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Linear polarization measurements of γ rays from ^{64}Zn

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The linear polarizations of ^{64}Zn γ rays, produced in the ^{59}Co(^{7}Li,$2n$) reaction with $E_{^7\text{Li}} = 18$ MeV, have been measured with a Ge(Li) two-crystal Compton polarimeter. These polarization values were used with previously obtained γ-ray angular distribution measurements to make unique parity assignments for several states. The 641- and 1619-keV γ rays have been found to be predominantly $E1$ transitions, and odd parity has been assigned to the levels at 2999 keV (3^-), 3925 keV (5^-), 4635 keV (7^-), 4981 keV (7^-), and 5681 keV (8^-). Even parity assignments have been confirmed for levels at 991 keV (2^+), 2736 keV (4^+), 3994 keV (6^+), and 4237 keV (6^+). Also, the spin assignments for levels at 2307 keV (4^+) and 4635 keV (7^-) have been confirmed.

[NUCLEAR REACTIONS ^{59}Co(^{7}Li,$2n$)^{64}Zn, $E=18$ MeV; measured linear polarization of γ rays; deduced parities and multipole mixing ratios in ^{64}Zn.]

I. INTRODUCTION

Linear polarization of γ rays has been known for some time to be sensitive to the change in parity between the initial and final states of the γ-ray transition,[1-3] and measurements of linear polarization have been used by a number of investigators for the purpose of deducing parities of nuclear states.[3-6]

As part of a program to systematically study nuclei in the $A \approx 70$ mass range, we have investigated high-spin states of ^{64}Zn by measurements of excitation functions, γ-γ coincidences, γ-ray angular distributions, and lifetimes. This work has been published previously.[7] We have now carried out linear polarization measurements on γ rays from ^{64}Zn to determine the parities of several states that were uncertain or undetermined with our previous experiments. As a result, the parity assignments of several states have been confirmed. We have also confirmed the spin assignments of two states for which the γ-ray distribution alone was compatible with two different assignments, but when taken with the polarization, strongly favored only one.

II. EXPERIMENTAL PROCEDURE

A 25-mg/cm^2 thick target of ^{59}Co on a 0.013-cm Ni backing was bombarded with 18-MeV ^{7}Li ions from the ORNL EN tandem accelerator. High-spin states of ^{64}Zn were populated via the ^{59}Co(^{7}Li,$2n$)^{64}Zn reaction.

Linear polarization of the deexcitation γ rays was measured with a γ-ray polarimeter placed 16 cm from the target at an angle of 90° to the beam direction. The polarimeter, developed at The Johns Hopkins University, has been described elsewhere.[5] It consists of two true-coaxial Ge(Li) detectors mounted in a single cryostat, which can be rotated so that the two detectors lie either in the reaction plane or on a line perpendicular to it.

An acceptable event consisted of a γ ray that was Compton scattered in either detector and then fully absorbed in the other. Thus, the signals from the two detectors were required to be in coincidence, and were summed to give the full γ-ray energy which was recorded in a 4096-channel analyzer. The energy resolution of the sum spectra was ~5 keV for a 1-MeV γ ray, as compared to ~3 keV for a single detector.

The polarization was deduced from the asymmetry between the count rate with the polarimeter at 0° and 90° to the reaction plane. To minimize the effects of possible efficiency changes, the polarimeter was rotated at intervals during the data taking. Three spectra at 0° and three at 90° were taken alternately and then summed. The total beam current for each spectrum was measured with a current integrator and used for normalization.

