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Gamma ray linear polarization measurements for ^{29}Al[†]

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Levels of ^{29}Al were populated with the ^{26}Mg$(\alpha, p)^{29}$Al reaction at $E_\alpha = 11.26$ MeV. The linear polarizations of γ rays emitted in the decays of the 1.40-, 1.75-, 2.22-, and 2.87-MeV levels were measured. The polarization measurements are consistent with known spin-parity assignments for the 1.40- and 2.87-MeV levels, respectively. When combined with previously available information they indicate an assignment of $\frac{3}{2}^+$ for the 2.22-MeV level and $\frac{7}{2}^+$ $(\frac{3}{2}^+)$ for the 1.75-MeV level.

[NUCLEAR REACTION ^{26}Mg(α, p), $E = 11.26$ MeV; measured linear polarization, $p\gamma$ coincidence. ^{29}Al levels deduced J, π. Enriched target.]

I. INTRODUCTION

An appreciable amount of evidence now exists for the applicability of the strong-coupling Nilsson model for the nuclei in the $2s$-$1d$ shell. Whereas nuclei near $A = 22$ are characterized by strong prolate deformations there is reason to believe that the region near $A = 29$ is one of transition from prolate to oblate shapes.[1] Such considerations have stimulated several experimental studies of ^{29}Al. A considerable amount of spectroscopic information has been gathered on the low-lying levels by means of reaction studies,[1-4] and angular correlation,[1,5,6] lifetime,[7,8] and β decay[9] measurements. There remain, however, a number of ambiguities in the spin assignments of the low-lying levels, and these uncertainties make a detailed evaluation of nuclear models difficult. For example, the applicability of the strong-coupling Nilsson model has been examined by several investigators,[1,6,7,9] and rotational bands have been proposed subject to various assumptions for the spin assignments. More recently, shell-model calculations have been made[10] with the Oak Ridge-Rochester codes. The level ordering predicted in the shell-model work is different in detail from that assumed in the Nilsson-model comparisons and, while the results of Ref. 9 are in disagreement with the shell-model order, additional information is needed for detailed comparisons.

The fact that the angular correlation measurements do not allow one to distinguish between various assumed spins for the excited states of ^{29}Al is related to the high ground state spin ($J = \frac{5}{2}$) which results in a characteristic insensitivity of the γ-ray angular distribution to the spin of the emitting level. Since the linear polarization of the γ radiation is also dependent on the spins and multipole ratios involved, it seemed reasonable that the measurements of the linear polarization of the γ rays emitted in the ^{26}Mg$(\alpha, p\gamma)^{29}$Al reaction could resolve some of the existing ambiguities. This was the purpose of the present experiment.[11]

II. EXPERIMENTAL PROCEDURE

A. Polarimeter

The five-crystal Compton polarimeter used in this experiment is similar to that of Taras and Matas[12] and consists of five identical 3.8-cm by 5.1-cm NaI detectors mounted as shown in Fig. 1. In all measurements reported here the polarimeter was positioned in the horizontal plane at 90° with respect to the incoming beam with the face of the center crystal at 15 cm from the target. The four outside crystals were shielded from direct radiation from the target by 5 cm of lead. Acceptable events were those producing a coincidence between the particle detector, the center (C) crystal, and either the horizontal (H) or vertical (V) crystals, but not both. For each valid coincidence, five digital words were generated corresponding to the particle energy, the center-crystal recoil-electron energy, the scattered γ energy (detected by H or V crystal), the time signal, and the routing information identifying the scattering plane as horizontal or vertical. A DDP-224 computer was used to collect the digital information and store it, event by event, on magnetic tape. For analysis the tape was read back, and pulse-height spectra were produced corresponding to the sum of center and vertical or center and horizontal detector pulses subject to selected windows on the proton and time

