Spin and parity measurements in ^{128,129}La

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(Received 21 November 1991)

Electron conversion coefficients and γ-ray angular distributions for high spin states in ^{128,129}La are reported. Angular distribution information on ^{129}La shows that previously proposed spin assignments for the side band in this nucleus are incorrect. The ^{128}La electron conversion coefficients show that the observed dipole transitions have $M1$ multipolarities. The results are discussed in terms of a proposal that nuclei near ^{128}Ba are statically octupole deformed.

PACS number(s): 23.20.En, 23.20.Nx, 27.60.+j

I. INTRODUCTION

It was suggested recently [1] that a number of nuclei in the vicinity of ^{128}Ba are statically octupole deformed. In odd-A and odd-odd nuclei, octupole deformation is signalled by the existence of closely spaced "parity doublets" of states with equal spins and opposite parities. In addition, parity doublets in statically octupole deformed nuclei in the $A = 145$ and 225 regions are often connected by $E1$ transitions as strong as 10^{-2} Weisskopf units (W.u.). One significant obstacle to the search for parity doublet structures and the identification of $E1$ transitions in this vicinity has been the lack of information on spins and parities of states in odd-A and odd-odd nuclei. In the present article, we report measurements of γ-ray angular distributions and electron conversion coefficients in the N=71 and 72 isotopes ^{128,129}La. High quality γ-γ coincidence data on high spin states in these nuclei have been available for several years [2, 3]. However, the tentative spin and parity assignments made for these nuclei have been based largely on assumptions arising from their assumed structure. Our data allow a more concrete basis for making these assignments and for investigating possible parity doublet structure in these nuclei.

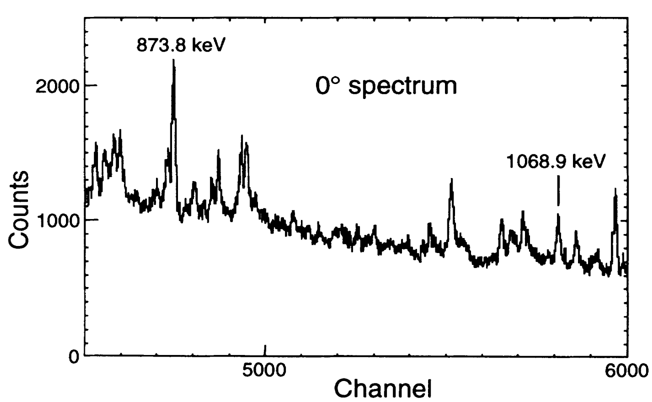

FIG. 1. A portion of the γ-ray spectrum taken at 0° during the angular distribution measurement. The two weakest γ rays measured here (873.8 and 1068.9 keV) are indicated.

II. γ-RAY ANGULAR DISTRIBUTION MEASUREMENTS

Angular distributions of seven γ rays in ^{129}La produced in the ^{115}In(^{18}O,4n) reaction at 80 MeV were measured. The ^{18}O beam was produced using the Florida State University Tandem Van de Graaff and Superconducting Linear Accelerators. A thick foil of natural In was used as the target (the natural abundance of ^{115}In is 93%). ^{129}La was the dominant reaction product. γ rays were detected in a bare n-type HPGe detector located approximately 50 cm from the target. The resolution of this detector was 2.1 keV FWHM at 1.33 MeV, and the detector's relative efficiency was 25%. Data were collected at angles of 0°, 30°, 45°, 60°, and 90°. Typical beam currents were 0.5 particle nA. A portion of the 0° singles spectrum showing the two weak γ rays analyzed here (873.8 and 1068.9 keV) is shown in Fig. 1. It can be seen in this spectrum that the two weak γ rays are quite well resolved. Peaks were integrated using the fitting program GELIFT [4]. The yields were normalized using the dead-time-corrected integrated beam current. The angular distribution of each γ ray was fitted by

$$W(\theta) = A_0[1 + a_2P_2(\theta) + a_4P_4(\theta)]. \quad (1)$$

TABLE I. Angular distribution coefficients for γ rays in ^{129}La.

