# Properties of the 4.403-MeV Excited State of $Al^{27}$†

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Using the Doppler-broadened 4.43-MeV gamma line from the reaction $N^{15}(p,\alpha)C^{12*}$, the 4.403-MeV level in $Al^{27}$ has been excited by resonant absorption. The de-excitation of this level was found to lead to the 2.21-MeV (11%) and the 1.01-MeV (32%) excited states as well as directly to the ground state of $Al^{27}$ (57%). From a self-absorption study, a value $g\Gamma_0=0.24\pm0.03$ eV was obtained for the product of the statistical factor $g=(2J_{exc}+1)/(2J_{gs}+1)$ and the partial width $\Gamma_0$ of the ground-state transition. The angular distribution of the 4.403-MeV resonance radiation was observed to be $W(\theta)=1+(0.30\pm0.05)\ P_2(\cos\theta)$, and that of the 3.39-MeV radiation to the 1.01-MeV state $W(\theta)=1-(0.24\pm0.12)\ P_2(\cos\theta)$. Of the possible spin-parity assignments, only $\frac{5}{2}^{\pm}$ and $\frac{7}{2}^{+}$ are compatible with the observed widths and the angular distributions, the most probable assignment being $\frac{5}{2}^{+}$, the least probable $\frac{7}{2}^{+}$. With a spin of $\frac{5}{2}$, the partial width for the 4.403-MeV ground-state transition becomes $\Gamma_0=(0.24\pm0.03)$ eV, and the total width of the level $\Gamma=(0.42\pm0.06)$ eV. The fact that resonance scattering from the 4.504-MeV level was not observed points to a spin of either $\frac{1}{2}$ or $\geq\frac{9}{2}$ for that level.

## I. INTRODUCTION

THE reaction $N^{15}(p,\alpha)C^*$ has been found to be a convenient source for resonance fluorescence experiments with $C^{12}$,[1] $B^{11}$,[1] and $Na^{23}$.[2] The Doppler-broadened gamma line from a gaseous target of $N^{15}H_3$ is 110 keV wide for proton energies around 3 MeV. $Al^{27}$ is known to have two levels, at 4.403- and 4.504-MeV excitation energy,[3] which fall into the energy interval covered by this reaction. Since the excitation energies were the only information available concerning these levels, it appeared to be of interest to obtain additional information from resonance scattering and self-absorption experiments. It turned out that most of the information obtained concerns the 4.403-MeV level.

## II. SCATTERING EXPERIMENTS

### A. Procedure

The procedure used was similar to that described in our study of $Na^{23}$.[2] The Al scatterer consisted of six layers of $\frac{1}{8}$ in. Al, separated by Al spacers to provide an average density comparable to that of Mg metal, which served as comparison scatterer. The inside diameter of the scatterers was $13\frac{1}{2}$ in., the outside diameter $15\frac{7}{8}$ in. For the experiments reported here the reaction $N^{15}(p,\alpha)C^{12*}$ was used at either the 3.0- or 3.3-MeV resonance[4] or, in one instance, at the $E_p=1.65$ MeV resonance.

### B. Composition of the Scattered Radiation

A typical pulse-height distribution of the resonance radiation, representing the difference between the pulse-height distributions measured with the Al and the Mg scatterers, is shown in Fig. 1. The energies indicated in this figure were obtained from comparisons with the 4.431-MeV line of $Na^{23}$ and with the direct 4.43-MeV gamma radiation. The shape of the line from $Al^{27}$ indicates that the 4.503-MeV level does not contribute appreciably to the resonance scattering. This is in agreement with our observation that the resonant scattering persisted at backward angles where the energy of the exciting radiation was smaller than 4.495 MeV. Data taken at the $E_p=1.65$-MeV resonance established a lower limit of 4.395 MeV for the excitation energy of the resonantly excited level. All the available

