Octupole correlations in neutron rich, odd-*A* lanthanum nuclei

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Neutron-rich, odd-*Z* nuclei ^{145}La and ^{147}La populated in spontaneous fission of ^{248}Cm were studied using the EUROGAM array. The experiment indicates the presence of similar octupole correlations in the studied La isotopes as found in the barium core nuclei. Alternating-parity structures were found in ^{145}La, indicating enhanced octupole correlations, as observed in ^{144}Ba, while in ^{147}La octupole effects are weakened by alignment phenomena, as seen in the core nucleus ^{146}Ba. [S0556-2813(96)03008-7]

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Theoretical calculations [1,2] have predicted a region of strong octupole effects in neutron-rich nuclei with atomic numbers near 56 and neutron numbers near 88. If these correlations are strong enough, the reduction in total energy they produce may induce a stable octupole deformation characterized by a nonzero value of deformation parameter β_3. Nuclei with $Z\sim56$ are favored candidates due to a predicted [1–3] gap in proton levels at $Z=56$ for $\beta_3\sim0.1$, with consequent large shell correction energy. The presence of strong octupole correlations in this region has been confirmed by studies of even-even isotopes, in which negative-parity bands have been observed [4,5] interlacing in spin with the positive-parity ground-state bands, the opposite parity sets usually being connected by strong electric dipole transitions. More distinctive signatures of octupole deformation are expected in odd-*A* isotopes. If reflection asymmetric mean fields are present at low energy in odd-*A* nuclei, parity doublet bands should be present in the low-energy structure. The predicted gap in proton levels for octupole deformed $Z=56$ nuclei should make Cs isotopes good candidates for observing parity doublets. However, recent experiments [6] have shown no evidence for strong octupole correlation effects in ^{141,143,145}Cs nuclei. If the distribution of proton orbits predicted in Ref. [1] is correct, the La isotopes with $Z=57$ should experience weaker octupole effects than $Z=55$ or $Z=56$ nuclei since the odd proton occupies an orbit whose energy increases as β_3 moves away from zero. We have studied previously unknown yrast decay schemes for ^{145}La and ^{147}La to examine this prediction. This work also extends a program designed to determine whether any odd-*A* nuclei in the lanthanide region show good characteristics of the parity doublet bands anticipated in reflection asymmetric nuclei.

The ^{145}La and ^{147}La nuclei were produced in the spontaneous fission of ^{248}Cm. The fission source consisted of 5 mg of curium oxide embedded uniformly in a pellet of potassium chloride. Three- and higher-fold γ-ray coincidence data were collected using the EUROGAM2 array at Strasbourg. This detector array consisted of 52 large Ge detectors in anti-Compton shields plus four planar Ge detectors (LEPS) used for the observation of x rays and low-energy transitions. Approximately 2.5×10^9 coincidence events were collected. The data were sorted into three separate three-dimensional arrays (cubes): (i) a ggl cube containing triple gamma coincidences between γ rays, two of which were observed in any Ge detector and one in any LEPS detector, (ii) a ggg cube containing triple coincidences between γ rays observed in any Ge detector, and (iii) a DCO cube containing triple coincidences between γ rays observed in Ge detectors at specific angles relative to each other. A two-dimensional projection of the DCO cube (DCO matrix) has been created as well to facilitate (approximate) γ-γ angular correlation measurements in some cases.

Assignment of γ rays to La isotopes was made by gating on the La x-ray line at 33.3 keV in the ggl cube. Identification of ^{145}La and ^{147}La was effected using γ-mass coincidences from γ-fragment measurements following the spontaneous fission of ^{252}Cf as described in Ref. [7]. Our identification agrees with the information on La isotopes reported previously [8,9]. In particular we confirm the 66 keV transition in ^{145}La [10] and the 167.4 keV transition in ^{147}La [11]. Gates set in the ggg cube on candidate lines corresponding to a particular La isotope enabled decay schemes for those nuclei to be obtained. The partial levels schemes constructed for ^{145}La and ^{147}La are shown in Fig. 1.