E_γ	a_2	a_4	$J_i \rightarrow J_f$
269.3[a]	+0.269(13)	-0.067(14)	$15/2^- \rightarrow 11/2^-$
474.8[a]	+0.300(20)	-0.067(22)	$19/2^- \rightarrow 15/2^-$
586.3[b]	+0.346(19)	-0.051(21)	
641.9[a]	+0.279(9)	-0.057(10)	$23/2^- \rightarrow 19/2^-$
785.6[a]	+0.186(20)	-0.052(22)	$27/2^- \rightarrow 23/2^-$
873.8[b]	+0.373(49)	+0.047(56)	
1068.9[b]	+0.299(14)	-0.068(16)	

[a]Energies taken from [5].
[b]Energies are those measured in the present experiment. The calibration used the 269.3, 474.8, 641.9, 785.6, and 910.5 keV adopted [5] γ rays in this nucleus. Uncertainties on these energies are 0.3 keV.

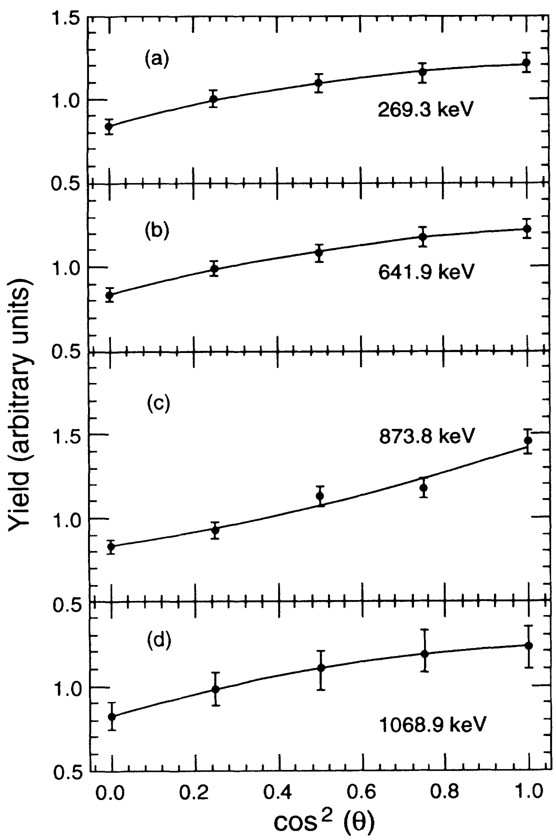

FIG. 2. γ-ray angular distributions and best-fit curves for (a) the 269.3 keV γ ray, (b) the 641.9 keV γ ray, (c) the 873.8 keV γ ray, and (d) the 1068.9 keV γ ray.

The fitted a_2 and a_4 values are listed in Table I. Angular distributions and fitted curves for several γ rays in ^{129}La are given in Fig. 2.

III. CONVERSION ELECTRON MEASUREMENTS

Conversion coefficients were determined for four transitions in ^{129}La and four more in ^{128}La. The ^{18}O+^{115}In reaction at beam energies of 80 and 85 MeV was used to produce ^{128,129}La. Once again, the experiments were performed at the Florida State University accelerator facility. The targets consisted of approximately 300 μg/cm^2 of InO evaporated onto a 50 μg/cm^2 carbon backing. Singles spectra of both γ rays and conversion electrons were taken. The γ rays were detected using an n-type HPGe detector of 25% relative efficiency and resolution of 2.1 keV (full width at half maximum) at 1.33 MeV. The Ge detector was approximately 25 cm from the target and was located at 90° to the beam axis. Conversion electrons were detected using a mini-orange electron spectrometer at 90° to the beam axis. The electron spectrometer included a liquid-nitrogen–cooled Si(Li) detector of 5 mm thickness and 1 cm diameter. The magnetic filter was similar to that described by Ishii [6], using five thin, flat permanent magnets placed around a central lead plug which shielded the Si(Li) detector from direct exposure to the target. While in-beam, the spectrometer yielded a resolution of 4 keV near 200 keV. An efficiency curve for the Ge detector was measured with a ^{152}Eu source. The efficiency curve for the electron spectrometer was obtained using open ^{152}Eu and ^{207}Bi sources.