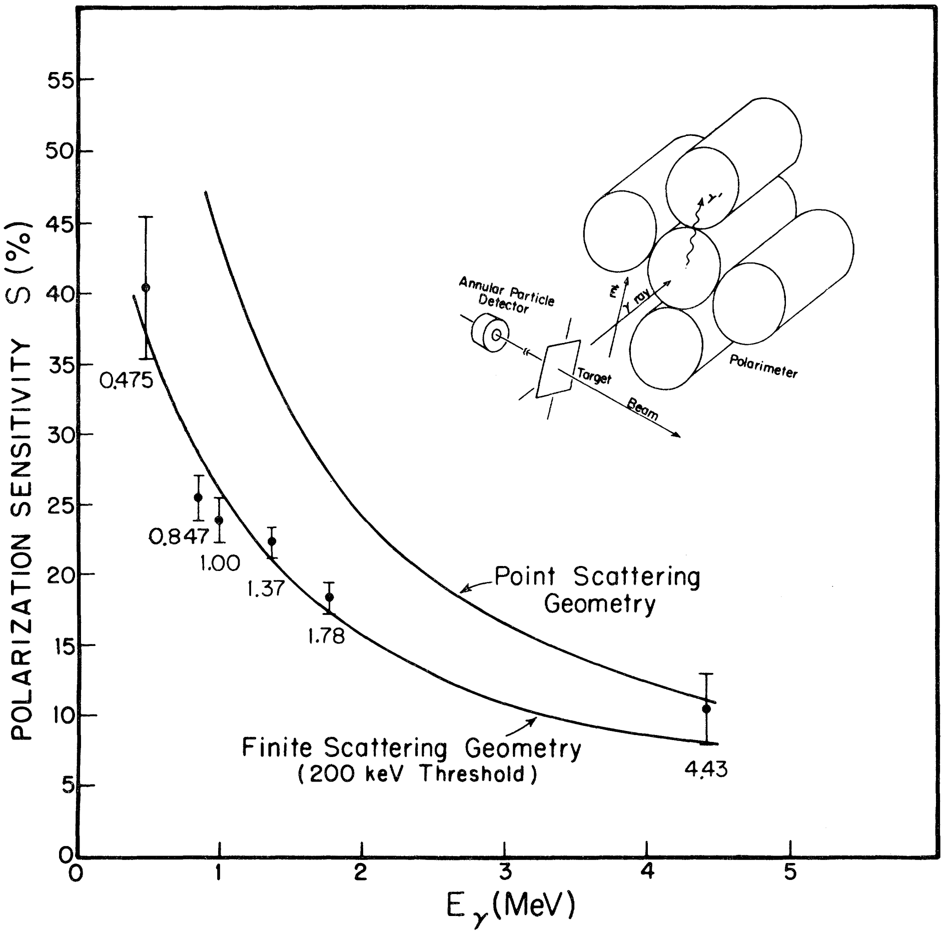

FIG. 1. Calculated and measured polarization sensitivity for the five-crystal polarimeter (shown in insert). The upper curve represents the results predicted for point detectors.

spectra and appropriate thresholds set on the center and outside detector signals.

A symmetry check of the polarimeter made with the unpolarized radiation from a radioactive source gave zero instrumental asymmetry to within 1%.

B. Calibration procedure

The experimental asymmetry A measured by the polarimeter is defined as $A=(N_v-N_h)/(N_v+N_h)$, where N_v and N_h are the number of γ rays scattered into the vertical and horizontal detectors, respectively. This asymmetry is proportional to the linear polarization. That is, $A=SP$ in which $P=(J_{\parallel}-J_{\perp})/(J_{\parallel}+J_{\perp})$, where $J_{\parallel}$ and $J_{\perp}$ are the intensities of γ rays with electric vectors respectively parallel and perpendicular to the reaction plane.[13] The proportionality factor S is called the polarization sensitivity and is dependent on the γ-ray energy and the geometry of the polarimeter.

For point detectors $S=(d\sigma_{90}-d\sigma_0)/(d\sigma_{90}+d\sigma_0)$, where $d\sigma_0$ and $d\sigma_{90}$ are the differential cross sections for Compton scattering parallel and perpendicular to the polarization vector of the incident radiation. Note that in this definition S is always positive.

For the five-crystal polarimeter used in the present work, S was determined both theoretically and experimentally. The calculation[14] was carried out by using the Klein-Nishina scattering formula and integrating over the finite geometry of the polarimeter subject to a threshold energy for detection of the recoil electron in the center detector and also a threshold on the scattered photon energy. The imposition of these thresholds effectively restricts the range of acceptable scattering angles.[15,16]

The polarization sensitivity was also determined experimentally by measuring the asymmetry ratio A for several γ rays of known linear polarization, again subject to the above-mentioned thresholds.

TABLE I. Results of the polarimeter calibration measurements.