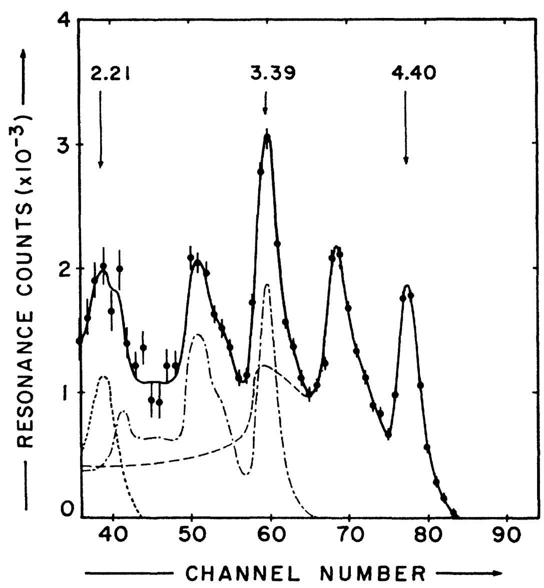


FIG. 1. Pulse-height distribution of the resonant gamma radiation which is observed when $Al^{27}$ is irradiated with the 4.4-MeV gamma line from the reaction $N^{15}(p,\alpha)C^{12*}$. The solid curve represents the difference of the pulse-height distributions measured with Al and Mg scatterers using a 3-in.×3-in. NaI detector. The proposed decomposition into contributions from 4.40-MeV (– – –), 3.39-MeV (–·–·–), and (2.19+2.21)-MeV (····) transitions is also indicated.

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information is thus in accord with the assumption that only the 4.403-MeV level in $Al^{27}$ was excited.

The pulse-height distribution shown in Fig. 1 clearly indicates considerable branching to levels other than the ground state. The peak at 3.39-MeV is attributed to the transition to the 1.01-MeV second excited state. After subtraction of the contributions of the 4.40- and 3.39-MeV transitions, a peak indicated in Fig. 1 by a dotted line remains. It is interpreted as originating from branching to the 2.21-MeV level, i.e., as being a composite 2.19+2.21-MeV peak. Below 2 MeV the errors in the differences between the counting rates with the Al and the Mg scatterers rapidly become so large that it is not possible to exclude some feeding of the 2.73-MeV level which would give rise to 1.72- and 1.01-MeV radiation. For the present analysis we shall assume that branching takes place only to the ground state, the 1.01- and the 2.21-MeV levels. From pulse-height distributions of the type shown in Fig. 1, which, incidentally, is a superposition of distributions measured at different scattering angles, one arrives at the following relative widths:

$$\Gamma_0/\Gamma=0.57\pm0.05\,,$$
$$\Gamma_1/\Gamma=0.32\pm0.05\,,$$
$$\Gamma_2/\Gamma=0.11\pm0.05\,.$$

### C. Line Shape $N(E)$

The number of resonantly scattered 4.4-MeV gamma rays may be expressed in the form

$$N_{\text{scatt}}=N(E_R)g(\Gamma_0^2/\Gamma)G\,, \qquad (1)$$

where $\Gamma_0$ is the partial width for the ground state transition, $\Gamma$ the total width of the level, $g$ the ratio of the statistical weights of the excited state and the ground state, respectively, $N(E_R)$ the number of gamma rays per eV interval at the resonant energy, and where $G$ contains all the geometrical and attenuation factors including the self-absorption due to the finite size of the scatterer. The energy resolution of the sodium iodide detector does not allow one to measure $N(E_R)$ directly. What is observed is the total number $N_T$ of 4.4-MeV photons in the incident beam. The fraction $N(E_R)/N_T$ falling into the resonant region depends on the detailed shape of the Doppler broadened line, this shape itself depending on the angular correlations in the reaction $N^{15}(p,\alpha)$. From previous data on $B^{11}$ and $C^{12}$,[1] a value $N(E_R)/N_T=8.4\times10^{-6}$ was considered to be appropriate for the evaluation of the $Al^{27}$ data at the $E_p=3.0$ MeV resonance. Recently, the advent of Li-drifted germanium detectors[5] has provided us with the possibility of measuring directly the detailed shape of the 4.4-MeV exciting radiation. Consequently, the radiation from the $N^{15}(p,\alpha)$ reaction was studied using a 1.1 $cm^2\times0.4$ cm Li-drifted germanium detector.