At 80 MeV, ^{129}La was the dominant reaction product, although a significant amount of ^{128}La was produced as well. Data were also taken at a beam energy of 85 MeV in order to increase the yield of ^{128}La. Calculations using the code PACE [7] predicted a maximum cross section for production of ^{129}La near 80 MeV, and the yields we observed during the experiments were consistent with this. However, PACE also predicted a yield maximum for ^{128}La near 95 MeV which did not prove to be correct. We collected spectra of γ rays and electrons at beam energies of 85, 90, and 95 MeV to find an optimum energy for the production of ^{128}La, and found that the best yield occurred near 85 MeV. Above this energy, the yield of all fusion-evaporation products decreased significantly. Average beam currents for the electron measurements were 4 particles nA. The analysis for ^{129}La was performed with the 80 MeV data. For analysis of transitions in ^{128}La, we added the spectra obtained at 80 and 85 MeV to enhance the statistics. The sums of the spectra of γ rays and electrons taken at 80 and 85 MeV are shown in Fig. 3.

The multipolarity of the 269.3 keV transition in ^{129}La was extracted by measuring the ratio of the K and L con-

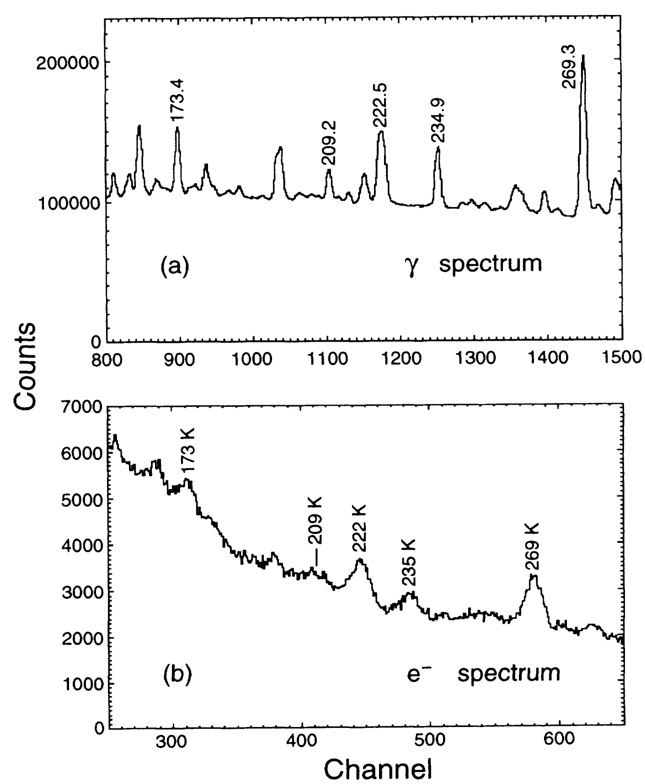

FIG. 3. (a) A low energy portion of the γ-ray spectrum taken in the conversion electron experiment. (b) A portion of the electron spectrum taken in the conversion electron experiment.

TABLE II. Electron conversion coefficients for ^{129}La.

E (keV)[a]	α_K	Multipolarity
269.3	0.051	$E2$
474.8	0.015(3)	$E2$
641.9	0.0055(19)	$E2$
785.6	0.0047(22)	$E2$

[a]Energies are taken from [5].

TABLE III. Electron conversion coefficients for ^{128}La.

E (keV)[a]	α_K	Multipolarity
173.4	0.22(7)	$M1/E2$
209.2	0.13(5)	$M1/E2$
222.5	0.12(3)	$M1/E2$
234.9	0.12(3)	$M1/E2$

[a]Energies are taken from [2].

version lines. The K and L peaks (at 230 and 263 keV, respectively) were integrated and efficiency corrected. The resulting K/L ratio was 4.0±1.2. For a 269.3 keV transition in La, the K/L ratios for pure $E1$, $E2$, and $M1$ transitions are [8] 7.6, 4.9, and 7.5, respectively. Therefore, we deduced from the K/L ratio that the multipolarity of the 269.3 keV transition is $E2$.