Reaction [a]	γ ray energy (MeV)	Predicted polarization	Measured asymmetry ratio A	Measured sensitivity S	Calculated sensitivity
^{56}Fe($pp'\gamma$)	0.847	0.56 ± 0.03	0.142 ± 0.006	0.254 ± 0.015	0.283
^{48}Ti($pp'\gamma$)	0.985	0.58 ± 0.03	0.138 ± 0.008	0.239 ± 0.015	0.258
^{24}Mg($pp'\gamma$)	1.37	0.78 ± 0.03	0.174 ± 0.006	0.224 ± 0.010	0.208
^{28}Si($pp'\gamma$)	1.78	0.80 ± 0.03	0.146 ± 0.006	0.183 ± 0.010	0.173
^{12}C($pp'\gamma$)	4.43	0.97 ± 0.02	0.101 ± 0.024	0.104 ± 0.025	0.08
$^{60}\mathrm{Co}\xrightarrow{\beta^-}{}^{60}\mathrm{Ni}$	0.45–0.50	0.39 ± 0.03	0.157 ± 0.023	0.403 ± 0.066	0.36

[a] The bombarding energies were 3.01 MeV for ^{56}Fe, ^{48}Ti, ^{24}Mg, and ^{28}Si and 5.37 MeV for ^{12}C.

The sensitivity calibration measurements were made with γ rays detected in singles from inelastic proton scattering from the first 2^+ states of even-even target nuclei. Since $2^+ \rightarrow 0^+$ radiation is pure $E2$, the polarization of γ rays detected at 90° can be obtained from the expression[13]

$$P=\frac{\frac{3}{2}A_2+\frac{5}{8}A_4}{1-\frac{1}{2}A_2+\frac{3}{8}A_4},$$

where A_2 and A_4 are the normalized angular distribution coefficients.

The reactions used for calibration in the present work are listed in Table I along with the γ energies, the polarizations predicted from the measured angular distributions, the experimental asymmetry ratios A, and the experimental and calculated sensitivities. The 0.475 MeV calibration point was obtained by Compton scattering through (70 ± 10)° of the 1.37-MeV radiation from a ^{60}Co source. The resulting polarization sensitivities are plotted as a function of energy in Fig. 1 along with the calculated sensitivity curve. The agreement was considered to be satisfactory with no arbitrary adjustment of the curve.

C. Measurements on ^{26}Mg($\alpha, p\gamma$)^{29}Al

In order to populate the low-lying levels of ^{29}Al, a 100 μg/cm^2 target enriched to 99.7% in ^{26}Mg (prepared by vacuum deposition onto a 20 μg/cm^2 ^{12}C foil) was bombarded by a 11.26 MeV α-particle beam from the Triangle Universities Nuclear Laboratory FN tandem Van de Graaff accelerator. An annular silicon detector covered by a 0.05 mm Mylar foil to stop the elastic α particles was used to detect protons emitted at angles between 175° and 185° with respect to the beam. The spectrum of proton pulses measured in coincidence with γ rays detected by the polarimeter is shown in Fig. 2. It is evident that the first four excited states of ^{29}Al are populated with reasonable strength.

Coincidence data were accumulated over a period of 38 h. On reading the magnetic tapes, pulse-

