Gamma Radiation from Low Levels of Al^{27}†

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The $Al^{27}(\alpha,\alpha'\gamma)$ reaction was investigated by using particle-gamma coincidence techniques and the 22-Mev alpha-particle beam from the Indiana University cyclotron. A 0.79 ± 0.03 Mev gamma-ray transition between the 3.0- and 2.21-Mev states of Al^{27} was observed. This result, together with other data, suggests that the 3.0- and 2.21-Mev states are the $9/2^+$ and $\frac{7}{2}^+$ members of a $K=\frac{5}{2}$ rotational band.

I. INTRODUCTION

ALMQVIST, Bromley, Gove, and Litherland have recently shown[1] that the rotational collective model gives a good qualitative description of many of the properties of the low-lying excited states of Al^{27}. The purpose of the present experiment was to investigate gamma-ray transitions from higher excited states of Al^{27} in order to test further the applicability of the collective model to this nucleus. A state at about 3.0 Mev excitation energy was found to decay strongly to the third excited state at 2.21 Mev. This result has a simple explanation in terms of the rotational collective model.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

The gamma radiations from Al^{27} were studied using the $Al^{27}(\alpha,\alpha'\gamma)$ reaction at a bombarding energy of $E_\alpha=22$ Mev. Standard fast-slow coincidence apparatus was arranged so that gamma rays in time coincidence with inelastically scattered alpha particles of a selected energy could be measured. In this way it is possible to study the decay of modes of individual excited states wherever they can be resolved by the particle detector.

The alpha-particle detector was a 10-mil thick $\frac{3}{4}$ in. diam CsI crystal placed $1\frac{1}{2}$ in. from the target at a forward angle of 30 deg from the beam direction. For the coincidence measurements, this crystal was covered by a $\frac{1}{4}$-in.$\times\frac{1}{2}$-in. slit collimator. The crystal was connected optically to an RCA type 6342 A multiplier phototube by a Lucite light pipe $1\frac{5}{8}$ in. long$\times\frac{3}{4}$ in. in diameter.

The gamma-ray detector was a Harshaw 3-in.$\times$3-in. NaI crystal mounted on a Du Mont type 6363 multiplier phototube. This detector was placed with its front face about 3 in. from the target perpendicular to the plane containing the beam and the particle detector.

Several precautions were taken to minimize background counts in the gamma-ray detector: (1) The NaI crystal was surrounded by 2 in. of lead, $\frac{1}{16}$ in. of cadmium, and 5 in. of boron-loaded paraffin. (2) The target chamber and both detectors were enclosed in a concrete hut with walls 15 in. thick. The 22-Mev alpha-particle beam from the cyclotron was collimated and stopped outside of this hut, so that the beam struck only the

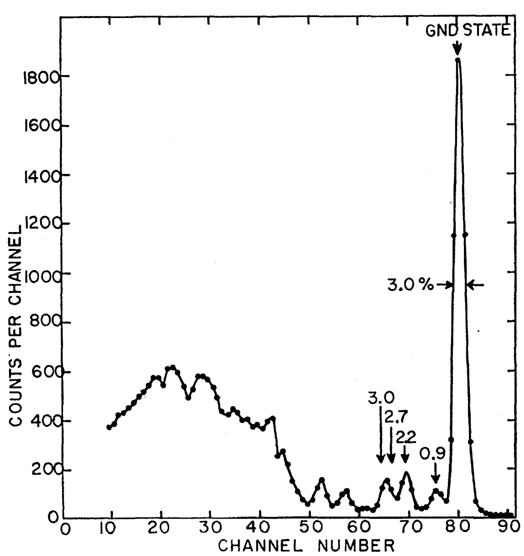

Fig. 1. Charged particle spectrum obtained with a 10-mil thick CsI crystal from the bombardment of a 0.2-mil aluminum foil with 22-Mev alpha particles.