The L conversion lines corresponding to the other transitions in ^{129}La were too weak for analysis. Therefore, we determined the multipolarities of the 474.8, 641.9, and 785.6 keV transitions by measuring their K conversion coefficients (the K conversion lines for other transitions in ^{129}La were too weak to be analyzed). These coefficients were determined by calculating the ratio of the yield of conversion electrons in the 80 MeV spectrum to the yield of γ rays, with each yield corrected for the detectors' relative efficiencies (as measured with the sources). This ratio was then multiplied by a normalization factor that was chosen to match the theoretical K conversion coefficient for the 269.3 keV $E2$ transition. The conversion coefficient results for ^{129}La are listed in Table II and plotted with theoretical values [8] for $E1$, $M1$, and $E2$ multipolarities in Fig. 4. Table II also lists the multipolarities indicated by the conversion results.

An identical analysis was performed using the combined 80 and 85 MeV spectra to determine K conversion coefficients for the 173.4, 209.2, 222.5, and 234.9 keV transitions in ^{128}La. Once again, the normalization factor was chosen to match the theoretical K conversion coefficient for the 269.3 keV transition. Conversion-coefficient results for ^{128}La are listed in Table III and plotted in Fig. 4.

IV. PARITIES IN THE ROTATIONAL BANDS OF ^{128}La

Godfrey *et al.* [2] found two rotational bands in ^{128}La (a partial level scheme is shown in Fig. 5) via their γ-γ coincidence study. In addition, they measured γ-ray angular distributions for a number of transitions in each band. They were able to determine that some of the transitions were $\Delta J = 1$ (dipole or mixed $M1/E2$) transitions and that others were stretched $E2$ transitions using the angular distribution results. The spins shown in Fig. 5 are based on this information and the assumption of bandhead spins from theoretical arguments. Godfrey *et al.* also assumed that the $\Delta J = 1$ transitions in the bands were $M1$ or mixed $M1/E2$ transitions, and not $E1$ transitions. This assumption leads to the conclusion that all of the states in a particular rotational band have the same parity. The parities assigned by Godfrey *et al.* and listed in Fig. 5 were determined using theoretical arguments.

We were able to measure conversion coefficients for two $\Delta J = 1$ transitions in each band. In band A, we extracted results for the 222.5 and 234.9 keV transitions. For band B, coefficients for the 173.4 and 209.2 keV transitions were found. In all four cases, the conversion co-

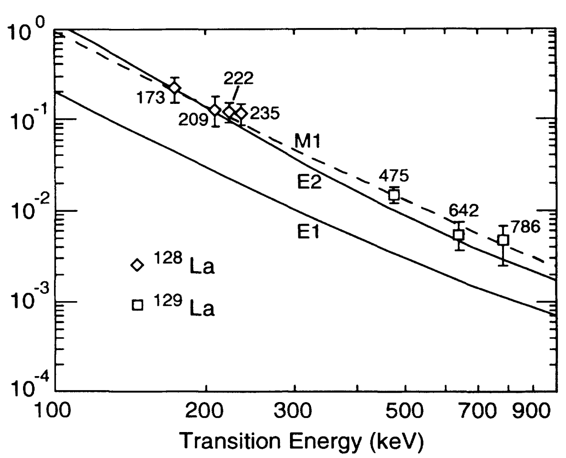

FIG. 4. A comparison of measured electron conversion coefficients with theoretical values [8] for $E1$, $M1$, and $E2$ multipolarities.

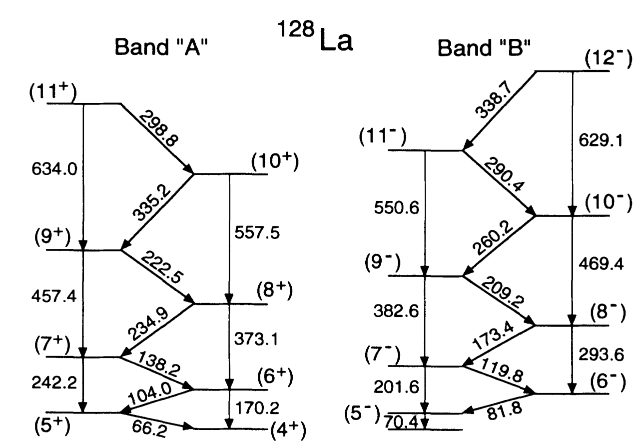

FIG. 5. The low spin part of the level spectrum of ^{128}La reported in [2]. The band heads are shown. The multipolarities of the 173.4, 209.2, 222.5, and 234.9 keV transitions are reported in this article.

efficients are consistent with $M1$ or mixed $M1/E2$ transitions; these transitions are clearly not $E1$ in character. These results confirm the proposal of Godfrey *et al.* that all of the states within a particular band indeed have the same parity. However, they do not confirm the parities of the bands. In order to do this, some other method of determining the parities of the bandheads of the rotational bands must be found.