III. ANALYSIS

Let the probability of emission of a γ ray from an aligned state at an angle of 90° to the alignment axis be $W(\phi)$, where ϕ is the angle which the polarization vector $\vec{E}$ makes with the reaction plane. Then, following Frauenfelder and Steffen,[2] we define the degree of polarization by

$$P=[W(0^\circ)-W(90^\circ)]/[W(0^\circ)+W(90^\circ)]. \qquad (1)$$

For mixed quadrupole/dipole transitions, the polarization can be given[1,4] in terms of the angular distribution coefficients, A_2 and A_4, as

$$P=\pm[3(A_2+b_2)+1.25A_4]/(2-A_2+0.75A_4), \qquad (2)$$

where

$$b_2=\frac{-8A_2\delta F_2(12J_iJ_f)}{3[F_2(11J_iJ_f)+2\delta F_2(12J_iJ_f)+\delta^2F_2(22J_iJ_f)]}. \qquad (3)$$

The functions $F_k(L_1L_2J_iJ_f)$ are standard (e.g., Ref. 8). The multipole mixing ratio $\delta=\langle J_f|L_2|J_i\rangle/\langle J_f|L_1|J_i\rangle$ is defined in the phase convention of Biedenharn and Rose.[9] The sign in Eq. (2) is positive for $E2/M1$ admixtures (no parity change) and is negative for $M2/E1$ admixtures (parity change).

The experimentally measured asymmetry in the counting rate is defined as

$$\Delta=[N(90^\circ)-N(0^\circ)]/[N(90^\circ)+N(0^\circ)], \qquad (4)$$

where $N(0^\circ)$ and $N(90^\circ)$ are the counting rates with the polarimeter axis oriented, respectively, parallel and perpendicular to the reaction plane.

Since Compton scattering is most probable in a direction perpendicular to the $\vec{E}$ vector, $N(90^\circ)$ will be greater than $N(0^\circ)$ when P is positive. P can be related to Δ by a positive efficiency Q defined by $Q=\Delta/P$, which must be determined for the polarimeter and experimental conditions. The calibration was effected using 29 γ rays from ^{64}Zn, ^{70}Ge, ^{78}Kr, ^{194}Pt, and ^{196}Pt that ranged in energy from 250 to 2000 keV. These were all known stretched $E2$ γ rays whose polarization P could be calculated from their angular distribution coefficients using Eq. (2), and for which Δ was measured experimentally. The efficiencies for these γ rays were fitted by least squares to the function

$$Q=Q_0(aE_\gamma+b), \qquad (5)$$

where a and b are adjustable parameters, and Q_0 is the efficiency for the ideal case of two point detectors. This can be shown[2,4] from the Klein-Nishina formula to be

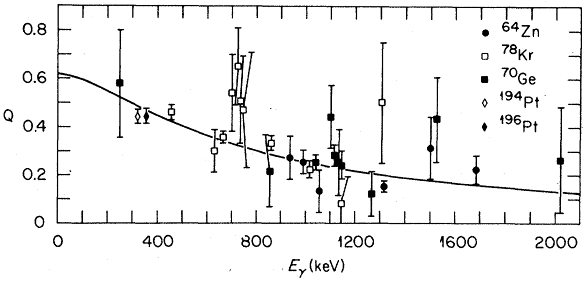

FIG. 1. γ-ray polarimeter efficiency Q vs E_γ. The experimentally determined efficiencies are all from stretched $E2$ transitions, and the curve is a least-squares fit to these data points using Eqs. (5) and (6).

$$Q_0=[1+(E_\gamma/m_0c^2)]/[1+(E_\gamma/m_0c^2)+(E_\gamma/m_0c^2)^2] \qquad (6)$$

for a scattering angle of 90°. The least-squares fit gave

$$a=(-4\pm5)\times10^{-5}\ \text{keV}^{-1}$$

and

$$b=0.62\pm0.03.$$

Figure 1 shows a graph of Q as a function of E_γ, calculated with these parameters, and also the data points with which the least-squares fit was obtained.