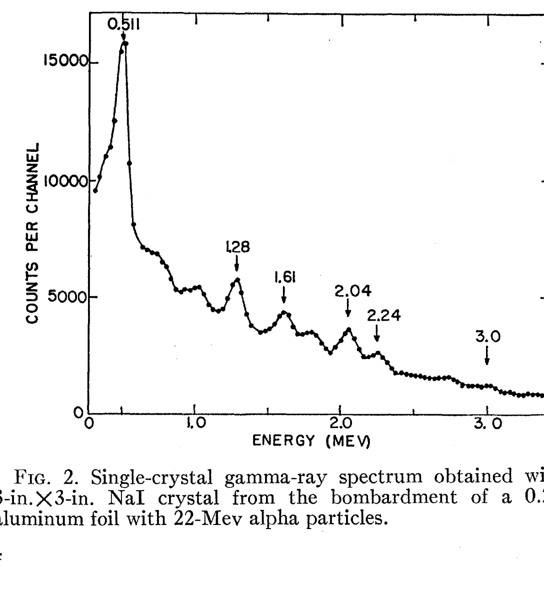

Fig. 2. Single-crystal gamma-ray spectrum obtained with a 3-in.$\times$3-in. NaI crystal from the bombardment of a 0.2-mil aluminum foil with 22-Mev alpha particles.

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* National Science Foundation Predoctoral Fellow.
[1] E. Almqvist, D. A. Bromley, H. E. Gove, and A. E. Litherland, Nuclear Phys. **19**, 1 (1960).

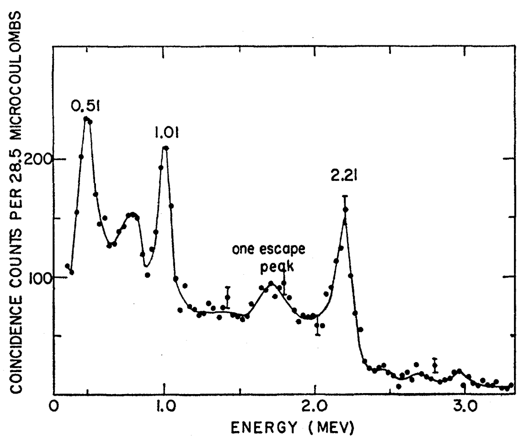

FIG. 3. Uncorrected gamma-ray spectrum coincident with inelastically scattered alpha particles corresponding to the 2.21-Mev state of Al^{27}.

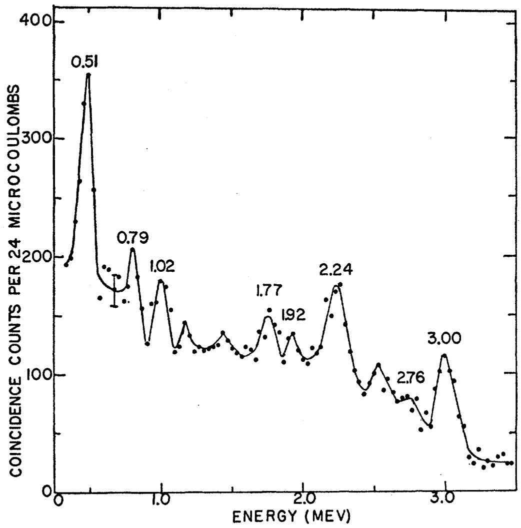

FIG. 4. Uncorrected gamma-ray spectrum coincident with inelastically scattered alpha particles corresponding to the 2.73-, 2.98-, and 3.00-Mev states of Al^{27}.

target (a 0.2-mil thick aluminum foil) inside the hut. (3) The cyclotron beam current was reduced to the very small level (~0.001 μa) used in this experiment largely at the arc source before acceleration, rather than by collimators after acceleration. This was done by reducing the opening in the arc cone from a normal size of $\frac{1}{8}$-in.×$\frac{1}{4}$-in. to a $\frac{1}{16}$-in. diam hole. Under the above conditions, background counts in the gamma-ray detector were negligible.

III. EXPERIMENTAL RESULTS

Figure 1 shows the charged particle spectrum obtained from the bombardment of a 0.2-mil aluminum foil with 22-Mev alpha particles. The peaks in the upper channels are due to scattered alpha particles. Some of the counts in the lower channels are due to deuterons from the $Al^{27}(\alpha,d)Si^{29}$ reaction. The inelastic alpha peaks are identified with the known[2] excited states of Al^{27} at 0.842, 1.013, 2.213, 2.732, 2.977, and 3.001 Mev. The states at 0.842 and 1.013 Mev and also at 2.732, 2.977, and 3.001 Mev are unresolved. The spectrum shown in Fig. 1 was taken with a $\frac{1}{16}$-in. diam collimator over the CsI crystal. For the coincidence measurements, a larger $\frac{1}{2}$-in.×$\frac{1}{4}$-in. slit collimator was used giving 7.5% energy resolution for the elastic peak instead of the 3.0% shown in Fig. 1. Under these conditions, the 2.21-Mev peak was only slightly resolved from the 3.0-peak. It was still possible, however, to adjust the differential pulse-height analyzer window for the particle counter to accept predominantly inelastic scattered alpha particles corresponding to the 2.21-Mev state. The 2.73-, 2.98-, and 3.00-Mev states were studied together.