These results also suggest that strong $E1$ transitions do not occur among the high spin states of ^{128}La. This will be discussed further in Sec. VI.

V. SPINS AND PARITIES IN THE ROTATIONAL BANDS OF ^{129}La

A rotational band built on the 173.7 keV state of ^{129}La was found by Ward *et al.* [9]. There is evidence from β-decay studies that the 173.7 keV state has $J^{\pi}=11/2^-$ [5]. Ward *et al.* also identified several members of a side band that feeds the members of the main rotational band located at 917.8 and 1559.7 keV. Smith *et al.* [3] were able to extend both of these bands. The level spectrum determined by Smith *et al.* is shown in Fig. 6, which also lists the spin assignments given for the main band by Ward *et al.* and Smith *et al.*, proposed on the basis of the assumed $11/2^-$ assignment of the bandhead and the angular distributions of the 269.3, 474.8, 641.9, 785.6, and 910.5 keV γ-rays reported by Ward *et al.*

The results of both our conversion and angular distribution measurements confirm the spin and parity assignments given in [3,9] for the main band. The angular distributions of the 269.3, 474.8, 641.9, and 785.6 keV γ rays are consistent with the $E2$ assignments suggested in [9] if the degree of alignment of the nuclei in this experiment corresponds to a value of the alignment parameter σ/J near 0.34. This parametrization of the alignment is defined by der Mateosian and Sunyar [10], and corresponds to the half-width of a Gaussian distribution of the m states.

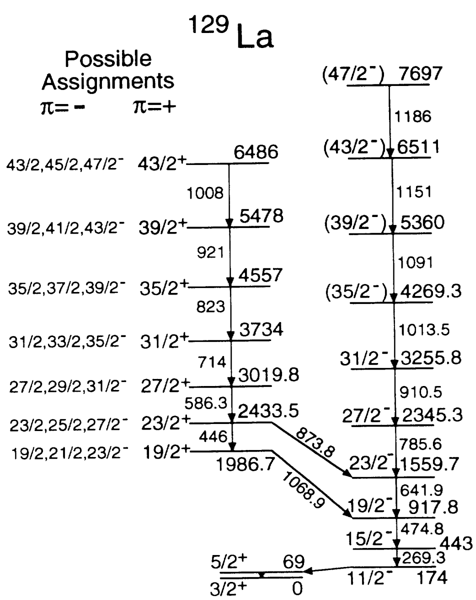

FIG. 6. The level spectrum of ^{129}La reported in [3]. The spin and parity assignments for the band built on the $11/2^-$ state are those given in [3] and supported by data reported here. The possible spin and parity assignments listed for the side band are those consistent with the angular distribution data reported here.