The dependence of the theoretical angular distribution coefficients on the physical parameters is given by

$$A_k=\alpha_k(J_i)B_k(J_i)[F_k(11J_iJ_f)+2\delta F_k(12J_iJ_f)+\delta^2F_k(22J_iJ_f)]/(1+\delta^2), \qquad (7)$$

where $B_k(J_i)$ is the statistical tensor for a system of nuclei completely aligned in a plane perpendicular to the beam direction, and $\alpha_k(J_i)$ is the attenuation coefficient of alignment (e.g., see Ref. 8). It is assumed that the population of magnetic substates can be described by a Gaussian function involving only one parameter, so $\alpha_4(J_i)$ is uniquely related to $\alpha_2(J_i)$. Since this assumption is dependent on the details of the reaction mechanism, spin assignments based on this analysis are not completely rigorous. However, values of α_4 extracted from the angular distributions of $\Delta J=2$, pure quadrupole, transitions are in good agreement with this assumption,[10] and we believe that results based on it are valid.

For possible values of the initial and final spins, the parameter $\alpha_2(J_i)$ and the multipole mixing ratio δ were changed in steps, and a goodness-of-fit index χ^2 was calculated at each step, where

$$\chi^2=\sum_{i=1}^{3}\chi_i^2=[A_{2_{\rm exp}}-A_{2_{\rm cal}}(J,\delta,\alpha)]^2/\epsilon_{A_2}{}^2+[A_{4_{\rm exp}}-A_{4_{\rm cal}}(J,\delta,\alpha)]^2/\epsilon_{A_4}{}^2+[P_{\rm exp}-P_{\rm cal}(J,\delta,\alpha)]^2/\epsilon_P{}^2\,. \tag{8}$$

$P_{\rm cal}$ was calculated with Eqs. (2) and (3) using the $A_{2_{\rm cal}}$ and $A_{4_{\rm cal}}$ calculated with Eq. (7). The experimental angular distribution coefficients, $A_{2_{\rm exp}}$ and $A_{4_{\rm exp}}$, were obtained from Ref. 7. In that work, γ-ray intensities $W(\theta)$ were measured at three laboratory angles, 0, 45, and 90°. $A_{2_{\rm exp}}$ and $A_{4_{\rm exp}}$ were calculated directly from the equation

$$W(\theta)=I_\gamma[1+A_{2_{\rm exp}}g_2P_2(\cos\theta)+A_{4_{\rm exp}}g_4P_4(\cos\theta)]\,, \tag{9}$$

with $\theta=0$, 45, and 90°. The corrections for the finite solid angle subtended by the Ge(Li) detector were calculated to be $g_2=0.99$ and $g_4=0.97$. ϵ_{A_k}, the uncertainty in $A_{k_{\rm exp}}$, was calculated from the equation

$$\epsilon_{A_k}{}^2=\sum_i\left(\frac{\partial A_{k_{\rm exp}}}{\partial W(\theta_i)}\right)^2\epsilon_{W(\theta_i)}{}^2\,, \tag{10}$$

where $\epsilon_{W(\theta)}$ includes the uncertainty in fitting the background under the photopeak. ϵ_P, the uncertainty in $P_{\rm exp}$, includes both the uncertainty in the asymmetry Δ and the uncertainty in the efficiency Q.

A value of χ^2 which would be exceeded with a probability of less than 1% in the event of a legitimate fit to the data was taken to exclude that combination of parameters. The value of χ^2 with this probability of occurring is determined by the number of degrees of freedom, that is, the number of experimental quantities minus the number of free parameters. Here, there are three experimental quantities, $A_{2_{\rm exp}}$, $A_{4_{\rm exp}}$, and $P_{\rm exp}$, and two parameters, δ and α_2. However, α_2 is not completely free, since it is physically restricted to values between zero and one, and to values less than those of levels higher in the cascade. Consequently, we chose to use two degrees of freedom to calculate the confidence limits for χ^2 (and one degree of freedom in fits involving only angular distributions).