Figure 2 shows the single-crystal gamma-ray spectrum obtained with a 3-in.×3-in. NaI detector from the bombardment of a 0.2-mil aluminum foil with 22-Mev alpha particles. This spectrum is uncorrected for background effects, which were small. The strongest peaks at 1.28 and 2.04 Mev are probably from the $Al^{27}(\alpha,d\gamma)Si^{29}$ reaction.[3] The peak at 2.24 Mev is probably from the $Al^{27}(\alpha,\alpha'\gamma)$ reaction. The 0.511- and 1.28-Mev gamma rays from an Na^{22} source were used for energy calibration of Fig. 2.

Figure 3 shows the gamma-ray spectrum in coincidence with inelastically scattered alpha particles corresponding to the 2.21-Mev state of Al^{27}. The total time required for collection of these data was 10 hr 45 min. No corrections have been applied for background or accidental coincidences. A true to accidental ratio of 8 is obtained by comparing Fig. 3 with Fig. 2. Figure 3 shows a strong peak corresponding to the ground state transition from the 2.21-Mev state. No cascade transitions to the 0.84- or 1.01-Mev states from the 2.21-Mev state were observed with an intensity as great as 20% that of the direct ground state transition. The 1.01-Mev peak is due to the inclusion of tails from the 1.01- and 2.73-Mev states within the window of the particle counter. The 0.511-Mev peak is due to accidental coincidences.

Figure 4 shows the uncorrected gamma-ray spectrum in coincidence with inelastically scattered alpha particles corresponding to the 2.73-, 2.98-, and 3.00-Mev states. The time required for this run was about $7\frac{1}{2}$ hr. This spectrum was decomposed into its individual line shapes

[2] D. J. Donahue, K. W. Jones, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **89**, 824 (1953); C. P. Browne, S. F. Zimmerman, and W. W. Buechner, *ibid.* **96**, 725 (1954); W. C. Porter, M. A. Rothman, and D. M. Van Patter, Bull. Am. Phys. Soc. **2**, 143 (1957).

[3] In both the $Al^{27}+\alpha$ and $F^{19}+\alpha$ reactions at 22-Mev bombarding energy, it is observed that the strongest gamma rays come from the $(\alpha,d\gamma)$ reaction. The $(\alpha,\alpha'\gamma)$ reactions are somewhat weaker, and the $(\alpha,p\gamma)$ and $(\alpha,n\gamma)$ reactions are very weak, in both cases. This is perhaps a general feature of alpha-induced reactions at this bombarding energy.

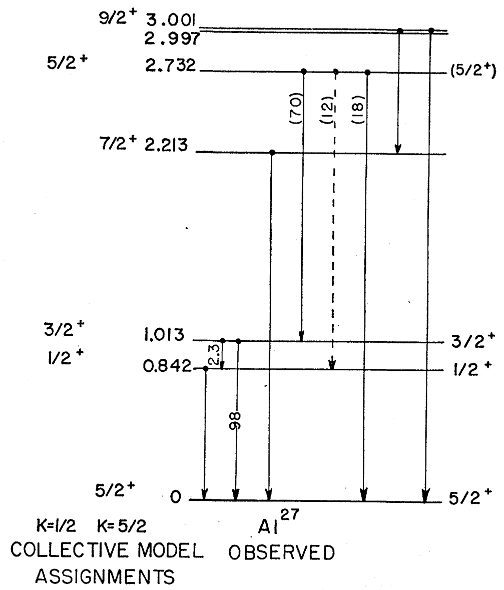

FIG. 5. Experimentally observed decay schemes of the low levels of Al^{27} and suggested collective model assignments.

using the data of Heath.[4] The gamma-ray energies and assignments obtained are listed in Table I. The unlabeled peaks in Fig. 4 are "escape" peaks from higher-energy gamma rays.