The assignments of the side band states at 1986.7 and 2433.5 keV states are not as straightforward. We first focus on the assignment of the 2433.5 keV state, which is deexcited by the 873.8 keV γ ray. This γ ray deexcites to the 1559.7 keV $23/2^-$ state. We assume that this γ ray has either a dipole or quadrupole multipolarity because transitions of higher multipolarities are relatively slow. In addition, we assume that the spin of the 2433.5 keV is not lower than that of the 1559.7 keV state because states far from the yrast line are not likely to be populated in a (HI,xn) reaction. With these constraints, the possible spin and parity assignments for the 2433.5 keV state are $23/2^+$, $23/2^-$, $25/2^+$, $25/2^-$, $27/2^+$, and $27/2^-$. The angular distribution of the 873.8 keV γ ray is consistent with that of a stretched quadrupole transition, either $E2$ or $M2$. Since the $E2$ multipolarity is consistent with the data, the $27/2^-$ assignment for the 2433.5 keV state cannot be eliminated. However, we can exclude the $M2$ possibility by the following argument. The 2433.5 keV state is also deexcited by the 446 keV γ ray, which appears to be a member of a rotational cascade of $E2$ transitions. The ratio of the intensity of the 873.8 keV γ ray to that of the 446 keV γ ray is [3] 2.1$\pm$0.3. If we make a conservative estimate that the 446 keV transition has a reduced matrix element $B(E2)$ of 100 W.u., then the transition probability of this γ ray is 8.3 $\times 10^{10}$ sec^{-1}. Therefore, the transition probability of the 873.8 keV γ ray is $(2.1\pm0.3) \times (8.3 \times 10^{10}$ sec$^{-1})$ = $(1.7\pm0.3) \times 10^{11}$ sec^{-1}. An $M2$ transition with this transition probability would have $B(M2)$ = 580 W.u., which is much larger than the recommended upper limit of 1 W.u. given by Endt [11]. Because the $M2$ multipolarity is excluded for the 873.8 keV γ ray, the $27/2^+$ assignment can be eliminated for the 2433.5 keV state. For the possibilities that the 2433.5 keV state has J values of 23/2 or 25/2, a mixture of dipole and quadrupole transitions must be considered. To analyze these possible spins, we have used a χ^2 analysis similar to that discussed by Taras and Haas [12] on our angular distribution data. First, we have extracted the alignment parameters σ/J for the 269.3, 474.8, and 641.9 keV γ rays in the main rotational band. They fall in a narrow range, with an average value of 0.338. In the present analysis, σ/J was fixed to this value. The χ^2 analyses for J = 25/2 and 23/2 are illustrated in Figs. 7(a) and 7(b). In these graphs, the dashed lines correspond to the 67% confidence level (a single standard deviation). It can be seen that the χ^2 lines fall below the 67% confidence limit for both J = 23/2 and 25/2. Consequently, neither of these spin assignments may be excluded.

For J = 25/2 [Fig. 7(a)], χ^2 reaches a minimum at δ=0.49, with a 1σ error bar of approximately 0.09. This result requires that the quadrupole fraction of the 873.8 keV transition intensity be approximately 19%. This

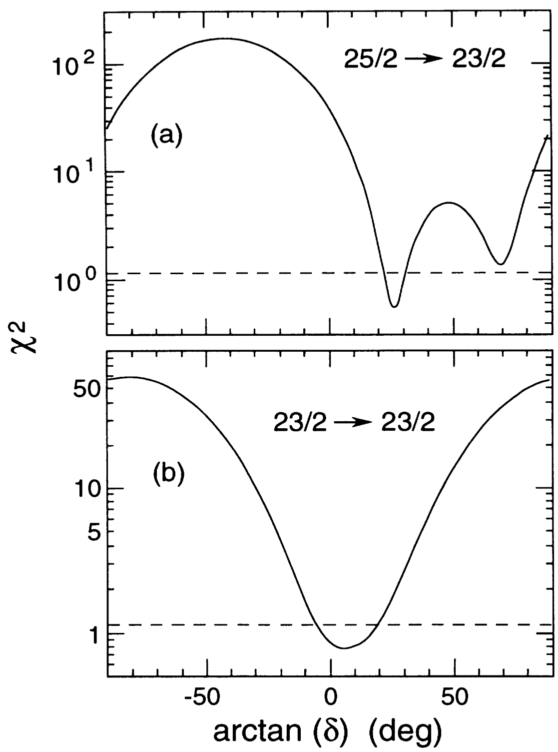

FIG. 7. Graphs of χ^2 vs the arctangent of the mixing parameter δ for the 873.8 keV γ ray with initial J values of (a) 25/2 and (b) 23/2. The dashed lines denote the 67% confidence level.

presents no problem if the parity of the state is negative so that the mixture is $M1/E2$. In other words, an assignment of $25/2^-$ is consistent with the data. However, we are able to exclude an $E1/M2$ mixture, and therefore the $25/2^+$ assignment proposed by Smith *et al.* [3], by an argument similar to that used to exclude the $27/2^+$ assignment. If 19% of the intensity of the 873.8 keV γ ray is $M2$, then the transition probability for the $M2$ would be $(3.2\pm0.6)\times10^{10}$ sec^{-1}, corresponding to 110 W.u. This transition rate is much faster than the recommended upper limit given by Endt [11] for $M2$ transitions of 1 W.u. Therefore, the combination of the data on the angular distribution and intensity of the 873.8 keV γ ray excludes the possibility of an $E1/M2$ mix and a $25/2^+$ assignment.

