}$ band, and using a value for $\hbar\omega$ calculated from the rotational band based on the ground state of Mg^{24}, the position of the fourth member with $J=\frac{7}{2}$ is predicted[3] to lie at an excitation of 2.89 Mev. The value of $\hbar\omega$ in this case is 11.1 Mev.

The model furthermore predicts[3] that the $M1$ part of the gamma-ray transitions between this fourth member of the rotational band based on the first excited state and the ground state and 1.61-Mev excited state (both members of a $K=\frac{5}{2}$ rotational band on the collective model interpretation) should be K-forbidden. In practice this is found[3] to attenuate reduced gamma-transition probabilities by about a factor of 10.

Finally, definite predictions for the gamma-ray branching ratios between levels in the same rotational band can be expected from the model.[15] These predictions,[3] for the band in question here, are illustrated in Fig. 12. In this figure the predicted intraband branching ratios for both the third and fourth members of the rotational band based on the first excited state of Al^{25} are shown as a function of the distortion parameter η[16] for two different values of κ, the parameter which measures the strength of the spin-orbit coupling. In both cases the crossover $E2$ transition is predicted to be appreciable compared to the $M1$-$E2$ cascade transition.

Qualitatively the characteristics of the 2.74-Mev level matches all these predictions. Its excitation energy suggests that the vibration-rotation correction term must be calculated using a different value of $\hbar\omega$ than obtained from the ground-state band of Mg^{24}. If the following values for the excitation energy of four members of this band are used: 0.461, 0.949, 1.810, and 2.739 Mev, then all the parameters in the above equation can be determined. Table I lists the parameters and compares them with those obtained previously from the first three members of this rotational band.[3] The principal difference is the lower value of $\hbar\omega$ required. From these new values of the parameters, one can now make a better estimate of the excitation energy of the fifth ($J=9/2+$) and sixth ($J=11/2+$) members of the band. These are 3.85 and 4.71 Mev, respectively. The former coincides exactly with the position of the broad $\frac{1}{2}$-resonance formed by 1.62-Mev p-wave protons. Since a $J=9/2+$ state would be formed by g-wave protons, it might be very difficult to find under these circumstances. Certainly no evidence for it has been obtained. The nearest level in Al^{25} presently known with

TABLE I. Comparison between the present parameters and the previous parameters required to fit the energy positions of levels associated with the $K=\frac{1}{2}+$ band based on the first excited state of Al^{25}. The previous parameters were obtained[3] from the first three levels only assuming that the vibrational energy was the same as required for the 0+, 2+, 4+ levels in Mg^{24}.

	Present values	Previous values
E_0 (kev)	314	311
A (kev)	181	176
a	−0.0667	−0.03
B (kev)	1.61	+0.70
$\hbar\omega$ (Mev)	7.68	11.1

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

[16] η depends both on the usual distortion parameter β and on the strength of the spin-orbit coupling.[3,15]

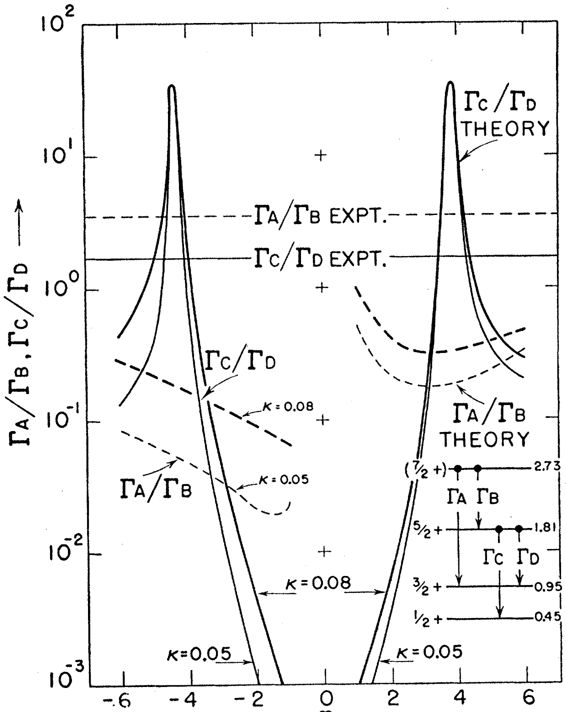

FIG. 12. The experimental gamma-ray branching ratios within the rotational band, based on the first excited state of Al^{25}, are compared with theory. For each of the two ratios shown the lower energy transition includes both $M1$ and $E2$ contributions. η is a parameter which depends both on the nuclear distortion and the strength of the spin-orbit coupling κ. Theoretical curves are shown for two values of this latter quantity.

suitable characteristics for the predicted $J=11/2+$ level at 4.71 Mev is the one at 4.90 Mev.[1] This is believed to have $J\geqslant\frac{5}{2}$ and $(J+\frac{1}{2})(\Gamma_p\Gamma_{p'}/\Gamma)=12$ ev. If this level had $J=11/2$ it could emit inelastic g-wave protons to the first excited state of Mg^{24}, and the single-particle limit for the width of such a process is approximately 40 ev. It does appear somewhat unlikely that the width for formation by $l=6$ protons would be as high as $12/(J+\frac{1}{2})=2$ ev (for $J=11/2$), but since barrier penetrabilities for such high orbital angular momenta are unavailable the single-particle limit cannot be estimated.

The measured intraband gamma-ray branching ratio for the new 2.74-Mev level is greater than the predicted value (see Fig. 12) favoring the $E2$ crossover transition. Exactly how much greater it is is somewhat uncertain. The horizontal dotted line representing the experimental value shown in Fig. 12 is actually approximately an upper limit to the value. The measured ratio is obtained from Fig. 11 to be 2.2±1.1. Increasing the value of the spin-orbit coupling strength improves the agreement by raising the predicted value. The $d_{\frac{5}{2}}-d_{\frac{3}{2}}$ splitting of 5.08 Mev in O^{17} would in fact require[3] $\kappa=0.13$. In this case the difference between the observed and calculated intraband branching of the 2.74-Mev level might be as small as a factor of two.

It thus appears that the characteristics of the 2.74-Mev level in Al^{25} are quite compatible with it being the fourth member of the rotational band with $J=\frac{7}{2}+$ based on the first excited state. The corresponding level in Mg^{25} is very likely that at 2.74 Mev,[17] which is found in the $Mg^{24}(d,p)$ reaction[18] to have no stripping pattern for the angular distribution of the relevant proton group.

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

[18] Hinds, Middleton, and Parry, Proc. Phys. Soc. (London) **71**, 49 (1958).