Octupole correlations in neutron-rich ^{145,147}La nuclei: Coriolis-limit-coupling bands with aligned $h_{11/2}$ proton

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Several new high-spin states are observed in the prompt γ-rays emitted from the neutron-rich, odd-Z ^{145,147}La fragments produced in the spontaneous fission of ^{252}Cf. Alternating parity bands are extended up to spins 41/2 and 43/2 in ^{145,147}La, respectively. A new band completes the evidence for two sets of parity doublets expected for octupole correlations. Eight $B(E1)/B(E2)$ ratios (four new) between two bands in ^{145}La are all essentially constant and somewhat larger than similar ratios in ^{143,144}Ba, where stable octupole deformation and/or correlations are reported. The new ratios out of the $31/2^-$ levels in both nuclei show a sharp spike compared to other states, presumably from a strong reduction in $E2$ strengths in this backbending region. In ^{145}La, collective bands show competition and coexistence between symmetric and asymmetric shapes. Band crossings occur in both nuclei around $\hbar\omega \approx 0.26$–0.30 MeV. Their backbends are associated with the alignment of two $i_{13/2}$ neutrons according to cranked shell model calculations. [S0556-2813(99)08402-2]

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I. INTRODUCTION

A nucleus with octupole deformation has an asymmetric shape in its intrinsic frame. Theoretical calculations in the deformed shell model suggest the existence of an island of stable octupole deformed nuclei around $Z=56$ and $N=88$ [1–3]. Strong evidence of stable octupole deformation and/or correlations have been reported in ^{142,143,144,146,148}Ba and ^{144,146}Ce [4–12]. Recently, Garrote, Egido, and Robledo [13] analyzed the transition to reflection asymmetric shape for $N=88$ nuclei at high angular momentum in the frame work of the cranked Hartree-Fock-Bogoliubov approximation. They found good agreement for the energy splitting of the even- and odd-parity states and $B(E1)$ transition probabilities. The interweaving of odd-spin, odd-parity levels with the ground rotational bands usually occurs only for spin 7 and above. Thus the lower spin states may be considered soft octupole vibrators, with mean octupole deformation exceeding zero-point amplitudes for the higher spins. Neutron-rich ^{145,147}La with $Z=57$ lie between the Ba($Z=56$) and Ce($Z=58$) nuclei, where stable octupole deformation and/or octupole correlations is found, and so are expected to be candidates for octupole deformation. From earlier β-decay measurements, some low-lying levels were reported in ^{145}La [14] and ^{147}La [15]. The high-excited states in these very neutron-rich nuclei are difficult to populate in (HI,xn) reactions. However, they are accessible through spontaneous fission (SF) and evidence for octupole correlations in ^{145,147}La up to intermediate spins was reported from SF studies of ^{248}Cm [16]. In previous work we have identified many high-spin states in several neutron-rich nuclei in this and other regions [7,9] populated in the SF of ^{252}Cf. Here we extend the data to give more definitive evidence concerning strong octupole correlation and its variation with rotation in ^{145,147}La.

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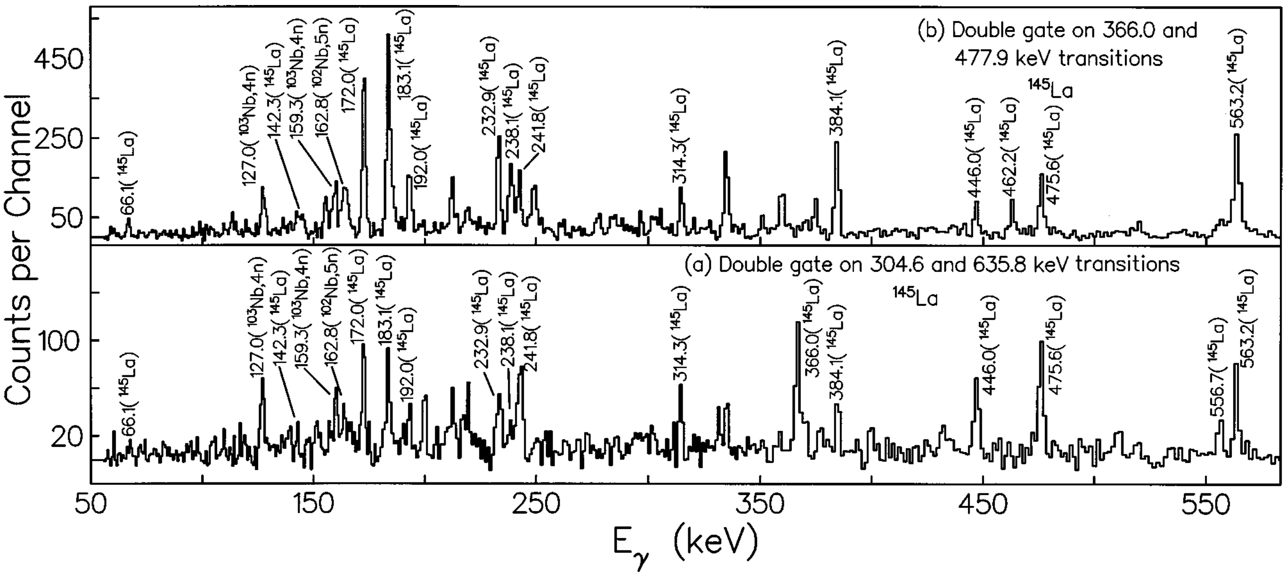

FIG. 1. (a) Partial γ-ray coincidence spectrum obtained by double gating on 304.6- and 635.8-keV transitions, and (b) partial γ-ray coincidence spectrum with double gates on 366.0- and 477.9-keV transitions in ^{145}La.