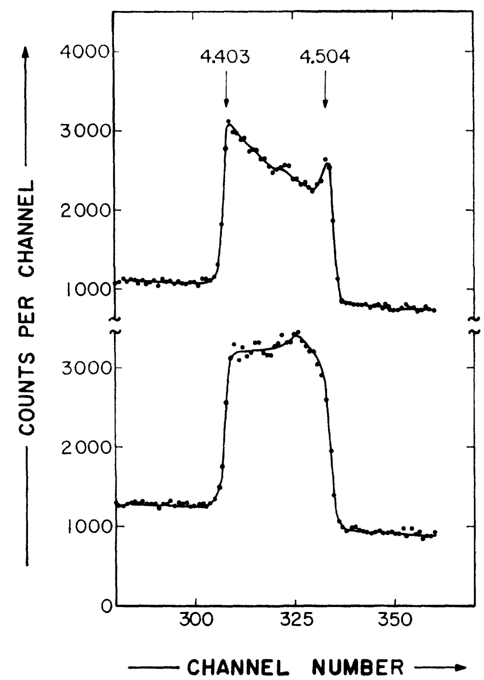


FIG. 2. Pulse-height distributions due to the Doppler broadened 4.4-MeV gamma line from the reaction $N^{15}(p,\alpha)C^{12*}$, observed at 25° to the beam with a 1.1 $cm^2\times0.4$ cm Li-drifted germanium detector. The region of the double escape peak is shown. The distribution in the lower portion of the figure was measured at the $E_p=3.00$-MeV resonance of the $N^{15}(p,\alpha)$ reaction, the other distribution at the $E_p=3.30$-MeV resonance.

Typical pulse-height distributions for the gamma radiation emitted in the direction of the scatterer, i.e., at an angle of approximately 25° with respect to the direction of the incident proton beam, are shown in Fig. 2. Since the proton beam had to traverse a 0.00025-in. tantalum window before entering the gas cell, bombarding energies of 3.42- and 3.69-MeV had to be used to excite the 3.0- and 3.3-MeV resonances, respectively. The line shapes depicted in Fig. 2 show that the intensity per eV at 4.403 MeV is smaller than the average for the line at the 3.0-MeV resonance and considerably larger than the average for the line at the 3.3-MeV resonance. This finding is in accord with the observation, made before the Ge detector was available, that the resonance scattering per gamma ray in the incident beam increased considerably as one went from the 3.0- to the 3.3-MeV resonance.

For the 3.0-MeV resonance, which was used for most of the experiments, the width of the gamma line is 108.4 keV. This means that the average number of gamma rays per eV interval is $9.23\times10^{-6}N_T$. At the energy 4.403 MeV of the $Al^{27}$ level, $N(E)$, according to Fig. 2, is approximately 6% smaller, i.e., $N(4.403)=8.67\times10^{-6}N_T$. This number is less than 3% larger than the value $N(4.403)=8.4\times10^{-6}N_T$ used for the preliminary evaluation when the data taken with the Ge detector were not yet available.

[5] See, e.g., G. T. Ewan and A. J. Tavendale, Can. J. Phys. 42, 2286 (1964).

### D. Angular Distribution

Pulse-height distributions of the scattered radiation were measured at the 3.0- and the 3.3-MeV resonances for scattering angles of 95°, 115°, and 138°. The observed pulse-height distributions were then decomposed into the contributions from the different transitions. The statistical accuracy and reliability of these decompositions was sufficiently good only for the two most energetic transitions, the 4.4-MeV ground state transition and the 3.39-MeV transition to the 1.01-MeV $\frac{3}{2}^+$ state. The distributions obtained at the two different bombarding energies agreed within the statistical errors. This was taken as an indication that the possible polarization of the incident radiation played a negligible role.

The angular distribution for the 4.4-MeV ground state transition was found to be well represented by $W(\theta)=1+(0.30\pm0.05)P_2(\cos\theta)$. However, a small $P_4$ term ($A_4<0.07$) could not be ruled out. To obtain the counting rates for the 3.39-MeV transition, the 4.4-MeV line had to be subtracted from the measured pulse height distributions. This led to an additional uncertainty in the angular distribution for the 3.39-MeV line as reflected in the large error in the best fit $W(\theta)=1-(0.24\pm0.12)P_2(\cos\theta)$.

### E. Determination of $g\Gamma_0^2/\Gamma$

Equation (1) in Sec. IIC is conveniently arranged for the evaluation of the scattering experiment in terms of $g\Gamma_0^2/\Gamma$. The geometrical factor $G$ was calculated taking into account the angular distribution of the 4.4-MeV radiation and the experimentally observed self-absorption (from Sec. III, below). Using this value for $G$, the scattering experiment then yielded:

$$g\Gamma_0^2/\Gamma=(0.14\pm0.01)\ \text{eV}.$$

## III. SELF-ABSORPTION EXPERIMENTS

The geometry used for the measurement of the self-absorption of the resonant radiation was that of the 115° scattering experiment. Al absorbers, 0.34 and 0.96 in. thick, were placed between the source and scatterer and nearer to the source, and the fractional reduction of the resonance scattering was observed. The 0.96-in. absorber reduced the resonance effect by 36%, the 0.34-in. absorber caused a 15% reduction. The nonresonant absorption was subtracted experimentally by inserting a Mg absorber of matched electronic absorption when the "zero Al absorber" point was taken.