In ^{145}La 26 new transitions were found, identifying 15 new excited levels. The levels in ^{145}La can be arranged into four bands, as marked in Fig. 1. For the ground state, spin and parity $I^{\pi}=(\frac{5}{2},\frac{7}{2})^+$ have been proposed [10]. The proposed spin assignments for other levels are based on double and triple directional correlation measurements [12], internal conversion coefficients, and branching ratios. Together, all the data obtained make a strong argument for the spin and parity assignments shown on the figure. The γ-γ angular correlations between the 384.2 keV and 238.0 keV γ rays are consistent with a stretched quadrupole nature for the two transitions. The correlation data are also consistent with the 172.0 keV γ ray connecting states differing in spin by 1. The

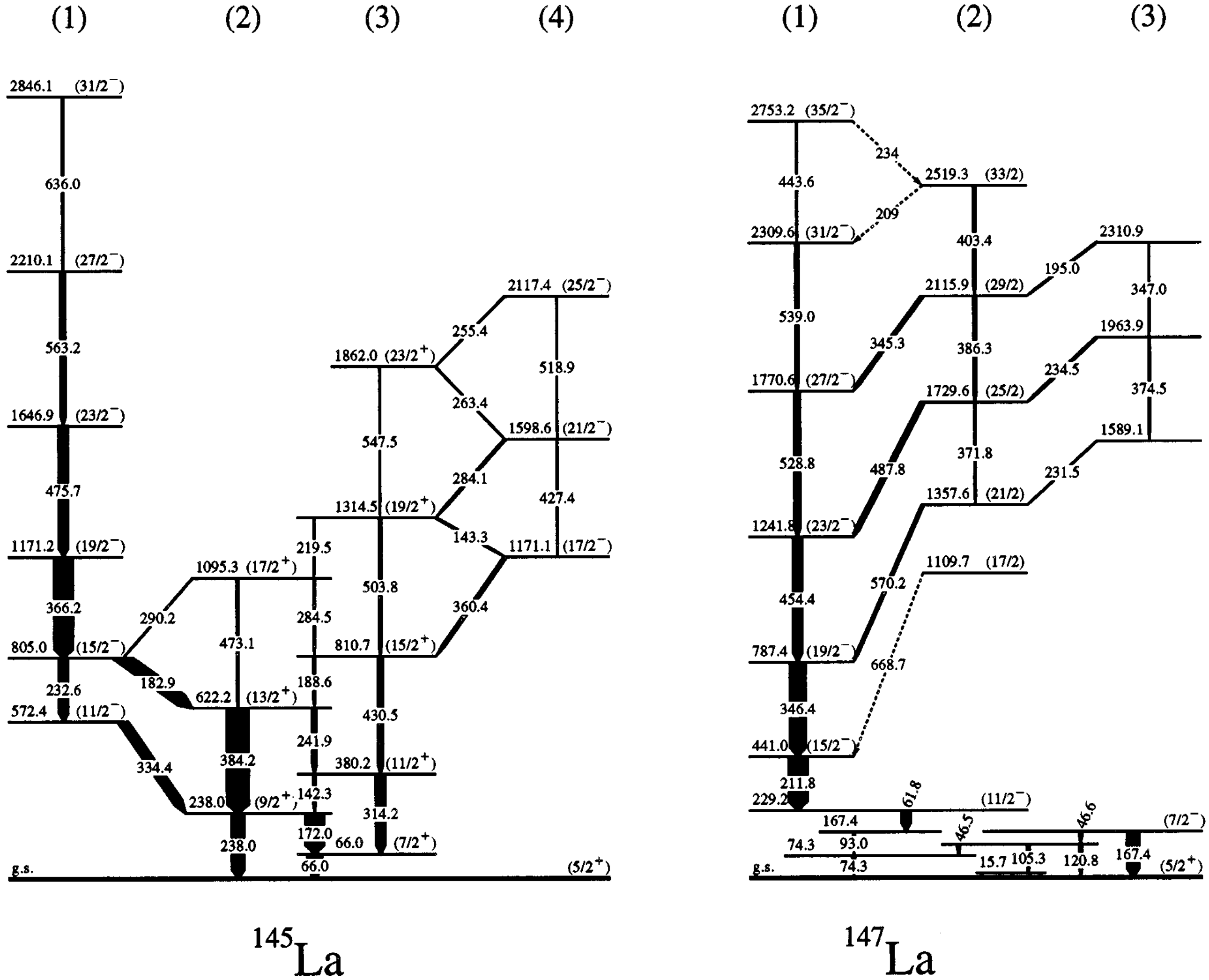

FIG. 1. Partial level schemes of ^{145}La and ^{147}La nuclei produced in spontaneous fission of ^{248}Cm. Band numbers indicated above levels schemes are discussed in the text.