II. EXPERIMENTAL TECHNIQUES

A ^{252}Cf source of strength 25 μCi was sandwiched between two Ni foils of thickness 11.3 mg/cm^2, and then sandwiched between 13.7-mg/cm^2-thick Al foils and placed at the center of the Gammasphere. This experiment was carried out with 72 Compton-suppressed Ge detectors. The data were recorded in an event-by-event mode. Three-dimensional histograms (cubes) of triple coincidence events (with the three γ-ray energies as axes) were then constructed and analyzed using the RADWARE software [17]. The width of the coincidence time window was about 1 μs, but narrower time gates could be implemented in software at the cube generation stage. Most of the data analyses presented below were performed on a cube with a 100-ns-wide coincidence requirement. New transitions were identified and assigned in the present work by setting several double gates on known transitions in ^{145,147}La and their Nb fission partners. Newly assigned transitions were then used as gates to identify additional transitions. Further experimental details can be found in Refs. [6–10].

III. RESULTS

A. ^{145}La

Figures 1 and 2 give examples of double-gated γ-ray spectra. The level scheme of ^{145}La is shown in Fig. 3 based on our new data. All the new transitions observed in the present work are marked with an asterisk. In Fig. 1(a), the γ-ray spectrum is obtained by double gating on the new 304.6- and the known 635.8-keV transitions in ^{145}La. One can clearly observe the known 232.9-, 366.0-, 475.6-, and 563.2-keV transitions in band 1 (see Fig. 3). In addition, one also observes two new transitions of energies 446.0 and 556.7 keV. Figure 1(b) is a γ-ray spectrum obtained by

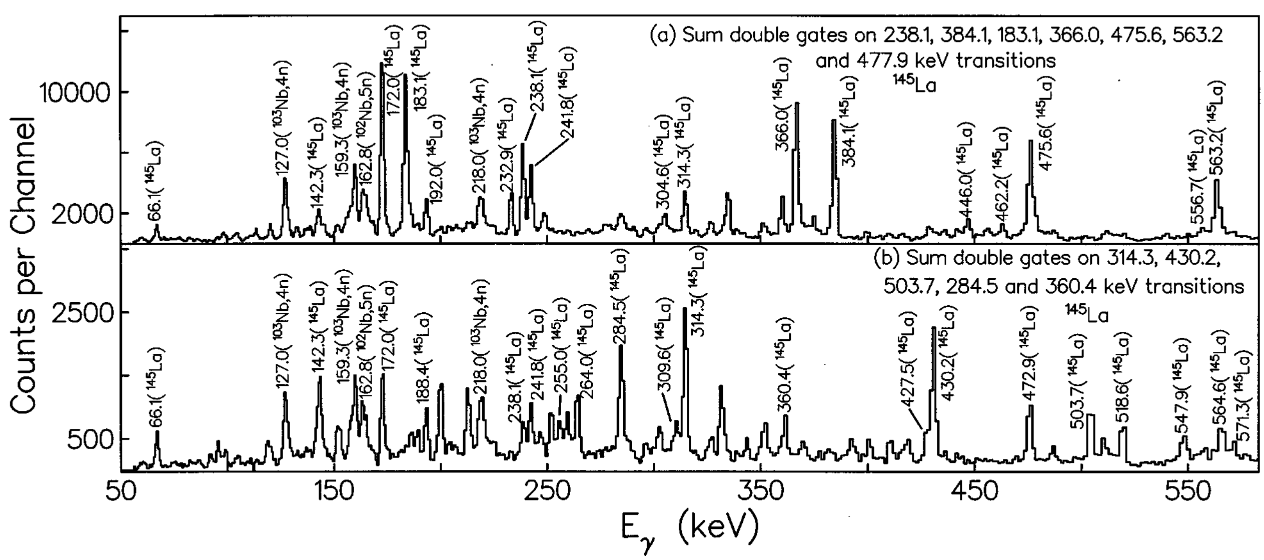

FIG. 2. (a) Sum of several possible double-gated spectra from transitions in bands 1 and 3 in ^{145}La, with gating transitions indicated. (b) Sum of several possible double gated spectra from transitions in bands 4 and 5 in ^{145}La, with gating transitions indicated.