IV. RESULTS

The results are presented in Table I. The first column gives the transition energy. The second column gives the initial and final spin and parity assignment obtained from previous excitation function and angular distribution studies[7] and from the present linear polarization measurements. The third and fourth columns give the angular distribution coefficients. The fifth column gives the experimentally measured polarization. The sixth column gives the polarization calculated from the experimental A_2 and A_4 using Eq. (2). This calculation was made for the transitions identified as stretched $E2$. For these transitions, $\delta=\infty$, $b_2=0$ in Eq. (2), and the calculation is independent of the choice of initial and final spins, but the sign will be positive for $E2$ or $M1$ transitions, and negative for $M2$ or $E1$ transitions. The seventh column gives the multipole mixing ratio

TABLE I. Angular distribution and polarization results from the ^{59}Co(^{7}Li, $2n$) ^{64}Zn reaction with $E_{^7Li}=18$ MeV.

E_γ (keV)	$J_i^\pi\rightarrow J_f^\pi$	$A_{2_{\rm exp}}$	$A_{4_{\rm exp}}$	$P_{\rm exp}$	$P_{\rm cal}^{\rm c}$	$\delta^{\rm d}$	Multipolarity
641.3	$7^-\rightarrow6^+$	$-0.29\pm0.04^{\rm b}$	$0.04\pm0.02^{\rm b}$	0.33 ± 0.06		-0.01 ± 0.03	$E1$
$770.5^{\rm a}$	$3^-\rightarrow4^+$ $4^+\rightarrow4^+$	0.00 ± 0.04	-0.01 ± 0.04	0.25 ± 0.12		-0.10 ± 0.04 -0.54 ± 0.12	$M2/E1$ $E2/M1$
807.4	$2^+\rightarrow2^+$	$-0.15\pm0.02^{\rm b}$	$-0.00\pm0.02^{\rm b}$	0.11 ± 0.03		-1.3 ± 0.3	$E2/M1$
936.7	$4^+\rightarrow2^+$	0.13 ± 0.02	0.00 ± 0.02	0.21 ± 0.06	0.21 ± 0.04	∞	$E2$
991.2	$2^+\rightarrow0^+$	0.14 ± 0.02	-0.01 ± 0.02	0.22 ± 0.03	0.22 ± 0.04	∞	$E2$
1056.3	$7^-\rightarrow5^-$	0.28 ± 0.02	-0.05 ± 0.02	0.26 ± 0.18	0.46 ± 0.04	∞	$E2$
1315.3	$4^+\rightarrow2^+$	$0.30\pm0.02^{\rm b}$	$-0.06\pm0.02^{\rm b}$	0.38 ± 0.06	0.50 ± 0.04	∞	$E2$
1500.6	$6^+\rightarrow4^+$	0.25 ± 0.05	-0.04 ± 0.03	0.7 ± 0.3	0.41 ± 0.10	∞	$E2$
1618.5	$5^-\rightarrow4^+$	-0.05 ± 0.06	-0.01 ± 0.02	0.44 ± 0.18		0.12 ± 0.04	$M2/E1$
1687.0	$6^+\rightarrow4^+$	0.25 ± 0.03	-0.05 ± 0.02	0.55 ± 0.15	0.40 ± 0.06	∞	$E2$
1799.4	$2^+\rightarrow0^+$	0.12 ± 0.03	-0.03 ± 0.03	0.0 ± 0.3	0.17 ± 0.05	∞	$E2$
2007.0	$3^-\rightarrow2^+$	0.05 ± 0.10	-0.09 ± 0.10	-0.2 ± 0.5			$M2/E1$
$2086.9^{\rm a}$	$3^-\rightarrow2^+$	0.21 ± 0.08	-0.04 ± 0.08	0.2 ± 0.5			$M2/E1$
	$4^+\rightarrow2^+$				0.33 ± 0.16	∞	$E2$

[a] Since $J^\pi=3^-$ or 4^+ for the 3078-keV level, δ and the multipolarity are given for each of these possible spins.

[b] Obtained via the ^{51}V(^{16}O, $p2n$) ^{64}Zn reaction.

[c] $P_{\rm cal}$ was calculated assuming a pure multipole transition with no change in parity.