K-conversion coefficients of the 66.0 keV and 172.0 keV transitions, obtained by gating in the ggl cube on preceding γ-ray lines, are 4 ± 1 and 0.5 ± 0.2, respectively. These values indicate that these transitions are not electric dipole ($E1$) and thus that they connect levels of the same parity. Therefore, the spin and parity of the 238.0 keV level are $\frac{9}{2}^+$ or $\frac{11}{2}^+$. The $\frac{9}{2}^+$ assignment is more likely (and consequently $I^\pi=\frac{5}{2}^+$ for the ground state) because this level is populated in the β decay of the $I^\pi=\frac{5}{2}^-$ ground state of ^{145}Ba. Triple angular correlations between the 182.9 keV γ ray and the following 384.2 and 238.0 keV $E2$ transitions are consistent with the 182.9 keV γ ray being a stretched dipole. The total conversion coefficient of that transition measured from the intensity balance in and out of the 622.2 keV level in a spectrum obtained by double gating on the 238.0 keV and 366.2 keV lines in the ggg cube is 0.15 ± 0.08. This value indicates that the 182.9 keV transition has $E1$ character and, with the angular correlation data, suggests spin and parity $I^\pi=\frac{15}{2}^-$ for the 805.0 keV state. Other assignments follow from the assumptions of stretched $E2$ character for the in-band transitions, supported by angular correlation data. The spin and parity assignments to the 1171.2, 1598.6, and 2117.4 keV levels are based on the observed branching ratios to the levels in the positive-parity band. If the interband transitions were of magnetic dipole character, they would have unusually large strengths compared with the strengths of the intraband transitions, assuming an intrinsic quadrupole moment of the size anticipated in this region. An additional argument supporting these assignments is the nonobservation of a transition between the 1171.2 keV and the 622.2 keV levels.

In ^{147}La 15 new levels were identified. We confirm transitions depopulating the levels at 74.3, 120.8, and 167.4 keV, observed in the β decay of ^{147}Ba [9]. The newly found 61.8 keV transition is in coincidence with all the other transitions. Since it was not observed in the β decay of ^{147}Ba, we have placed it on top of the 167.4 keV level. Conversion coefficients for the 61.8 keV transition, obtained from the coincidence data, of $\alpha_K=6\pm1$ and $\alpha_{\text{tot}}=12\pm2$ indicate its $E2$ character. An $E1$ character has been proposed for the 167.4 keV transition [9]. The present angular correlation data and the total conversion coefficient of 0.05 ± 0.02 confirm the stretched $E1$ character for this transition. Consequently, the spin and parity of the 167.4 keV level are $I^\pi=\frac{3}{2}^-$ (as proposed in [9]) or $I^{\pi}=\frac{7}{2}^{-}$. The latter values are more likely since otherwise the spin of the 229.2 keV level is less than $\frac{9}{2}$, in which case it should be populated in the β decay of the $I=(\frac{3}{2}^{-})$ ground state of ^{147}Ba and there should be a transition from the 229.2 keV level to the ground state. The lack of such observations suggests higher spin for the 167.4 keV and 229.2 keV levels. This is consistent with the fact that the fission process favors population of yrast levels and it is unlikely that one would observe a high-spin structure decaying to an $I=\frac{3}{2}$, 167.4 keV level rather than to the $I=\frac{5}{2}$ ground state. It is therefore proposed that the spins of the 167.4 keV and 229.2 keV levels are $I^{\pi}=\frac{7}{2}^{-}$ and $I^{\pi}=\frac{11}{2}^{-}$, respectively. Angular correlation data suggest that the yrast band above the 229.2 keV state consists of stretched $E2$ transitions. From the present data we could not find the multipolarity of the interband transitions but the most likely spin for the 1357.6 keV level is $I=\frac{21}{2}$, considering its excitation energy and the decay pattern. The 668.7, 209, and 234 keV transitions drawn as dashed lines in Fig. 1 are obscured by similar transitions in other nuclei. This prevents their firm placement in ^{147}La.