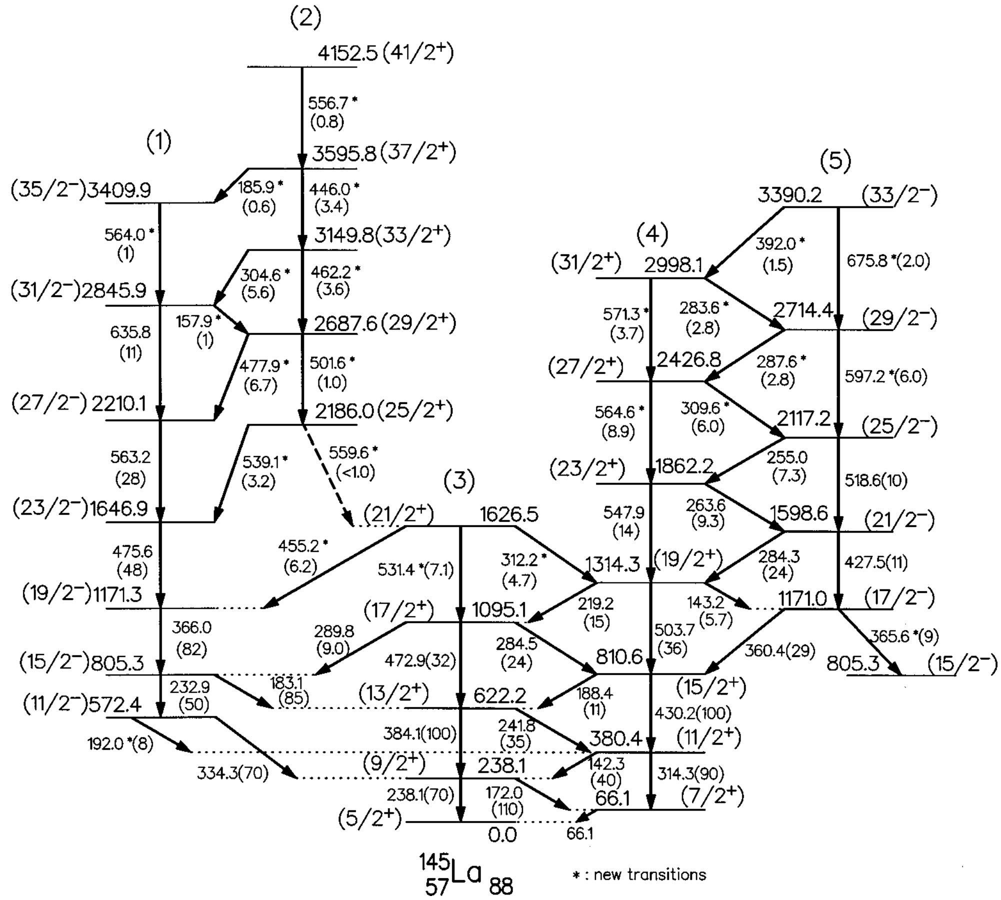

FIG. 3. Level scheme of ^{145}La. New transitions are indicated with an asterisk.

double gating on the known 366.0 keV, and another new transition of energy 477.9 keV. One sees clearly the transitions in band 1 reported earlier [16]. In Fig. 2(a), we show a coincidence spectrum obtained by summing several double-gated spectra for bands 1 and 3. The gate energies are listed in the figure. One sees the transitions that belong to band 1 and to a new band 2 in the level scheme of ^{145}La (see Fig. 3). Similarly, in Fig. 2(b), we show a coincidence spectrum obtained by summing several double-gated spectra of transitions in bands 4 and 5. One sees the new transitions that belong to bands 4 and 5 in the level scheme of ^{145}La.

In the early β-decay experiments, the spin and parity of the ^{145}La ground state were assumed to be $(5/2^+,7/2^+)$ [14]. Based on systematics, the ground state of ^{145}La was assigned as $(5/2^+)$ by Urban *et al.* [16], and we concur with that assignment. Based on internal conversion coefficients, branching ratios and triple angular correlations, a parity change between bands 1 and 3 and the spin sequence of levels including a $13/2^+$ assignment to the level at 622.2 keV in ^{145}La were established [16]. The I^π assignments for the newly observed levels in this work are based on assumed stretched $E2$ transitions in each band and $E1$ interband transitions. The total internal conversion coefficient of the 143.2-keV transition was measured to be 0.05 ± 0.05, in agreement with an $E1$ value of 0.08 but not with an $M1$ value of 0.40. This establishes the parity change between bands 4 and 5. In ^{145}La, 11 new levels and 22 new γ transitions, mostly at high spin, were identified. Of particular interest is the discovery of a new high-spin band 2 beginning at 2186.0 keV with intertwined crossing transitions to band 1, as shown in Fig. 3. At low spin, the 192.0-keV transition between the 572.4- and 380.4-keV levels was identified and of particular importance, and the 365.6-keV $M1$ transition between the $17/2^-$ and $15/2^-$ members of the two parity doublets was observed. Similar crossing transitions at the bottom of the two parity doublet structures are also observed in ^{143}Ba [9].