[d] δ was calculated using $A_{2_{\rm exp}}$, $A_{4_{\rm exp}}$, and $P_{\rm exp}$.

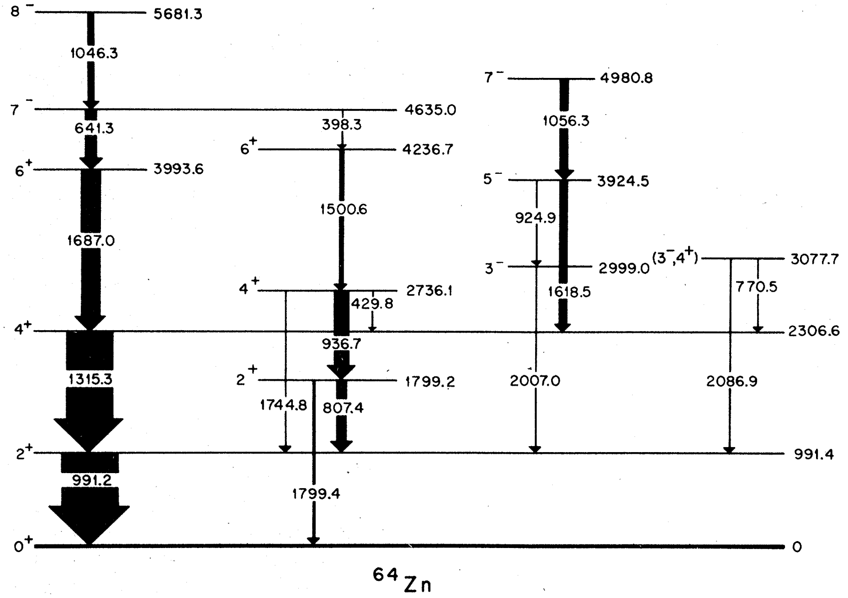

FIG. 2. Levels and transitions of ^{64}Zn. Energies of transitions are in keV and have uncertainties of ± 0.4 keV. The basis for some of the parity assignments is discussed in Sec. IV.

δ calculated from the experimental value of P_{exp} with Eqs. (2) and (3); experimental values for A_2 and A_4 are used in Eq. (2). Since Eq. (3) is quadratic in δ, two values are obtained. The one selected is the one which agrees with the δ obtained from a χ^2 fit of the angular distributions and polarization. Note that since the experimental A_2 and A_4 values are used, the δ obtained here using the polarization measurement does not depend on any assumptions about the parameter α_2. The last column gives the multipolarity of the transition.

We see good agreement between the experimental and calculated polarization values for the stretched $E2$ transitions. This provides strong evidence that they are $E2$ rather than $M2$, since in the latter case P_{cal} would have the opposite sign.

The level scheme for ^{64}Zn is shown in Fig. 2. The earlier angular distribution and excitation function measurements[7] did not uniquely establish the parities of the 4635- and 2999-keV levels, or the spin and parity of the 3078-keV level. We shall consider each of these cases now.

The 4635-keV level is deexcited by the 641-keV γ ray, which has a measured polarization of 0.33 ±0.06. Figure 3 shows a graph of χ^2 versus arctan δ for the angular distribution data only, with a fixed value of $\alpha_2 = 0.85$. Here, initial spins $J = 4$, 6, and 8 can be ruled out, but $J = 5$ and 7 are fitted equally well. Figure 4 shows a graph of χ^2 versus arctan δ for the angular distribution and polarization measurements, again with a fixed value of $\alpha_2 = 0.85$. Here, positive parities can be ruled out immediately, and $J^\pi = 7^-$ is clearly favored over $J^\pi = 5^-$. This establishes the spin and parity of the 4635-keV level as $J^\pi = 7^-$. Since the 1046-keV γ ray that feeds this level was found to be an $E2$ transition,[7] the parity of the 5681-keV level is also negative. This is a good example of a case where knowledge of the polarization plus the angular distribution permitted a unique spin assignment, while knowledge of the angular distribution alone did not.