In analyzing the self-absorption experiment, the cross section was assumed to have the Doppler form $\sigma(E)=A\exp\{-[(E-E_R)/\Delta]^2\}$, since a preliminary estimate indicated that $\Gamma\ll\Delta$, where $\Delta=E_\gamma(2kT/Mc^2)^{1/2}=6.58$ eV is the thermal Doppler width of the 4.403-MeV absorption line. With these assumptions, a mean value

$$g\Gamma_0=(0.24\pm0.03)\ \text{eV}$$

was obtained for the product of the statistical weight ratio and the partial width of the 4.403-MeV ground state transition in $Al^{27}$.

## IV. CONCLUSIONS

### A. Spin of the 4.403-MeV Level

The nonisotropic angular distribution of the 4.403-MeV resonance radiation immediately excludes spin $\frac{1}{2}$ for the 4.403-MeV level. The rather strong 3.39-MeV transition to the 1.01-MeV spin $\frac{3}{2}$ level excludes spins $\geq\frac{9}{2}$. One is thus left with the six spin-parity combinations $\frac{3}{2}\pm$, $\frac{5}{2}\pm$, and $\frac{7}{2}\pm$.

With a spin assignment of $\frac{3}{2}$, the quadrupole transition to the 2.21-MeV $\frac{7}{2}^+$ state would have to be enhanced by at least a factor of 200. Since this exceeds any enhancement ever measured in a light nucleus, spin $\frac{3}{2}$ is considered ruled out. The absence of any appreciable branching to the 0.84-MeV $\frac{1}{2}^+$ excited state may be cited as an additional argument against spin $\frac{3}{2}$. However, since other selection rules may be effective, this argument is much weaker.

An assignment of $\frac{7}{2}^-$ to the 4.403-MeV level can be ruled out because it would lead to an unreasonably high enhancement of the 3.39-MeV $M2$ transition. The assignment $\frac{7}{2}^+$ would make the 3.39-MeV transition an electric quadrupole with an enhancement factor of 40. While such an enhancement is not very probable in light nuclei, it is not sufficiently large to permit one to rule out the $\frac{7}{2}^+$ assignment.

The angular distribution of the 4.4-MeV resonance radiation can be fitted with quadrupole-dipole mixing ratios $\delta_{4.4}^2\approx10^{-2}$ for either spin $\frac{5}{2}$ or $\frac{7}{2}$. These spins are also compatible with the observed angular distribution of the 3.39-MeV radiation.

For a $\frac{5}{2}$ assignment, the best fit to the observed angular distribution of the 4.4-MeV radiation is obtained with a quadrupole-dipole mixing amplitude $\delta_{4.4}=+0.13\pm0.06$. With this value of $\delta_{4.4}$ the experimental angular distribution for the 3.39-MeV radiation is reproduced if $\delta_{3.39}$ falls into the interval $-0.15<\delta_{3.39}<0.05$. These are certainly reasonable mixing amplitudes if the parity is positive, and for negative parity they may be accommodated with $M2$ enhancements which are smaller than ten. With a spin of $\frac{5}{2}$, the absence of the 3.56-MeV transition to the 0.84-MeV $\frac{1}{2}^+$ level is not surprising. Unless this quadrupole transition were enhanced by more than an order of magnitude, one would not expect to notice its affect on the pulse-height distribution (Fig. 1).

### B. Lifetime of the 4.403-MeV Level

Using the most probable spin value $\frac{5}{2}$, the ratio of the statistical factors becomes $g=1$, and the self-absorption experiment yields

$$\Gamma_0=(0.24\pm0.03)\ \text{eV}.$$

This width is comparable with other $M1$ widths in light nuclei and also with the widths encountered for slow $E1$ transitions.

Comparison of $\Gamma_0$ with the result of the scattering experiment (3$E$) leads to a branching ratio $\Gamma_0/\Gamma = 0.58\pm0.08$, in very good agreement with the ratio $\Gamma_0/\Gamma = 0.57\pm0.05$ obtained from the analysis of the pulse-height distribution (IIB). For the total width of the level, one finally has

$$\Gamma = (0.42\pm0.06)\text{ eV},$$

corresponding to a mean life

$$\tau_{\text{level}} = 1.57\times10^{-15}\text{ sec}.$$

### C. Spin of the 4.504-MeV Level

The absence of appreciable resonance scattering from the 4.504-MeV level of $Al^{27}$, which falls within the range of the $N^{15}(p,\alpha)C^{12}$ gamma line, makes it rather probable that the 4.504-MeV level has either spin $\frac{1}{2}$ or a spin $\geq \frac{9}{2}$.