B. ^{147}La

In Fig. 4, we show a coincidence spectrum obtained by summing several double-gated spectra in ^{147}La. The gate energies are listed in the figure. One sees the new transitions that have been assigned to ^{147}La (see Fig. 5). In Ref. [15], I^π of the ground state and of the 167.7- and 120.8-keV levels were tentatively assigned as $(5/2)^+$, $(3/2)^-$, and $(3/2,5/2)^+$, respectively. Ref. [16] proposed the spins and parities of $7/2^-$ and $11/2^-$ for 167.7 and 230.0 keV, respectively, on the basis of the $E2$ character of the 62.3-keV transition and the $E1$ character of the 167.7-keV transition. Also, the spins and parities of band 1 starting with the 230.0-keV level are assigned under the assumption of stretched $E2$ transitions, as determined by angular correlations. We concur with all these assignments, and propose tentative spins and parities of band 2 in ^{147}La based on comparisons with the analogous band 2 in ^{145}La. In ^{147}La, six new levels and nine new transitions, primarily at high spins, were identified as shown in Fig. 5 including the 210.0- and 233.3-keV transitions which were identified only tentatively in Ref. [16]. A new level observed

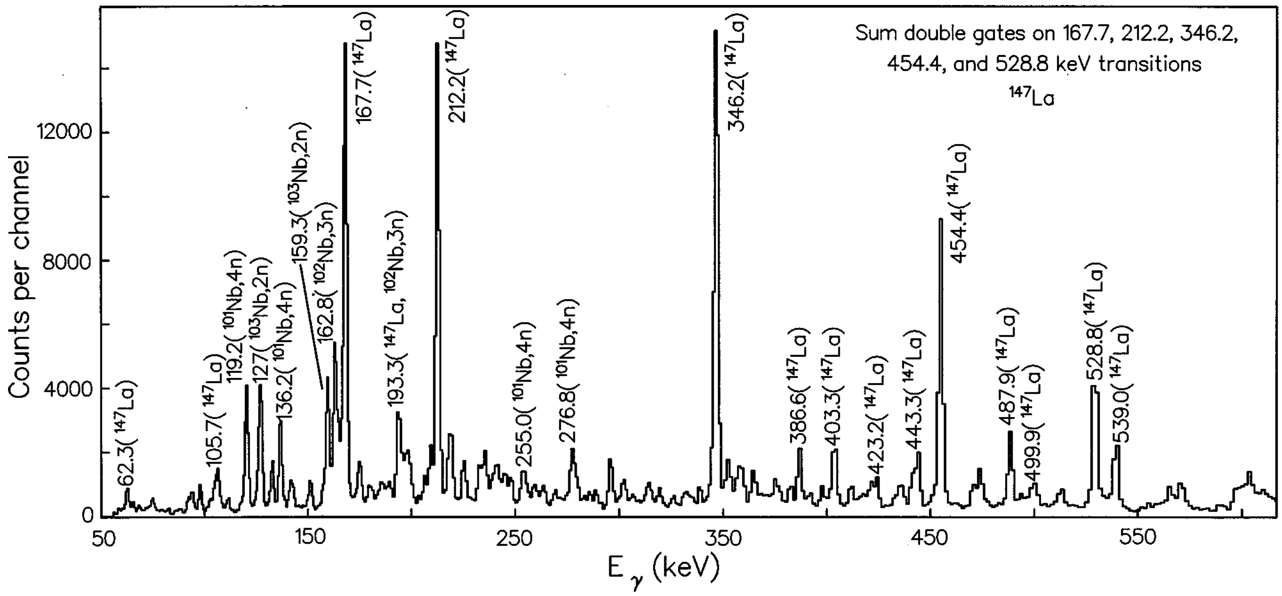

FIG. 4. Sum of several possible double-gated spectra in ^{147}La, with gating transitions indicated.

at 1031.6 keV is linked by a 589.4-keV transition to the 442.2-keV level, with a tentative 327.3-keV feeding transition. No evidence was found for a tentative 668.7-keV transition from a 1109.2-keV level as given in Ref. [16].

IV. DISCUSSION

Bands 3 and 4 in ^{145}La, from the ground state up to the $I^{\pi}=(21/2^{+})$ level, appear to form a mildly aligned band (probably mainly Coriolis mixed $5/2^{+}[413]$ and $3/2^{+}[422]$). These two signature partner bands with stretched $E2$ transitions within the band are linked by $M1/E2$ transitions at least up to $21/2^{+}$. This strong-coupled collective structure represents a well-deformed symmetric rotor shape in ^{145}La. The cluster of even-parity levels near the $5/2^{+}$ ground state in ^{147}La has uncertain spin and band structure. Plots of the kinetic moments of inertia (J_1) versus $\hbar\omega$ for each band are shown in Fig. 6. Up to $\hbar\omega=0.27$ MeV ($I=23/2$), bands 3 and 4 in ^{145}La have identical J_1's. This also supports the above interpretation of their symmetrical rotor shape. The strong-coupled ground band in ^{145}La is assigned a $g_{7/2}$ proton configuration [15]. The signature splitting at the low end of this band (3-4) implies predominant $g_{7/2}$ character, with the $d_{5/2}$ admixture becoming comparable at higher spins. Based on the energies in band 1, the deformation is slightly larger in ^{147}La ($N=90$) than in ^{145}La ($N=88$).