It may happen that for one value of α_2, one initial spin and parity give the best minimum χ^2, while for another value of α_2, a different initial spin and parity give the best minimum χ^2. In Fig. 5, for each value of α_2, a δ was found which minimized χ^2, and this minimum χ^2 was plotted as a function of α_2. It should be noted that δ is not held constant, but is varied to give the minimum χ^2 at each point. In general, χ^2 will have a minimum for two values of δ, as can be seen in Figs. 3 and 4. This is the reason that there are two branches for each initial spin value in Fig. 5. Here, one branch results from values of δ whose magnitude is greater than one, and the other branch results from values whose magnitude is less than one. Figure 5 shows that $J^\pi = 7^-$ is clearly favored over $J^\pi = 5^-$, even though the latter falls slightly below the arbitrary 1% limit for some values of α_2.

The levels at 2999-, 3925-, and 4981-keV are

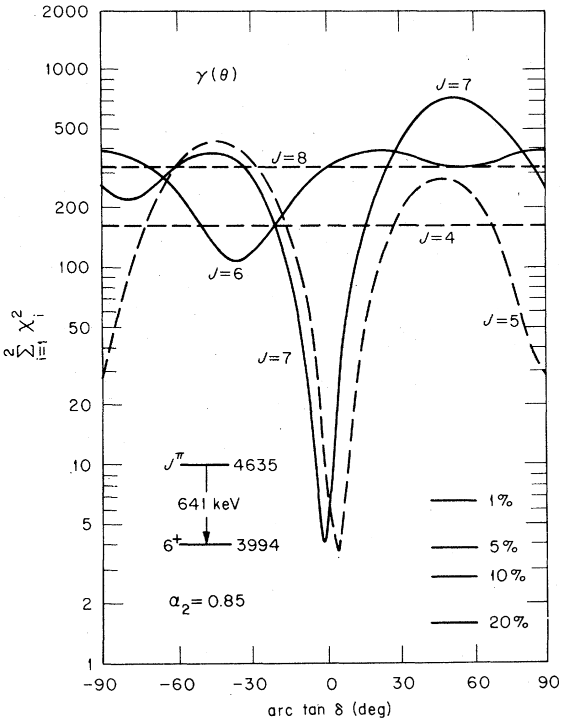

FIG. 3. Comparison between experimental and theoretical results for the angular distribution only of the 641-keV γ ray as a function of δ for $a_2 = 0.85$. For the initial spins of $J = 4$ and 8, δ properly has only the values $\pm\infty$, and χ^2 should be shown as points at arctan $\delta = \pm 90°$. χ^2 for these spins is shown as a line only to aid in making a comparison with χ^2 for the other spins. The numbers in percent are the confidence limits.

expected to have the same parity since the transitions between them are identified as stretched $E2$.[7] A parity change for the 1056-keV transition is in fact ruled out by its polarization measurement (see Table I). We previously reported[7] the angular distribution coefficients of the 1619-keV γ ray, measured via the ${}^{51}\mathrm{V}({}^{16}\mathrm{O},p2n){}^{64}\mathrm{Zn}$ reaction, to be consistent with an initial spin of $J = 5$ and a mixing ratio $\delta = -5.4 \pm 0.7$. This large δ suggested an $E2$ transition, implying positive parity for the 3925-keV level. However, we had a known problem with the 1619-keV γ ray in the earlier work in that substantially different angular distribution results were obtained for it from two different reactions. Also, for reasons discussed in this reference,[7] negative parity was expected.

With the present polarization measurement for the 1619-keV γ ray obtained via the ${}^{59}\mathrm{Co}({}^{7}\mathrm{Li},2n){}^{64}\mathrm{Zn}$ reaction, and with the angular distribution coefficients obtained via this same reaction, we find that, for an initial spin of $J = 5$, a change of parity is strongly favored. This result can be seen in Fig. 6, which shows a graph of χ^2 versus arctan δ.

