Linear-polarization measurements of the reaction γ rays from $^{96}Zr(^{18}O, 4n\gamma)^{110}Cd$†

A. H. Lumpkin and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York 11973

K. A. Hardy
The Johns Hopkins University, Baltimore, Maryland 21218
Florida International University, Miami, Florida 33144

Y. K. Lee
The Johns Hopkins University, Baltimore, Maryland 21218
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The strong linear polarizations of the deexcitation γ rays from the $^{96}Zr(^{18}O, 4n\gamma)^{110}Cd$ reaction at 60 MeV were measured using a Ge(Li) two-crystal Compton polarimeter. Previous experiments with this reaction resulted in the identification of a side band feeding into the known 4^+ and 6^+ states via two dipolar γ rays from states with spins 5 and 7 and with energies of 996 and 399 keV, respectively. These two dipole transitions were found to be $E1$. Several other known quadrupole transitions were found to be $E2$. Thus we assign odd parity to the levels at 2538 keV (5^-), 2878 keV (7^-), and 3344 keV (9^-). The feasibility of such measurements with this polarimeter is discussed.

[NUCLEAR REACTIONS $^{96}Zr(^{18}O, 4n\gamma)$, $E = 60$ MeV; enriched ^{96}Zr target. Linear polarizations of ^{110}Cd γ rays measured.]

I. INTRODUCTION

The high alignments of nuclear states following (HI, xn) reactions result in anisotropic angular distributions relative to the beam direction and strong linear polarizations of the deexcitation γ rays. Since the letter of Diamond *et al.* on such nuclear alignment,[1] in-beam reaction γ-ray spectroscopy has emphasized angular distribution measurements as a tool for multipolarity assignments and determinations of spin changes. It is evident that linear-polarization measurements are a valuable complement to such studies since they provide a convenient means for determining the parity of the multipole radiation. The energy resolution and polarization sensitivity of a Ge(Li) two-crystal Compton polarimeter described previously makes such studies feasible.[2-4]

In the present experiment, the reaction γ rays from $^{96}Zr(^{18}O, 4n\gamma)^{110}Cd$ were studied. Previous γ-γ coincidence measurements and angular-distribution measurements resulted in the identification of an $L = 2$ cascade from spin 14 to the ground state. In addition, a side band was found to feed into the known 4^+ and 6^+ states from states of spin 5 and 7 with dipolar γ rays of 996 and 399 keV, respectively.[5] The angular-distribution coefficients were consistent with pure or near pure multipoles so linear-polarization measurements should be direct parity measurements. The parity of the side band would then be determined.

II. EXPERIMENTAL

The $^{96}Zr(^{18}O, 4n\gamma)^{110}Cd$ reaction was used to populate high-spin states in ^{110}Cd nuclei. The Brookhaven National Laboratory MP tandem Van de Graaff facility was utilized to produce a 100-nA beam of $^{18}O^{6+}$ ions at 60 MeV for bombardment of the enriched ^{96}Zr metal target. During the experiment the polarimeter was 10 cm from the target and at 90° to the beam direction. Each of the two crystals comprising the polarimeter had an active volume of 4 cm^3. The signals from the crystals were amplified, summed in a summing amplifier, and applied through a linear gate and biased amplifier to a multichannel analyzer. To select the Compton events of interest, a coincidence in time was required between the energy deposited by the Compton electron in the scattering crystal and the energy absorbed from the scattered photon in the analyzing crystal. With a constant-fraction timing technique, time resolutions of about 25 nsec were achieved and the required condition to "open" the linear gate was provided so that summed coincidence spectra would be accumulated. A system similar to this is described in Ref. 2. Summed coincidence spectra were taken alternately with the plane containing the two polarimeter detectors oriented at 0 and 90° to the reaction plane. A total of 20 experimental runs were made, 10 at 0° and 10 at 90°, with an over-all energy resolution of about 4 keV at 400 keV to 7 keV at 1 MeV. The spectra were normalized to the integrated beam current, and the normalization was checked with the singles counting rates in the polarimeter and in a separate monitor detector and the unpolarized 511-keV radiation from the target activity.