It is clear from the strong backbend at the $25/2^{+}$ level and only an upper limit for a $(25/2^{+})\rightarrow(21/2^{+})$ transition connecting bands 2 and 3 in ^{145}La that a real change in structure occurs at this point. This is the reason we have separated the higher-energy states labeled band 2 from band 3 to emphasize this change in structure. Likewise, band 4 shows a sharp

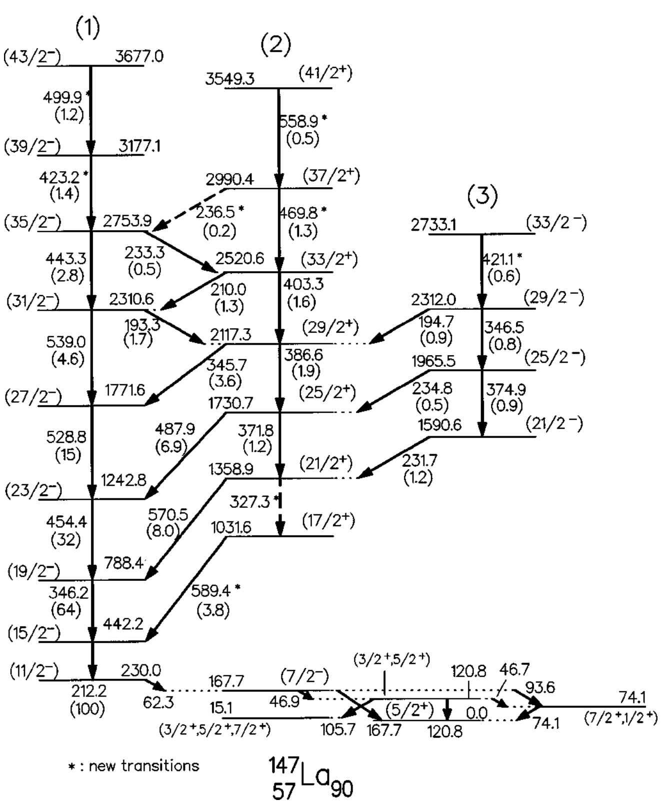

FIG. 5. Level scheme of ^{147}La. New transitions are indicated with an asterisk.

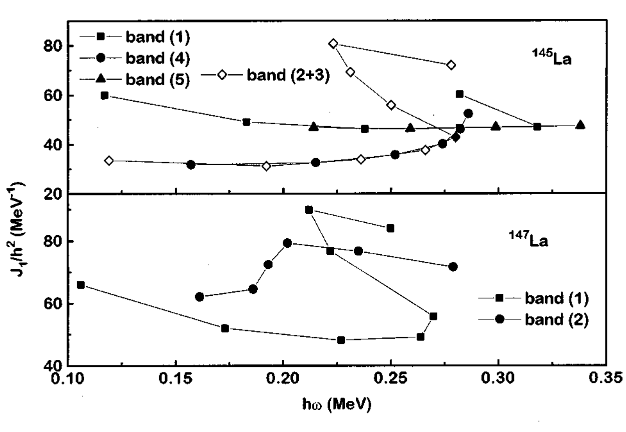

FIG. 6. Plot of J_1 vs $\hbar\omega$ for bands in ^{145,147}La.

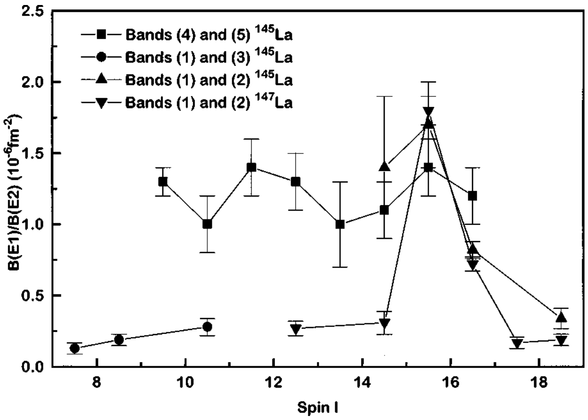

FIG. 7. Plots of the $B(E1)/B(E2)$ ratios vs spin I in ^{145,147}La.

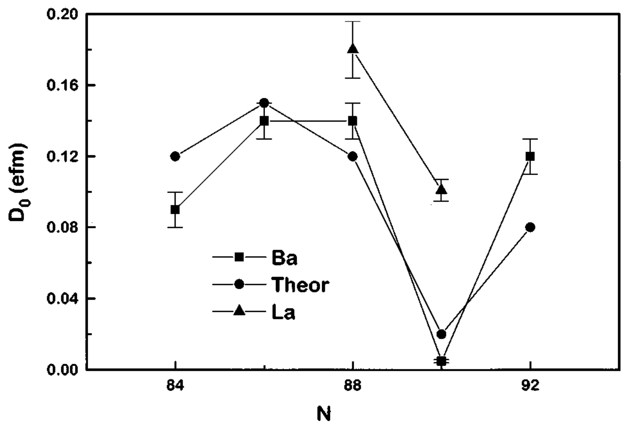

FIG. 8. Plots of intrinsic electric dipole moments D_0 for Ba and La nuclei.

upbend beginning at the $23/2^+ \rightarrow 19/2^+$ transition that is not seen in band 5. This suggests that the $23/2^+$, $27/2^+$, and $31/2^+$ levels are not a continuation of band 4, even though an appreciable $E2$ strength connecting the upper and lower states of what is called band 4 is observed. The negative parity bands 1 in ^{145}La and ^{147}La have very similar J_1's from $(11/2^-)$ to $(27/2^-)$. A backbend occurs at above $(31/2^-)$ in both ^{145}La and ^{147}La. In the positive parity band 2, the J_1's again indicate a change in structure from the lower spin states in band 3 in ^{145}La around the $(25/2^+)$ state.