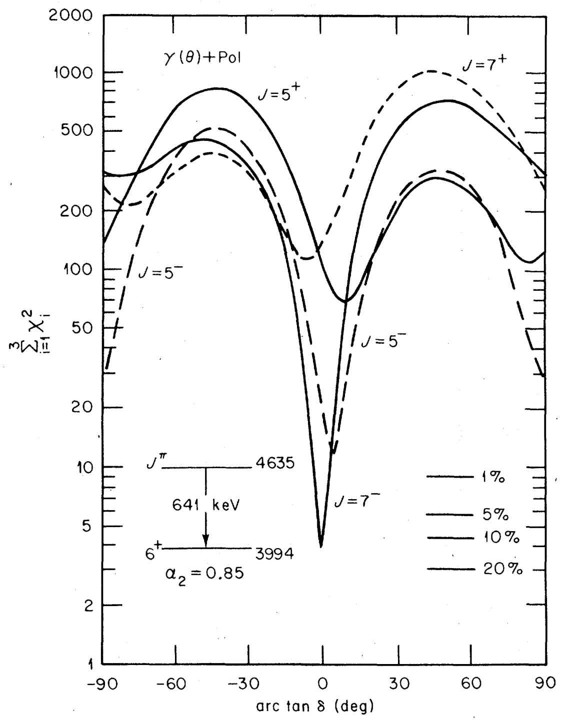

FIG. 4. Comparison between experimental and theoretical results for the angular distribution and polarization of the 641-keV γ ray as a function of δ for $a_2 = 0.85$. The numbers in percent are the confidence limits.

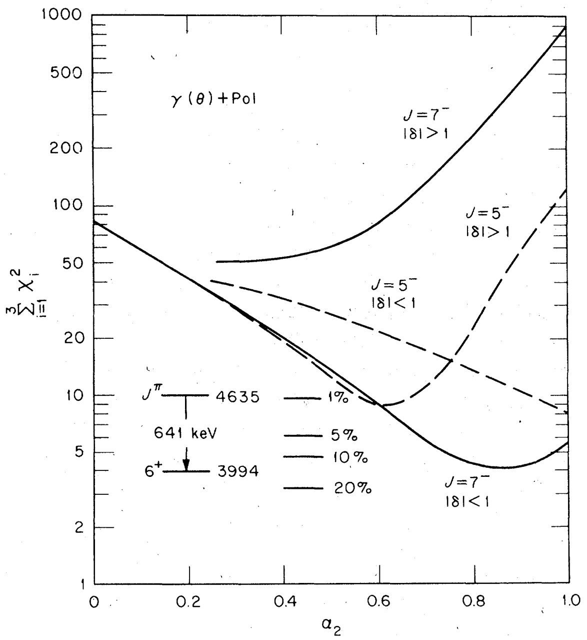

FIG. 5. Comparison between experimental and theoretical results for the angular distribution and polarization of the 641-keV γ ray as a function of a_2 for the δ which minimizes χ^2. The numbers in percent are the confidence limits.