III. RESULTS

The natural reference plane for a discussion of the γ-ray linear polarizations[6,7] is the plane defined by the ion beam direction and the γ-ray direction (the reaction plane). Polarization is then $P = J_{\parallel}/J_{\perp}$, the ratio of the number of γ rays emitted with their electric vectors parallel and perpendicular to the reaction plane, respectively. Experimentally one measures the quantity $N = N_0/N_{90} = N_{\parallel}/N_{\perp}$, the ratio of the coincidence counting rates when the plane of the detectors is parallel and perpendicular to the reaction plane. P and N are connected through the relation

$$\frac{N_{\parallel}}{N_{\perp}} = \frac{P+R}{PR+1},$$

where R is the asymmetry ratio of the polarimeter. R is a measure of the sensitivity of the system to linear polarization when account is taken of the finite size of the detectors. For ideal geometry (point detectors), $R = d\sigma_{90}/d\sigma_0$ is the ratio of the differential cross sections for Compton scattering perpendicular and parallel to the polarization vector of the incident photon. Since the Klein-Nishina formula[6] predicts the preferential scattering of γ rays at right angles to the plane of polarization, R is greater than one and its value depends on the incident photon energy and the Compton scattering angle. This means that for γ rays polarized in the reaction plane $P > 1$, but $N < 1$ due to the preferential scattering mentioned and vice versa. Solving the above relation for polarization we obtain

$$P = \frac{R-N}{NR-1}.$$

The data were analyzed by extracting the areas under the photopeaks in the sum spectra by a least-squares-fitting procedure and determining N for each γ ray. The asymmetry-ratio calculations had been done as in Ref. 2 and checked by using the highly polarized radiation from the ^{24}Mg$(p,p'\gamma)^{24}$Mg and the ^{28}Si$(p,p'\gamma)^{28}$Si reactions.[7] The γ-ray linear polarizations were then determined. The almost certainly pure $E2$ character of the majority of the quadrupole transitions also provided an additional check of the calibration of the polarimeter over a reasonably large energy region. Since the γ-ray angular-distribution measurements[5] had previously been determined in experiments at the same beam energy and with the same target, those measured angular-distribution coefficients were used to calculate the polarizations expected for a given multipole and parity for each transition.[8] For pure multipoles the relations between polarization P and the angular-distribution coefficients are:

$$P = \frac{1 - 2a_2/a_0}{1 + a_2/a_0}$$

for pure $E1$ with

$$P(M1) = [P(E1)]^{-1}$$

and

$$P = \frac{1 + a_2/a_0 + a_4/a_0}{1 - 2a_2/a_0 - \frac{1}{4}a_4/a_0}$$

for pure $E2$ with

$$P(M2) = [P(E2)]^{-1}.$$

Here a_0, a_2, and a_4 are the coefficients which appear in the usual Legendre polynomial expansion of the γ-ray angular distributions. A comparison of these predictions and the experimental polarizations then allowed the parities to be determined.

The measured angular-distribution coefficients from the previous study[5] are given in Table I. These coefficients, together with the known assignments of spin 4 to the 1542-keV level and of spin 6 to the 2480-keV level (see Fig. 2) provide a firm basis for the spin assignments[5] of 5, 7, and 9 to the ^{110}Cd levels at 2538, 2878, and 3344 keV, respectively. Spin assignments of 4 to the 2538-

TABLE I. ^{110}Cd angular-distribution summary ^{96}Zr(^{18}O, $4n\gamma$) ^{110}Cd at 60 MeV.

Transition energy (keV)	Assignment $I_i \to I_f$	a_2/a_0	a_4/a_0
658	$2^+ \to 0^+$	0.285 ± 0.005	-0.066 ± 0.008
885	$4^+ \to 2^+$	0.289 ± 0.007	-0.069 ± 0.010
938	$6^+ \to 4^+$	0.322 ± 0.009	-0.075 ± 0.013
795	$8^+ \to 6^+$	0.327 ± 0.014	-0.077 ± 0.021
335 [a]	$10^+ \to 8^+$	0.333 ± 0.011	-0.093 ± 0.016
561	$12^+ \to 10^+$	0.311 ± 0.013	-0.083 ± 0.019
996	$5 \to 4^+$	-0.264 ± 0.025	...
399	$7 \to 6^+$	-0.210 ± 0.015	...
339 [a]	$7 \to 5$	0.300 ± 0.026	-0.083 ± 0.039
466	$9 \to 7$	0.308 ± 0.023	-0.050 ± 0.034

[a] The 339-keV γ ray which appears in the decay scheme has an intensity about $\frac{1}{4}$ that of the 335-keV transition.

keV level and of 6 to the 2878-keV level can be completely excluded by the following considerations. Both the 996- and the 399-keV γ-ray angular distributions exhibit a large negative P_2 coefficient and a negligible P_4 coefficient. For a $\Delta J=0$ γ-ray transition from a state whose m-state distribution is peaked about the $m=0$ state relative to the beam direction, the observed coefficients of P_2 would require[9] a large quadrupole admixture in the radiation. Such a quadrupole admixture would result in a large coefficient for the P_4 term in the angular distribution, in disagreement with experiment.