The $B(E1)/B(E2)$ ratios shown in Fig. 7 are given in Table I. For bands 4 and 5, all eight ratios are remarkably constant from the $19/2^+$ level to the $33/2^-$ level. These ratios indicate that there is a shift from a symmetric shape to a stable asymmetric octupole-quadrupole interaction around spin $(19/2^+)$ in ^{145}La.

In Fig. 8 we plot our plateau values of intrinsic electric dipole moment D_0 for the ^{145,147}La bands. They are combined with data from Fig. 11 of Urban *et al.* [16], which shows their corresponding D_0 values for the even-even Ba nuclei, in essential agreement with the theoretical values of Butler and Nazarewicz [18]. It is interesting that the La nuclei also show the sharp dip in D_0 at 90 neutrons that occurs for the bariums, if we use plateau values away from the spin 31/2 backbend where $B(E2)$ values may drop.

The $B(E1)/B(E2)$ ratios in bands 4 and 5 in ^{145}La are comparable to or larger than those found in its ^{144}Ba core and in the octupole parity doublets in ^{143}Ba, where experiment and theory are in agreement with stable octupole deformation in these nuclei. The large (larger than in ^{143,144}Ba) and essentially constant values of the $B(E1)/B(E2)$ ratios over this extended spin range support an octupole correlation at higher spins. One sees quite different behavior between bands 1 and 3 at low spin and bands 1 and 2 at high spin in ^{145}La. The $B(E1)/B(E2)$ ratios at low spin for bands 1 and 3 are a factor of 4 smaller than for bands 4 and 5; we attribute the low values of band 3 to its configuration mixing. For bands 1 and 2 at higher spin in ^{145}La, the ratios start at a factor of 6 higher than for bands 1 and 3, then peak, followed by a sharp drop of more than a factor of 5 at the highest spin. Likewise in ^{147}La, the ratios for bands 1 and 2 start out with the first two ratios low as for bands 1 and 3 in ^{145}La, show a sharp peak at the same transition as in ^{145}La, and then drop more than a factor of 6 to a level below the initial values but similar to those in ^{145}La. The sharp peaks in both cases are likely due to a strong reduction in $E2$ strength related to a change in structure between bands 2 and 3 in ^{145}La around $25/2^+$ and a similar change at the same spin in ^{147}La, rather than to a sudden increase in $E1$ strength. It is most likely that bands 1 and 2 have very similar structures in ^{145,147}La, at least at the higher spin where band 2 emerges in ^{145}La.

Even though the $B(E1)/B(E2)$ ratios are different by a factor of 2 in bands 1-2 at highest spin and 4-5, these bands are likely to form a set of two bands of parity doublets expected when octupole correlations are present, as found in ^{143}Ba. Since bands 1, 2, 4, and 5 have different moments of inertia, this suggests that the deformation may not be stable. The $s=+i$ bands 1 and 2 in ^{145}La and ^{147}La have similar structural features. Both the negative parity bands 1 may have the odd proton in an $h_{11/2}$ spectator orbital, and the bands 2 have energies suggesting Ba core octupole bands built on the $h_{11/2}$ proton spectator. For the ground band in ^{146}Ba, J_1 backbends at 0.28 MeV, which agrees with the value of 0.27 MeV for the backbend of the $(11/2^-)$ band in ^{147}La (Fig. 6). The $(11/2^-)$ band in ^{145}La does not backbend until 0.30 MeV, which is consistent with the upbend in ^{144}Ba at this same value. A comparison of the $s=+i$ band levels in ^{145}La and ^{147}La with those of the $N=88$ and 90 isotones ^{144}Ba and ^{146}Ba is shown in Fig. 9, where the bandhead energies are normalized to zero. The energies of both the positive and negative bands between the isotones are quite similar to each other. Thus the $s=+i$ bands in ^{145}La and ^{147}La most probably originate from the single-particle $\pi h_{11/2}$ orbital coupled with the ^{144}Ba and ^{146}Ba even-even cores, respectively. Indeed, Fig. 9 level patterns point to a textbook example of a Coriolis-limit coupling scheme. At smaller deformations and smaller moments of inertia at the boundary of a spheroidal region, Coriolis mixing of Bohr-Mottelson strong coupled orbitals can lead to a limiting coupling scheme where the high-j orbital, here $h_{11/2}$, couples to the core spin R to a resultant spin I. The residual interaction with the prolate deformed field should make the stretched band $I=j,j+2,j+4\ldots$, lowest in energy.

The difference between a decoupled $h_{11/2}$ scheme and a Coriolis-limit-coupling scheme is that the former would have considerable degeneracies among all couplings of core rotation and decoupled particle j, whereas Coriolis-limit cou-

TABLE I. Electric dipole transition strengths in ^{145,147}La. $B(E2;15/2^- \rightarrow 11/2^-) \approx 0.25 \times 10^4 e^2$ fm^4 for ^{145}La and $0.30 \times 10^4 e^2$ fm^4 for ^{147}La, respectively. A constant quadrupole moment was assumed for each nucleus, although an increase with spin is possible.