IV. DISCUSSION OF EXPERIMENTAL RESULTS

Figure 5 summarizes the gamma-ray decay modes of the low-lying states of Al^{27}. The 0.84- and 1.01-Mev states have been investigated in detail recently by Almqvist *et al.*[1] The strong ground state transition from the 2.21-Mev state has been observed by several investigators.[5–9] The upper limits obtained from the present experiment for the intensities of cascade transitions from the 2.21-Mev state agree with the results of Ranken, Bonner, Castillo-Bahena, Harlow, and Rabson.[9] Ranken *et al.*[9] have shown that the 2.73-Mev state decays predominately to the 1.01-Mev state. In Fig. 4 most of the counts corresponding to this transition at about 1.72 Mev are due to the one escape peak of the 2.21-Mev gamma ray. The ratio of the intensity of the 1.77 ± 0.05-Mev gamma ray to that of the 2.76 ± 0.06-Mev gamma ray obtained from Fig. 4 is 0.7. This number does not represent a branching ratio for the state, however, since the measurement was made at only one angle. According to Ranken *et al.*,[9] the branching ratio of the $2.73\rightarrow1.01$ Mev cascade to the ground state transition is equal to or greater than 3.8.

[4] R. L. Heath, Atomic Energy Commission Research and Development Rept. IDO-16408, 1957 (unpublished).
[5] M. A. Rothman, H. S. Hans, and C. E. Mandeville, Phys. Rev. **100**, 83 (1955).
[6] R. B. Day, Phys. Rev. **102**, 767 (1956).
[7] I. L. Morgan, Phys. Rev. **103**, 1031 (1956).
[8] C. Van der Leun, P. M. Endt, J. C. Kluyver, and L. E. Vrenken, Physica **22**, 1223 (1956).
[9] W. A. Ranken, T. W. Bonner, R. Castillo-Bahena, M. V. Harlow, and T. A. Rabson, Phys. Rev. **112**, 239 (1958).

TABLE I. Energies and assignments of gamma rays from the reaction $Al^{27}(\alpha,\alpha'\gamma)$.

E_γ[a] (Mev)	Assignment
0.79 ± 0.03	2.977 or $3.001\rightarrow2.213$
1.02 ± 0.03	$1.013\rightarrow0$
1.77 ± 0.05	$2.732\rightarrow1.013$
1.92 ± 0.05(?)	$2.732\rightarrow0.842$
2.24 ± 0.06	$2.213\rightarrow0$
2.76 ± 0.06	$2.732\rightarrow0$
3.00 ± 0.06	2.977 or $3.001\rightarrow0$

[a] Uncorrected for possible Doppler shifts.

There is a slight indication in Fig. 4 for a $2.73\rightarrow0.84=1.89$ Mev transition. This is not definitely established and is labeled in Table I with a question mark and in Fig. 5 by a dotted line.

It is seen from Fig. 4 that either the 2.98- or 3.00-Mev state decays to the 2.21-Mev state, giving rise to a 0.79-Mev cascade gamma ray. The ground state transition from one of the states at 3.0 Mev is also observed. The energy measurement is not precise enough to establish whether it is from the 2.98- or 3.00-Mev state.

It is not possible to obtain accurate branching ratios from the present data because (1) the coincidence measurements were taken at only one angle, and (2) the efficiency of the coincidence apparatus varied with gamma-ray energy, falling off rapidly at low energies. The branching ratio numbers given in Fig. 5 for the 2.73-Mev state are, therefore, placed in parentheses to indicate some uncertainty.

V. COLLECTIVE MODEL INTERPRETATION OF RESULTS

The significant new result of the present experiment is the establishment of the strong $3.0\rightarrow2.21$ Mev transition. This result has a simple interpretation in terms of the rotational collective model[10] which has been found[1] to be successful in describing the low-lying levels of Al^{27}. On the basis of this model, the proton configuration, external to the O^{16} core, for Al^{27} is expected to be $(\frac{1}{2})^2(\frac{3}{2})^2\frac{5}{2}$, and the neutron configuration $(\frac{1}{2})^2(\frac{3}{2})^2(\frac{5}{2})^2$, for values of the distortion parameter η between 0 and +3 (prolate). This gives $\frac{5}{2}+$ spin and parity for the ground state of Al^{27} in agreement with experiment. The $\frac{7}{2}+$ member of the rotational band based on the $\frac{5}{2}+$ ground state is predicted[1] to be at about 1.85-Mev excitation energy. A low-lying $9/2^+$ state is also predicted. The 0.84-, 1.01-, and 2.73-Mev states are interpreted[1] to be the $\frac{1}{2}+$, $\frac{3}{2}+$, and $\frac{5}{2}+$ members of a $K=\frac{1}{2}$ rotational band based on the proton configuration $(\frac{1}{2})^2(\frac{3}{2})^2\frac{1}{2}$.