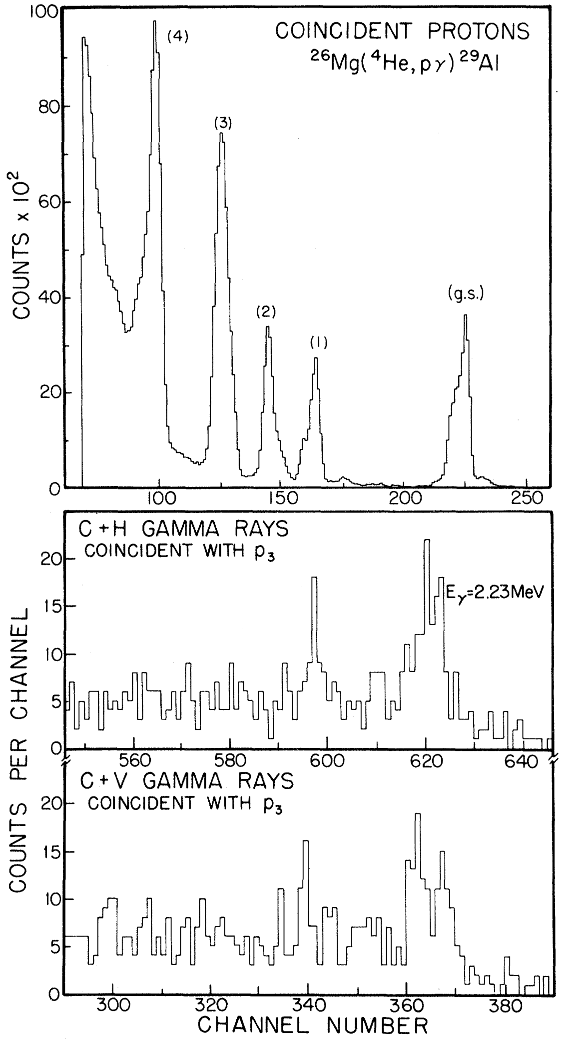

FIG. 2. The upper pulse-height spectrum is that of the particles from the ^{26}Mg($\alpha, p\gamma$)^{29}Al reaction in coincidence with γ rays detected by the polarimeter. The lower two spectra are those of the summed center-plus-horizontal and center-plus-vertical detectors of the polarimeter in coincidence with the ^{29}Al third-excited-state proton group.

TABLE II. Comparison of predicted and measured γ-ray polarizations for $^{26}Mg(\alpha,p\gamma)^{29}Al$.

$E_i \to E_f$				δ		Polarization (90°)	
(MeV)	$J_i^\pi \to J_f^\pi$	Ref. 1	Ref. 5	Ref. 6	Adopted	Predicted	Measured
1.40 → 0	$\frac{1}{2}^+ \to \frac{5}{2}^+$					0	-0.41 ± 0.34
1.75 → 0	$\frac{3}{2}^+ \to \frac{5}{2}^+$	$0.22^{+0.10}_{-0.06}$	$0.14^{+0.26}_{-0.18}$	$-0.15 < \delta < 0.21$	$0.22^{+0.10}_{-0.06}$	$-0.43 < P < 0.27$	
		$2.2^{+0.4}_{-0.5}$	$2.75^{+2.92}_{-1.27}$	$2.4 < \delta < 19.0$	$2.2^{+0.4}_{-0.5}$	$-0.79 < P < -0.72$	
	$\frac{5}{2}^+ \to \frac{5}{2}^+$	$0.20^{+0.06}_{-0.07}$	0.34 ± 0.15	$0.29 < \delta < 0.67$	$0.20^{+0.06}_{-0.07}$	$0.79 < P < 0.87$	
	$\frac{7}{2}^+ \to \frac{5}{2}^+$	-0.24 ± 0.03	$-0.19^{+0.09}_{-0.08}$	$-0.23 < \delta < 0.03$	-0.24 ± 0.03	$-0.78 < P < -0.71$	-0.36 ± 0.43
2.22 → 0	$\frac{3}{2}^+ \to \frac{5}{2}^+$	$0.24 < \delta < 2.0$	$0.11 < \delta < 2.99$	$0.14 < \delta < 0.53$	$0.14 < \delta < 0.53$	$-0.59 < P < -0.25$	-0.29 ± 0.34
				$1.2 < \delta < 2.6$	$1.2 < \delta < 2.6$	$-0.81 < P < -0.71$	
	$\frac{5}{2}^+ \to \frac{5}{2}^+$	0.16 ± 0.08	$0.21^{+0.15}_{-0.16}$	$0.10 < \delta < 0.32$	$0.10 < \delta < 0.32$	$0.75 < P < 0.88$	
		$-2.3^{+0.5}_{-0.6}$	$-2.45^{+0.34}_{-0.43}$				
2.87 → 1.40	$\frac{3}{2}^+ \to \frac{1}{2}^+$	$0.00^{+0.13}_{-0.08}$	0.00 ± 0.21				
				$-0.09 < \delta < 0.25$	$0.00^{+0.13}_{-0.08}$	$-0.36 < P^{a} < -0.25$	-0.51 ± 0.22 [a]
		1.7 ± 0.5	$1.80^{+1.27}_{-0.71}$	$1.03 < \delta < 2.14$	1.7 ± 0.5	$0.23 < P^{a} < 0.37$	

[a] Effective polarization for the mixture of the two unresolved γ rays from the 2.87 → 1.40 → 0 cascade.

height spectra were generated for the summed $C+H$ or $C+V$ detector pulses subject to appropriate windows on the coincident proton spectra. Accidental coincidences were subtracted. An example of the $C+H$ and $C+V$ sum spectra is shown in Fig. 2. The full-energy peaks in each of these spectra were summed after subtraction of background, and the asymmetry ratios were calculated. The corresponding polarizations were then determined by using the sensitivity from the calibration curve in Fig. 1.