The angular distribution coefficients for the 339- and 466-keV transitions are consistent with $L=2$ "stretched" transitions from highly aligned states. Since the state at 2878 keV has been assigned[5] spin 7, the 466-keV angular distribution is consistent with a spin-9 assignment to the 3344-keV state.

For transitions of the $J\rightarrow J-1$ type, the angular-distribution measurements are consistent with a small quadrupole admixture into both the 996- and 399-keV transitions. The maximum quadrupole admixture allowed by the coefficients is small in both cases ($|\delta|<\sim 0.06$). Such small possible quadrupole admixtures would not alter the parity conclusions deduced from the experimental N_0/N_{90} ratios.

In Table II the measured linear polarizations are given in column 2 and the error limits on the measurement in column 3. The data are presented in this way because the error limits are not symmetric around the most probable value of polarization. Column 4 shows the polarizations calculated from the angular-distribution coefficients given in Table I with the error range in column 5 and the assumed $L\pi$ for the calculation in column 6. As can be seen from this table, the expected $E2$ character of all of the quadrupole transitions is borne out, while the dipolar transitions of 399 and 996 keV are both $E1$.

In Fig. 1 the polarimeter sum spectra at 0° (crosses) and 90° (circles) are shown for the 399-keV ($7^-\rightarrow 6^+$), 466-keV ($9^-\rightarrow 7^-$), 938-keV ($6^+\rightarrow 4^+$), and 996-keV ($5^-\rightarrow 4^+$) transitions. For this visual comparison a constant was added (channel by channel) to the 0° spectrum to match the baseline with the 90° spectrum for the γ rays shown. The large Compton background from the many $E2$ transitions is also polarized and is the main contributor to the difference in the baseline heights. The electric field vectors for electric multipole γ rays which are radiated from the aligned states at 90° to the beam are expected to be in the reaction plane. Such γ rays thus should be preferentially Compton scattered at 90° to this plane. In the figure the photopeak intensities are indeed higher in the 90° sum spectrum and this qualitatively shows the electric character of the γ rays. The high alignment of the states and the sensitivity of the system produce the large effects.

TABLE II. ^{110}Cd γ-ray polarization measurements ^{96}Zr(^{18}O, $4n\gamma$) ^{110}Cd at 60 MeV. AD means angular distribution.

E_γ	Polarization (exp)	Error on P_{exp}	Polarization (AD)	Error on P_{AD}	$L\pi$
658	3.13	$2.77<P<3.55$	2.73	$2.63<P<2.83$	$E2$
885	3.81	$2.80<P<5.00$	2.77	$2.63<P<2.92$	$E2$
938	2.56	$2.01<P<3.37$	3.32	$3.09<P<3.58$	$E2$
795	3.05	$1.91<P<5.63$	3.42	$3.04<P<3.87$	$E2$
335[a]	2.57	$2.07<P<3.26$	3.47	$3.16<P<3.82$	$E2$
561	3.97	$2.69<P<6.63$	3.07	$2.78<P<3.42$	$E2$
996	1.95	$0.77<P<7.20$	2.07	$1.94<P<2.21$	$E1$
			0.48	$0.45<P<0.52$	$M1$
399	2.07	$1.65<P<2.66$	1.79	$1.72<P<1.87$	$E1$
			0.56	$0.53<P<0.58$	$M1$
466	10.10	$3.74<P<195.2$	3.17	$2.66<P<3.84$	$E2$

[a] The presence of the weak unresolved 339-keV γ ray (see Table I) has only a small effect on the 335-keV polarization measurement because of its similar angular distribution and its $E2$ character.