	E_γ(keV)	$I_i^\pi \rightarrow I_f^\pi$	I_γ	$B(E1)/B(E2)$ (10^{-6} fm^{-2})	D_0 (e fm)
^{145}La	503.7	$19/2^+ \rightarrow 15/2^+$	36(3)	1.3(1)	0.19(1)
Bands 4	143.2	$19/2^+ \rightarrow 17/2^-$	5.7(3)		
and 5	427.1	$21/2^- \rightarrow 17/2^-$	11(1)	1.0(1)	0.14(1)
	284.3	$21/2^- \rightarrow 19/2^+$	24(2)		
	547.9	$23/2^+ \rightarrow 19/2^+$	14(1)	1.4(1)	0.20(1)
	263.6	$23/2^+ \rightarrow 21/2^-$	9.3(5)		
	518.6	$25/2^- \rightarrow 21/2^-$	10(4)	1.3(5)	0.17(3)
	255.0	$25/2^- \rightarrow 23/2^+$	7.3(3)		
	564.6	$27/2^+ \rightarrow 23/2^+$	8.9(4)	1.0(1)	0.17(1)
	309.6	$27/2^+ \rightarrow 25/2^-$	6.0(4)		
	597.2	$29/2^- \rightarrow 25/2^-$	6.0(4)	1.1(1)	0.17(1)
	287.9	$29/2^- \rightarrow 27/2^+$	2.8(3)		
	571.3	$31/2^+ \rightarrow 27/2^+$	3.7(3)	1.6(2)	0.22(1)
	283.9	$31/2^+ \rightarrow 29/2^-$	2.8(3)		
	675.8	$33/2^- \rightarrow 29/2^-$	2.0(1)	1.4(1)	0.19(1)
	392.0	$33/2^- \rightarrow 31/2^+$	1.5(1)		
Bands 1	232.9	$15/2^- \rightarrow 11/2^-$	50(2)	0.15(1)	0.035(2)
and 3	183.1	$15/2^- \rightarrow 13/2^+$	85(7)		
	472.9	$17/2^+ \rightarrow 13/2^+$	32(4)	0.21(3)	0.075(5)
	289.8	$17/2^+ \rightarrow 15/2^-$	9.0(2)		
	531.4	$21/2^+ \rightarrow 17/2^+$	7.1(4)	0.30(2)	0.092(3)
	455.2	$21/2^+ \rightarrow 19/2^-$	6.2(3)		
Bands 1	501.6	$29/2^+ \rightarrow 25/2^+$	1.0(1)	1.5(2)	0.22(1)
and 2	477.5	$29/2^+ \rightarrow 27/2^-$	6.7(3)		
	635.8	$31/2^- \rightarrow 27/2^-$	11.0(5)	1.9(4)	0.22(2)
	157.6	$31/2^- \rightarrow 29/2^+$	1.0(2)		
	462.2	$33/2^+ \rightarrow 29/2^+$	3.6(2)	0.90(7)	0.16(1)
	304.6	$33/2^+ \rightarrow 31/2^-$	5.6(3)		
	446.0	$37/2^+ \rightarrow 33/2^+$	3.4(2)	0.37(7)	0.11(1)
	185.9	$37/2^+ \rightarrow 35/2^-$	0.6(1)		
^{147}La	371.8	$25/2^+ \rightarrow 21/2^+$	1.2(1)	0.27(2)	0.097(4)
Bands 1	487.9	$25/2^+ \rightarrow 23/2^-$	6.9(2)		
and 2	386.6	$29/2^+ \rightarrow 25/2^+$	1.9(2)	0.31(4)	0.104(7)
	345.7	$29/2^+ \rightarrow 27/2^-$	3.6(3)		
	539.0	$31/2^- \rightarrow 27/2^-$	4.6(3)	1.8(2)	0.24(2)
	193.3	$31/2^- \rightarrow 29/2^+$	1.7(2)		
	403.3	$33/2^+ \rightarrow 29/2^+$	1.6(2)	0.72(14)	0.16(2)
	210.0	$33/2^+ \rightarrow 31/2^-$	1.3(2)		
	443.3	$35/2^- \rightarrow 31/2^-$	2.8(2)	0.19(8)	0.08(2)
	233.3	$35/2^- \rightarrow 33/2^+$	0.5(2)		
	469.8	$37/2^+ \rightarrow 33/2^+$	1.3(2)	0.21(11)	0.09(2)
	236.5	$37/2^+ \rightarrow 35/2^-$	0.2(1)		

pling makes aligned and antialigned bands lower than the others. In the Coriolis-limit scheme the projection Ω of j on the nuclear symmetry axis is no longer conserved, but the rotational angular momentum R of the core becomes conserved. It has been suggested [16] that the negative parity band 5 in ^{145}La may correspond to an octupole phonon coupled to the ground-state band. The parity of band 3 in ^{147}La is not clear, but it is possible that this band originates from an octupole phonon coupling to the $h_{11/2}$ proton orbital [16]. The strong backbending observed at $\hbar\omega \approx 0.27$ MeV in bands 2 and 3 and the very weak intensity of the 559.6-keV transition if present in ^{145}La may be caused by the shape changing from symmetric quadrupole to include stable octupole deformation as the spin increases.