III. RESULTS OF THE POLARIMETER MEASUREMENTS

In the collinear geometry employed in the present experiment, the $^{26}Mg(\alpha,p)$ reaction populates only the $m=\pm\frac{1}{2}$ magnetic substates in ^{29}Al. The linear polarization of the γ rays emitted at a given angle thus depends only on the spin-parity of the levels and the multipole mixing ratio of the γ rays. The procedure used in this work was to calculate the polarization of the γ rays emitted at 90° for different assumed values of the initial and final level spins and for the corresponding values of the mixing ratios indicated by the angular correlation results of earlier workers. A comparison of these predictions is carried out in Table II. Columns 3, 4, and 5 list the mixing ratios from the angular correlation experiments of Refs. 1, 5, and 6 for each value of $J_i \to J_f$ consistent with these

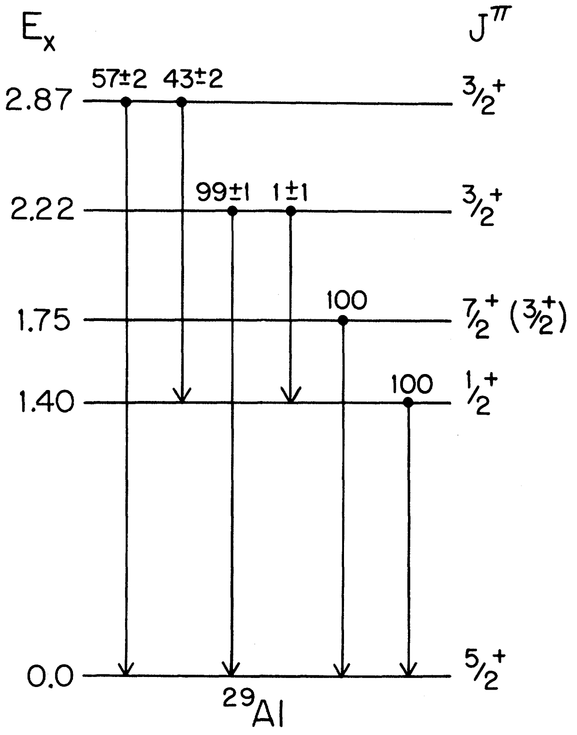

FIG. 3. Energy level diagram for ^{29}Al lower states, showing spin-parity assignments consistent with the results of the present work and earlier published work. The level energies are those of Ref. 9, and the branching ratios are those of Ref. 7.

TABLE III. Spin-parity assignments, multipole ratios, and implied transition strengths consistent with results of the present work and previously available information.

$E_i \rightarrow E_f$ (MeV)	$J_i^\pi \rightarrow J_f^\pi$	δ [a]	τ [c] (fs)	$M1$ strength ($\times 10^{-2}$ W.u.)	$E2$ strength (W.u.)
$1.75 \rightarrow 0$	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	-0.24 ± 0.03	80 ± 40	6.8	6.2
	$(\frac{3}{2}^+) \rightarrow \frac{5}{2}^+$	$0.22^{+0.10}_{-0.06}$		6.9	5.3
$2.22 \rightarrow 0$	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	$0.14 < \delta < 0.53$	110 ± 50	2.3 [b]	2.5 [b]
		$1.2 < \delta < 2.6$		0.6 [b]	19.9 [b]
$2.87 \rightarrow 1.40$	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$0.0^{+0.13}_{-0.08}$	150 ± 70	3.0	≤ 2.4

[a] From column 6, Table II.

[b] Calculated from midrange value of δ.

[c] From Ref. 8.

results and those of Refs. 7 and 9. An adopted set of mixing ratios and the respective ranges of linear polarization consistent with them are listed in columns 6 and 7. The values of $P(90°)$ listed in column 7 correspond to even parity for the emitting level. An assumption of odd parity (not ruled out for the 1.75-MeV level by earlier measurements) would change the sign but not the magnitude of the calculated polarization. The measured polarizations are listed in column 8 and the conclusions indicated for each level are discussed below.