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# Gamma-Gamma Directional Correlation in $Pr^{143}$

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The directional correlations of four $\gamma$–$\gamma$ cascades in $Pr^{143}$ fed from the decay of $Ce^{143}$ have been studied. The correlation functions for the 293–57, 232–493, 591–293, and the 668–57-keV cascades are found to be: $W(\theta_{293-57}) = 1+(0.112\pm0.009)P_2(\cos\theta)+(0.000\pm0.014)P_4(\cos\theta)$, $W(\theta_{232-493}) = 1-(0.176\pm0.008)P_2(\cos\theta) - (0.001\pm0.012)P_4(\cos\theta)$, $W(\theta_{591-293}) = 1+(0.146\pm0.015)P_2(\cos\theta)+(0.003\pm0.026)P_4(\cos\theta)$, and $W(\theta_{668-57}) = 1+(0.063\pm0.018)P_2(\cos\theta)$, respectively. Knowing the spin of the ground state of $Pr^{143}$ as $\frac{7}{2}^+$ and the recently measured spin of the ground state of $Ce^{143}$ as $\frac{3}{2}^-$, and from the analysis of the angular-correlation results combined with the log $ft$ values of $\beta$ transitions from $Ce^{143}$, the levels of $Pr^{143}$ have been assigned spins and parities as follows: ground state, $\frac{7}{2}^+$; 57 keV, $\frac{5}{2}^+$; 351 keV, $\frac{3}{2}^+$; 493 keV, $\frac{7}{2}^+$; 725 keV, $\frac{5}{2}^+$; 942 keV, $\frac{3}{2}^+$ or $\frac{5}{2}^+$; 1160 keV, $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$; and 1395 keV, $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

## I. INTRODUCTION

THE energy levels of $Pr^{143}$ populated from the decay of the 33-h $Ce^{143}$ have been investigated recently by detailed scintillation and coincidence studies.[1] Excited states of $Pr^{143}$ at 57, 351, 493, 725, 942, 1160, and 1395 keV were established. The measured spin[2] of the ground state of $Pr^{143}$ from atomic-beam studies is $\frac{7}{2}$. In order to investigate further the properties of the excited states and the nature of the gamma transitions from these states, gamma-gamma angular-correlation measurements have been made.

The angular correlation of the 293–57-keV cascade has been measured previously by Rao and Hans[3] and by Bożek *et al.*[4] The results have been reanalyzed by Graham *et al.*[5] using the multipolarities of these transitions as determined from internal-conversion studies and the measured value of the spin of $Pr^{143}$ as $\frac{7}{2}$. Since the contributions of the many higher-energy gamma rays,[1] in coincidence with the 293-keV $\gamma$ ray, have not been taken into account by these authors, it was necessary to remeasure the angular correlation of the 293–57-keV cascade by minimizing these contributions.

From the systematics of the neighboring odd-neutron nuclei the spin of the ground state of $Ce^{143}$ was expected to be $\frac{5}{2}^-$ or $\frac{7}{2}^-$ due to the coupling of three $f\frac{7}{2}$ neutrons outside the closed shell. Since the recent measurement[6] of the ground-state spin of $Ce^{143}$ shows it to be $\frac{3}{2}$, the spins of the excited states of $Pr^{143}$ inferred from the log $ft$ values of the $\beta$ transitions from $Ce^{143}$ are to be revised. This has been discussed in Sec. III.

## II. EXPERIMENTAL PROCEDURES AND RESULTS

The angular-correlation apparatus consisted of three scintillation detectors with NaI(Tl) crystals coupled to RCA 6810-A photomultipliers. Two of the counters were identical with 2-in.×2-in. crystals, while the third one was mounted with either a 1.5-in.×0.5-in. crystal when a 57-keV $\gamma$ ray was detected or a 1.5-in.×1.5-in. crystal for the 232- and 293-keV $\gamma$ rays. The three counters were mounted in a horizontal plane with their axes passing through the center where the source was kept. The distance of the detectors from the source was 7 cm in each case. The two identical detectors were kept fixed

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