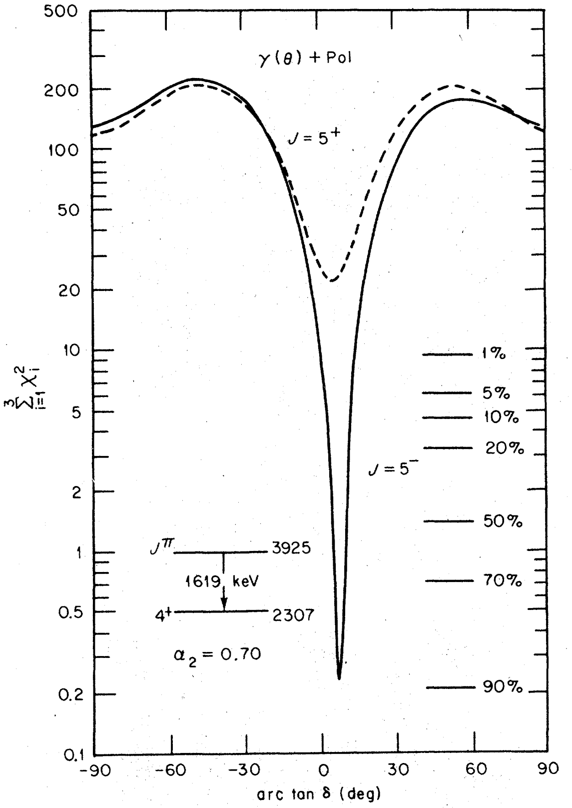

FIG. 6. Comparison between experimental and theoretical results for the angular distribution and polarization of the 1619-keV γ ray as a function of δ for $\alpha_2 = 0.70$. The numbers in percent are the confidence limits.

$J^\pi = 5^-$ is clearly preferred for the initial spin and parity, and $\delta = 0.12 \pm 0.04$ indicates that the transition is predominantly $E1$.

We therefore conclude that the levels at 2999, 3925, and 4981 keV have odd parity. Other groups report odd parity for the 2999-keV level.[11-14] A possible explanation of the differences in δ and the angular distribution results obtained via the two reactions is that the 3925-keV level is actually a degenerate doublet. However, the fact that the branching ratio for the 1619- and 925-keV γ rays is the same, within experimental error, for both reactions, does not support this hypothesis.

The spin and parity of the 3078-keV level were limited to $J^\pi = 3$ or 4^+ by the angular distribution measurements.[7] The polarization of the 2087-keV γ ray contributed nothing new due to its large uncertainty. The polarization of the 771-keV γ ray was compatible with a spin of $J = 3$ or 4, but for spin of $J = 3$, strongly favored negative parity. Thus, the spin and parity of the 3078-keV level are limited to $J^\pi = 3^-$ or 4^+. Systematics favor $J^\pi = 4^+$, since no neighboring nucleus is known to have two 3^- states this low in energy.

The polarization results rule out a parity change for the 937-, 991-, 1056-, 1315-, 1501-, and 1687-keV transitions and thus confirm the earlier parity assignments of the levels from which these transitions occur. In the case of the 1315-keV transition, the angular distribution is compatible with a spin assignment $J = 2$ or 4 for the 2307-keV level. For $J = 2$, however, the polarization result is consistent only with a parity change with a value of $\delta = 2.2 \pm 0.2$, which implies a predominantly $M2$ transition. Since an $M2$ transition is not consistent with the short lifetime of this state,[7] the present result confirms the $J^\pi = 4^+$ assignment for the 2307-keV level.

V. DISCUSSION

The spacing of the 4981-, 3925-, and 2999-keV levels, and the $E2$ enhancements[7] of the 1056- and 925-keV γ rays connecting them, suggest that these levels may be members of an odd-parity collective band. This might be similar to the octupole rotational band reported in ^{74}Se (Ref. 15). The energies of the 3925- and 4981-keV levels are similar to those of the 5^- and 7^- levels in ^{66,68}Zn and ^{68,70}Ge (Refs. 16–18, and 10, respectively) with the difference, however, that in each of these nuclei a 6^- state is observed between the 5^- and 7^- states. It is possible that if an analogous 6^- state exists in ^{64}Zn, it is very close to the 4981-keV level, and consequently is populated very weakly.

The $E2$ enhancement[7] of the 1046-keV γ ray suggests that the 8^- 5631-keV level may possibly be a member of a collective band with the 7^- 4635-keV level as the bandhead. However, it should be noted that shell model calculations do predict reasonably well the $E2$ enhancements for the lower levels.[7]

In conclusion, it is seen that linear polarization measurements provide an extremely useful adjunct to γ-ray angular distributions in determining parities and spins of nuclear levels.

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