A. 1.40-MeV level

The known $\frac{1}{2}^+$ assignment for the 1.40-MeV first excited state[4] requires that the 1.40-MeV γ ray be unpolarized. The measured polarization $P(90°) = -0.49 \pm 0.34$ is in poor agreement with the expected value but, in view of the large error in P, was considered to be consistent with the $\frac{1}{2}^+$ assignment.

B. 1.75-MeV level

The polarization obtained for the $1.75 \rightarrow 0$ MeV transition is $P(90°) = -0.36 \pm 0.43$. It is apparent from Table II that this result eliminates assignments of $\frac{5}{2}^+$ and $\frac{7}{2}^-$ but is consistent with $\frac{3}{2}^+$, $\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{7}{2}^+$. Further restrictions on the assignment are discussed in Sec. IV.

C. 2.22-MeV level

The measured polarization for the $2.22 \rightarrow 0$ MeV transition is $P(90°) = -0.29 \pm 0.34$. Table II shows that this result definitely rules out $\frac{5}{2}^+$. Since measurements of Ref. 9 have previously restricted J^π to $\frac{3}{2}^+$ or $\frac{5}{2}^+$, the 2.22-MeV level can be assigned $J^\pi = \frac{3}{2}^+$ rigorously.

D. 2.87-MeV level

The NaI(Tl) polarimeter is incapable of resolving the 1.47 and 1.40 MeV γ rays resulting from the $2.87 \rightarrow 1.40 \rightarrow 0$ MeV cascade. The measured polarization for the unresolved mixture is $P(90°) = -0.51 \pm 0.22$, in agreement with the value indicated in Table II for the known $\frac{3}{2}^+$ assignment for the 2.87 MeV level. Of the two values of the multipole ratio allowed by the angular correlation results, the polarization measurement selects the value $0.00^{+0.13}_{-0.08}$ for the $2.87 \rightarrow 1.40$ transition.

IV. SYNTHESIS OF PRESENT AND PREVIOUS INFORMATION

Some additional restrictions on the spin and parity of the 1.75-MeV level are made possible by utilization of the lifetime measurements of Beck *et al.*[8] (listed in column 4 of Table III) together with the experimental mixing ratios to calculate limits on the transition strengths. If the lower limit for $|\delta|$ from Ref. 1 and the upper limit on τ from Ref. 8 are used, the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ possible assignments imply $M2$ transition strengths >50 and >30 Weisskopf units (W.u.) respectively, and can therefore[17] be rejected. It has previously been pointed out in Ref. 7 that $J^\pi = \frac{3}{2}^+$ can be ruled out subject to the assumption that the even-parity[2] 3.58-MeV level has $J = \frac{9}{2}$ since this would imply a $3.58 \rightarrow 1.75$ MeV $M3$ transition competing strongly (84%) with a higher energy $3.58 \rightarrow 0$ MeV transition. The best evidence for $J\ (3.58) = \frac{9}{2}$ is the analysis by Jones[4] of total cross-section data based on a statistical compound nucleus theory. The same analysis favors $J\ (1.75) = \frac{7}{2}$ and $J\ (2.23) = \frac{3}{2}$—all consistent with the results of the present work. Thus, for the 1.75-MeV level, $J^\pi = \frac{7}{2}^+\ (\frac{3}{2}^+)$.

V. CONCLUSIONS

The ^{29}Al levels up through 2.87 MeV are shown in Fig. 3. The present work, together with information previously available, has led to assignments of $\frac{3}{2}^+$ for the 2.22-MeV level and $\frac{7}{2}^+\ (\frac{3}{2}^+)$ for the 1.75-MeV level. The $\frac{3}{2}^+$ assignment for the 2.87-MeV level is confirmed with $\delta = 0.00^{+0.13}_{-0.08}$ selected from the two possibilities quoted in Ref. 1. These conclusions are summarized in Table III along with the implied transition strengths.

The level order is in agreement with that assumed in the Nilsson model interpretations of Refs. 1, 6, 7, and 9. The shell-model calculations of de Voigt and Wildenthal, on the other hand, reverse the order of the $\frac{3}{2}^+$ and $\frac{7}{2}^+$ levels.

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