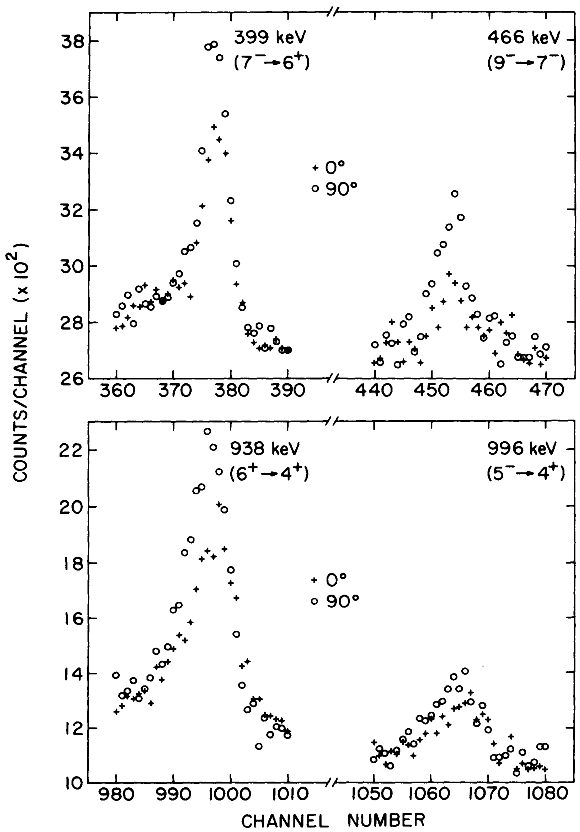

FIG. 1. Polarimeter sum spectra measured with the plane of the polarimeter detectors at 0° (crosses) and 90° (circles) to the reaction plane.

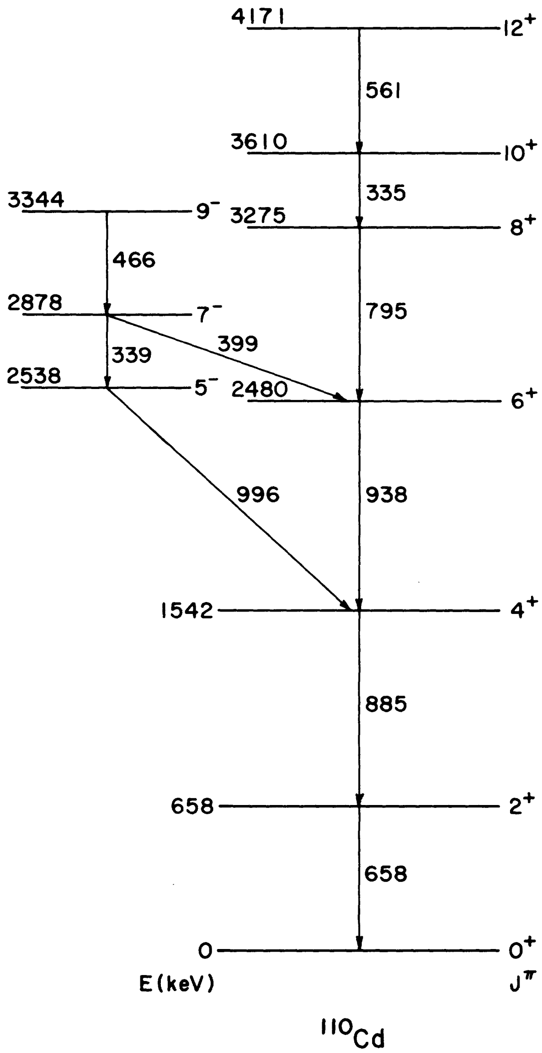

FIG. 2. Partial decay scheme of ^{110}Cd.

IV. DISCUSSION

A partial level scheme for the high-spin states populated in this study is shown in Fig. 2. The $E1$ transitions to the 1542-keV (4^+) and 2480-keV (6^+) levels allow the assignment of odd parity to the levels at 2538 keV (5^-) and 2878 keV (7^-). The spin-9 state at 3344 keV must have odd parity because it decays by the 466-keV $E2$ γ ray to the 2878-keV (7^-) level. The assignment of odd parity to the spin-5 level at 2538 keV is in agreement with the assignment of Kovrigin, Peker, and Sychikov[10] via internal-conversion coefficient studies of $^{110}In^m$ decay and the recently reported $^{109}Ag(^3He, d)^{110}Cd$ work of Auble *et al.*[11] The level assigned as 5^- by Kovrigin, Peker, and Sychikov[10] at 2876 keV is probably a different level from the 7^- state at 2878 keV, since those authors observed no 339-keV transition from this state. In addition, a 5^- assignment to the level observed in this reaction cannot be reconciled with the angular-distribution measurements.

In conclusion, linear-polarization studies of γ rays produced in heavy-ion-induced reactions are clearly feasible with the two-section Ge(Li) polarimeter. The strong linear polarizations which accompany the high alignments produced in such reactions give large effects which compensate for the problem of counting efficiency. These results encouraged the Johns Hopkins group to construct a polarimeter based on two Ge(Li) coaxial detectors whose greater counting efficiency (with better energy resolution and comparable polarization sensitivity) should extend the usefulness of such systems in heavy-ion nuclear spectroscopy. Measurements with the new polarimeter have been performed on ^{108,106}Cd and on some odd-A isotopes and will be reported at a later time.

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