The χ^2 graph for an initial spin of 23/2 shows that δ is consistent with zero [δ=0.10(22)]. Therefore, the $23/2^-$ assignment cannot be eliminated. For a $23/2^+$ assignment, the χ^2 result indicates that the 873.8 keV transition can be a pure $E1$ γ ray, and that no significant $M2$ intensity is required. As a result, the $23/2^+$ assignment is also allowed by the data. We can summarize these arguments by saying that the 2433.5 keV state can have J^π values of $23/2^+$, $23/2^-$, $25/2^-$, and $27/2^-$. However, the $25/2^+$ assignment proposed by Smith *et al.* is excluded by the data.

Under the assumptions stated for the 2433.5 keV state, the possible assignments for the 1986.7 keV state are $19/2^+$, $19/2^-$, $21/2^+$, $21/2^-$, $23/2^+$, and $23/2^-$. If the 446 keV transition which connects the 2433.5 and 1986.7 keV states is a stretched $E2$ member of a rotational cascade, then the exclusion of the $27/2^+$ and $25/2^+$ assignments for the 2433.5 keV state eliminates the $23/2^+$ and $21/2^+$ possibilities for the 1986.7 keV state. The data for the 1068.9 keV transition are consistent with a stretched $E2$ transition, so the $23/2^-$ assignment is allowed.

For $J = 21/2$, the χ^2 analysis [Fig. 8(a)] yields δ=0.37(16), so that a significant fraction (approximately 12%) of the intensity of the 1068.9 keV transition must be quadrupole. This is consistent with a $21/2^-$ assignment, for which the mixture would be $M1/E2$. This result also supports the exclusion of the $21/2^+$ possibility, because a significant $M2$ intensity would be required.

The χ^2 analysis for a $J = 19/2$ assignment [Fig. 8(b)] is consistent with δ=0, so that both $19/2^-$ and $19/2^+$ assignments are allowed. In short, assignments of $19/2^+$, $19/2^-$, $21/2^-$, and $23/2^-$ are allowed for the 1986.7 keV state. The $21/2^+$ assignment proposed by Smith *et al.* is excluded by the present data.

He *et al.* [13] have recently published new coincidence data on ^{129}La, and they have extracted directional correlation of oriented nuclei (DCO) ratios for both the 873 and 1068 keV transitions. Their results exclude the pure (δ=0) stretched dipole possibility for both γ rays, and therefore the possibility that they are stretched $E1$ transitions. Consequently, both the measurements reported here and the results of He *et al.* [13] exclude the $21/2^+$

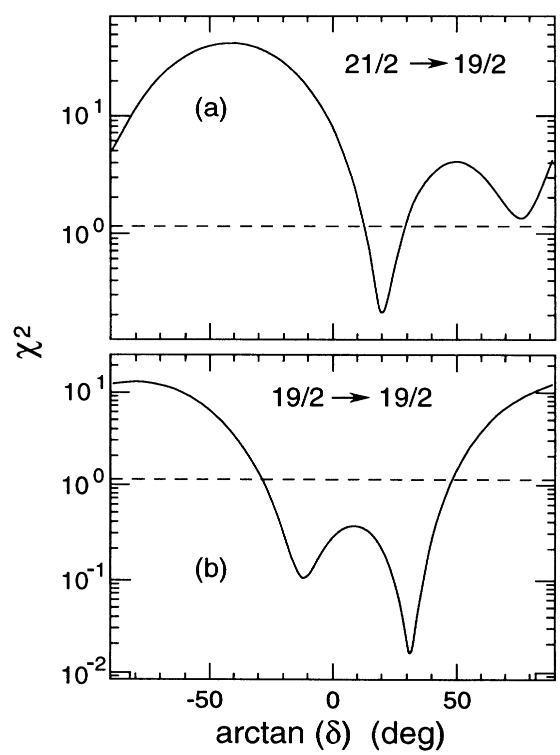

FIG. 8. Graphs of χ^2 vs the arctangent of the mixing parameter δ for the 1068.9 keV γ ray with initial J values of (a) 21/2 and (b) 19/2. The dashed lines denote the 67% confidence level.

assignment for the 1986 keV state and the $25/2^+$ assignment for the 2433 keV state.

The allowed spin assignments for states in the side band are listed in Fig. 6.