Another surprising result is that both negative parity bands 1 and 5 in ^{145}La to the highest spin observed, $I = (29/2)$, are identical bands, i.e., have the same J_1. We think they are signature partners of the $h_{11/2}$ proton-plus-core

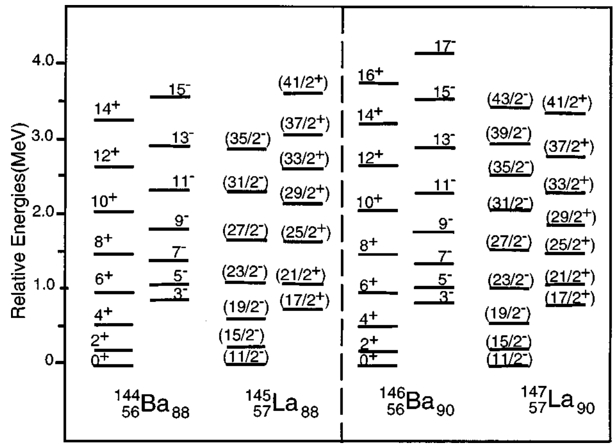

FIG. 9. Comparison of octupole deformation band levels between ^{144}Ba and ^{145}La (for $s=+i$ bands 1 and 2) and ^{146}Ba and ^{147}La (for $s=-i$ bands 1 and 2). The energies of $(11/2^-)$ levels in ^{145,147}La are taken as zero.

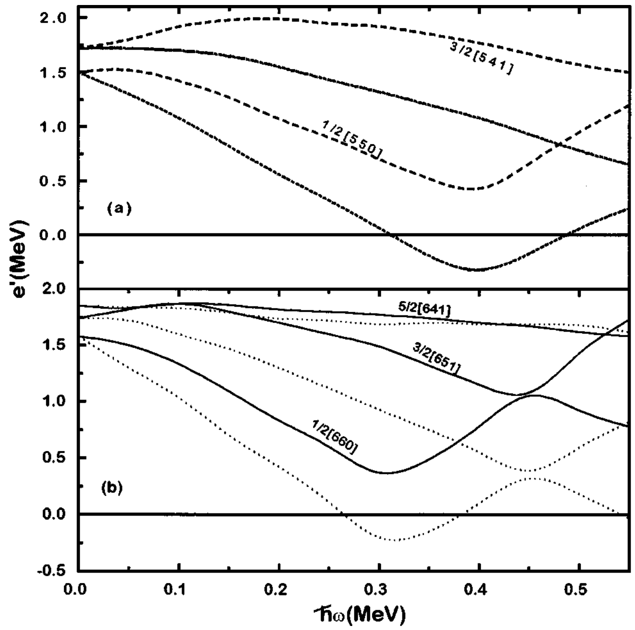

FIG. 10. Cranked shell model calculations for proton quasiparticles (a) and neutron quasiparticles (b) plotted against rotational frequency.

octupole band. In order to make an interpretation of the observed backbends of band 1 in both nuclei, we employed cranked shell model calculations to determine whether the proton orbital ($\pi h_{11/2}$) or the neutron orbital ($\nu i_{13/2}$) is responsible for the band crossings at the observed rotational frequencies. The method of calculation is the same as in Ref. [17]. The standard parameters used in the calculation were as follows: quadrupole deformation $\beta_2=0.165$; octupole deformation $\beta_3=0.06$; hexadecapole deformation $\beta_4=0$; pairing gap parameters, $\Delta_p=1.007$ and $\Delta_n=1.312$; and Fermi levels for protons and neutrons, $\lambda_p=-10.5576$ and $\lambda_n=-5.0667$. The calculated Routhians for protons (a) and neutrons (b) are shown in Fig. 10. A band crossing caused by the alignment of the two $i_{13/2}$ neutrons occurs at $\hbar\omega=0.32$ MeV, which is close to the experimental values of 0.30–0.26 MeV in the ^{145,147}La isotopes. The crossing related to the alignment of $h_{11/2}$ protons is predicted to occur at $\hbar\omega=0.40$ MeV, which is much higher than the observed values. Hence, we believe that the $i_{13/2}$ neutron orbital is responsible for backbending in ^{145,147}La. This interpretation is reasonable because the crossing corresponding to two $h_{11/2}$ protons is blocked by the odd proton.

V. CONCLUSIONS

New high-spin levels in collective bands were observed in ^{145,147}La, and the spins and parities were tentatively assigned from systematics. Intertwined bands connected by strong $E1$ transitions indicate octupole correlations. The experimental $B(E1)/B(E2)$ ratios in ^{145,147}La exhibit similarities to the ratios in the Ba isotones but differ from that in ^{146}Ba. In ^{145}La, a quadrupole ground state collective band with a well-deformed symmetric shape coexists and competes with octupole correlated bands with asymmetric shape at higher spins. Our data indicate that the octupole correlations are present at high spin beginning at intermediate spins. Based on cranked shell model calculations, the backbends observed at $\hbar\omega\approx0.26$–0.30 MeV are interpreted as the rotational alignment of two $i_{13/2}$ neutrons.

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