A possible explanation for the strong $3.0\rightarrow2.21$ Mev

[10] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.—fys. Medd. **27**, No. 16 (1953); S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.—fys. Medd. **29**, No. 16 (1955).

gamma-ray transition is that the 2.21-Mev state and either the 2.98- or 3.00-Mev state are the $\frac{7}{2}^+$ and $9/2^+$ members of the $K=\frac{5}{2}$ rotational band as indicated in Fig. 5. The 3.0-Mev state would then be expected to decay strongly to the 2.21-Mev state by an $M1$ transition and more weakly to other states because of higher spin differences.

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Coupled Square Well Model for Elastic Scattering*

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A simple model for s-wave neutron scattering is provided by representing the scattering potential by a pair of coupled square wells. Such a model produces resonances that exhibit the giant resonance effect. We have compared isolated resonances given by this model for two types of coupling with the Breit-Wigner formula. We find that for a resonance with a width of about 16 kev, the resonant part of the scattering does indeed have the Breit-Wigner form. The resonance energy is found to be considerably shifted from the energy of the bound state that exists in the zero-coupling-strength limit. Also the nonresonant part of the scattering amplitude is considerably different from both the hard-sphere scattering amplitude and the zero-coupling-strength limit scattering amplitude. This last result is in accord with expectations based on R-matrix theory.

IN a recent paper,[1] a simple model (denoted hereafter by A) for the elastic scattering of s-wave neutrons was discussed. Sharp resonances were introduced into the slowly varying optical-model scattering amplitude by weakly coupling a second mode of motion (the compound-nucleus mode) to the motion in the incident channel. It was shown that the reduced widths of the sharp resonances in the model exhibit the giant-resonance behavior which has been observed in nuclear scattering. Here we shall consider the application of the Breit-Wigner single-level formula to these sharp resonances. The results will be compared with those for another type of simple model (B) for the same process.

The scattering interaction for model A consists of a square-well potential modified by allowing transmission through the origin through a square barrier to another well. The second square well provides the second (compound nucleus) mode of motion. Explicitly, the potential has the form

$$\begin{aligned} V(r)&=0, & r&>R_1\\ &=-V_1, & 0&<r<R_1\\ &=V_2, & -R_2&<r<0\\ &=-V_3, & -(R_2+R_3)&<r<-R_2\\ &=\infty, & r&<-(R_2+R_3). \end{aligned} \tag{1}$$

For $r>R_1$ the radial wave function has the form $r\psi=e^{-ikr}-\eta e^{ikr}$. The amplitude of the outgoing wave, η, can be written in terms of the hard sphere amplitude $\eta_{\text{H.S.}}$ as

$$\eta=-\eta_{\text{H.S.}}S,$$

where

$$\begin{aligned} \eta_{\text{H.S.}}&=e^{2i\xi},\quad \xi=-kR_1,\\ S&=e^{2i\Phi},\quad \Phi=-\arctan(Z/\Gamma_1),\\ Z&=\frac{\cot K_1R_1-b}{1+b\cot K_1R_1}=\cot(K_1R_1+y),\\ b&=\tan y=b_0/\Gamma_2,\\ b_0&=\frac{\tanh K_2R_2+\Gamma_3\tan K_3R_3}{1+\Gamma_3\tan K_3R_3\tanh K_2R_2}, \end{aligned} \tag{2}$$

K_1, K_2, K_3 are the wave numbers for the particle in potentials V_1, V_2, V_3 and $\Gamma_1=k/K_1$, $\Gamma_2=K_2/K_1$, $\Gamma_3=K_2/K_3$.

The scattering amplitude is proportional to $A=1-\eta=1+\eta_{\text{H.S.}}S$. In the limit of zero coupling ($V_2=\infty$) we have $\Gamma_2=\infty$, so b becomes zero and $Z=\cot K_1R_1$ which gives the slowly varying amplitude A_0 due to the square well V_1. For weak coupling ($K_2\gg k$, K_1, K_3), Γ_2 is large and it becomes possible to write b_0 in the form:

$$\begin{aligned} b_0&=1-\delta\beta,\\ \delta&=2e^{-2K_2R_2}\ll 1,\\ \beta&=(1-\Gamma_3\tan K_3R_3)/[1+(1-\delta)\Gamma_3\tan K_3R_3]. \end{aligned} \tag{3}$$

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† On leave of absence from Rice University, Houston, Texas.

[1] W. Tobocman and D. E. Bilhorn, Phys. Rev. **115**, 1275 (1959).