While the present results allow a number of assignments for the states in the side band, a determination of the parities of the 1986.7 and 2433.5 keV states could clarify the situation considerably. The present electron experiment was not sensitive enough to measure the 873.8 and 1068.9 keV transitions. However, if these transitions are found to be $E1$ by a more sensitive conversion electron measurement or by a γ-ray polarization measurement, then the side-band states must have positive parities, and the spins would be fixed to unique values.

The possibility that the side band has positive parity is particularly interesting because of the proposal [1] that static octupole deformation occurs in this mass region. If the side band has positive parity, then close parity doubling begins to develop at $J = 39/2$ (a spacing of 117 keV between doublet members) and at 43/2 reaches a 26 keV spacing. It has recently been shown that parity-doubling behavior occurs in ^{129}Ba. However, the behavior in ^{129}La is clearly different from that in ^{129}Ba: Close doublets occur at low spins in ^{129}Ba, while close spacing does not develop in ^{129}La until high spins. This may indicate that octupole deformation does not occur until high spins in ^{129}La. Only two closely spaced doublets are seen in ^{129}La ($J = 39/2$ and 41/2) and it would clearly be desirable to extend both bands to higher spins in order to see whether the doubling persists over a range of angular momenta.

VI. $E1$ TRANSITIONS IN ^{128,129}La

The positive and negative parity members of alternating parity bands and parity doublets in the $A = 145$ and 225 region are often connected by $E1$ transitions as strong as 10^{-2} W.u. These strong $E1$ transitions are caused by the octupole shape, which polarizes the charge in the nucleus and yields a "collective" electric dipole moment [14]. In ^{128}La, no $E1$ transitions are observed, suggesting that the $E1$ matrix elements in this nucleus are weak. In ^{129}La, two possible $E1$ transitions are seen (the 873.8 and 1068.9 keV transitions). However, the absence of $E1$'s deexciting higher members of the side band once again suggest that the $E1$ matrix elements connecting the two bands are weak. Absolute transition strengths have not been measured for either of the two observed $E1$ transitions; however, it is possible to estimate the strength of the 873.8 keV transition by examining the branching ratio with respect to the competing 446 keV $E2$ transition. If both $E1$ and $E2$ transitions deexcite a state, then the ratio of the reduced matrix elements (with each matrix element in units of W.u.) of the two transitions can be calculated from the branching ratio using the expression

$$\frac{B(E1)}{B(E2)}(\text{W.u.}) = \frac{I(E1)}{I(E2)}\frac{E(E2)^5}{E(E1)^3}(7.10 \times 10^{-7})A^{2/3} \qquad (2)$$

where $I(EL)$ is the intensity of the γ ray, $E(EL)$ is the energy of the transition (in MeV), and A is the atomic mass. If we estimate that the 446 keV transition has a reduced matrix element of 100–200 W.u., then we can deduce that the $B(E1)$ value for the 873.8 keV transition is in the range 1×10^{-4}– 2×10^{-4} W.u. We conclude that the $E1$ transitions in ^{128,129}La are not as strong as some of those observed in the $A = 145$ and 225 regions. However, not all octupole deformed nuclei have strong $E1$ transitions. Mach *et al.* [15] found weak $E1$ transitions in ^{146}Ba, which they argue is octupole deformed. The weakest of the $E1$ transitions they measured connects the 3_1^- and 2_1^+ states and has a strength of 1.7×10^{-6} W.u. We conclude that the absence of strong $E1$ transitions in ^{128,129}La does not exclude the possibility of static octupole deformation near this region.

VII. CONCLUSIONS

We have reported measurements of conversion coefficients in ^{128,129}La and γ-ray angular distributions in ^{129}La. These measurements demonstrated that the dipole transitions in ^{128}La are magnetic, and that the spin assignments proposed by Smith *et al.* [3] for the side band in ^{129}La are incorrect.

Our result on ^{129}La opens the possibility that parity doubling, which is a behavior characteristic of static octupole deformation, occurs in this nucleus near $J = 39/2$. However, the data on ^{128,129}La demonstrate that the $E1$ transitions in these nuclei are not as strong as some of those occurring in the octupole-deformed nuclei of the $A = 145$ and 225 regions.

This work was supported by the National Science Foundation and the State of Florida.

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