The positive-parity levels in ^{145}La (bands 2 and 3), which are linked by $M1/E2$ transitions, form a strongly coupled band based on the $g_{7/2}$ proton configuration as suggested in [1]. This is supported by similar values of the $(g_K-g_R)/Q_0$ parameter, 0.11(1) on average, deduced for bands 2 and 3, following the procedure described in [13]. The situation is less clear, in terms of configuration, for the two negative-parity bands (1 and 4). The alignments of the two positive-parity bands (2 and 3) are identical and so are the alignments of the two negative-parity bands (1 and 4). This is shown in Fig. 2. The observation of interlocking $E1$ transitions may suggest that the whole structure observed in ^{145}La corresponds to a parity doublet. However, while similar alignments and the presence of pronounced interband transitions support a structural similarity of bands 2 and 3, the negative-parity bands (1 and 4) show large signature splitting and there are no linking transitions between them. The situation here is similar to that observed in ^{151}Pm [14] and ^{153}Eu [15], where the positive-parity levels show different magnetic properties from the negative-parity levels in parity-doublet-like structures. It is likely that the two negative-parity bands in ^{145}La are of different origin. Similar alignments, approximately 3 units higher than for the positive-parity bands, suggest that one band may correspond to the $d_{5/2}\rightarrow h_{11/2}$ proton excitation and the other to an octupole phonon coupled to the ground-state band. The band on top of the 572.4 keV level shows characteristics of a unique-parity configuration and probably corresponds to the $h_{11/2}$ proton excitation, while the other band could be due to an octupole phonon coupled to the ground-state band. The lack of any pronounced backbending, as is also observed in the core nucleus ^{144}Ba and is related to strong octupole correlations [16], suggests the presence of strong octupole effects in ^{145}La. This is supported by the presence of $E1$ transitions in the decay scheme. The corresponding $B(E1)/B(E2)$ branching ratios are shown in Fig. 3. Their values, approaching 10^{-6} fm^{-2} at medium spins, are as high as observed in ^{144}Ba. It is interesting to note that $B(E1)/B(E2)$ ratios for transitions between bands 3 and 4 (three points at high spins) are larger than those for $E1$ transitions between bands 1 and 2 (the two lower points). This could be due to the odd particle occupying the $h_{11/2}$ proton orbital, thereby blocking the $d_{5/2}$-$h_{11/2}$ contribution to octupole correlations [17].

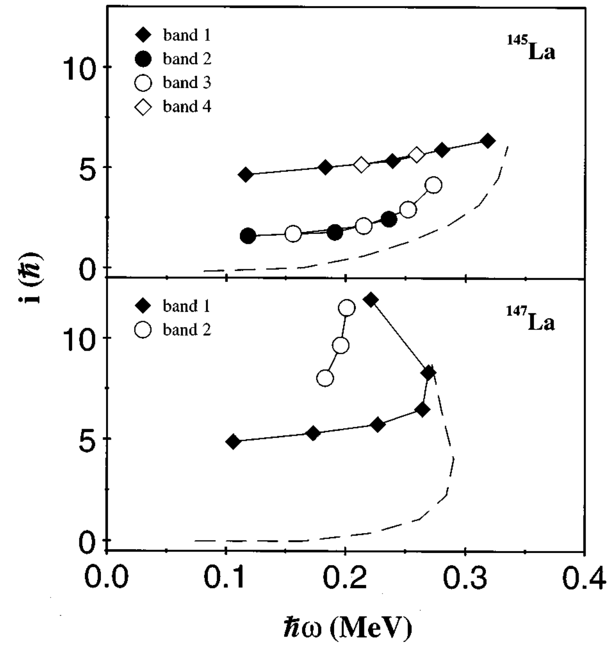

FIG. 2. Alignments in the ground-state alternating-parity bands of ^{145}La and ^{147}La. The Harris parameters used were $\Theta_0=19\hbar^2$/MeV and $\Theta_1=80\hbar^4$/MeV^2. Dashed lines represent alignment plots for ground-state bands in ^{144}Ba (upper panel) and ^{146}Ba (lower panel). Band numbers are as defined in Fig. 1.

The 229.2 keV level in ^{147}La is most likely due to proton excitation to the $h_{11/2}$ orbital. The excitation scheme above the 229.2 keV level resembles the ground-state band in ^{146}Ba [4] with an octupole band decaying to it. A possible explanation of the decay scheme observed in ^{147}La is in terms of ^{146}Ba core excitations coupled to the odd proton in the $h_{11/2}$ orbital. The fact that one observes two rather non-rotational bands (2 and 3), instead of one regular octupole band, results from a specific coupling of the octupole phonon to the $h_{11/2}$ proton orbital [17]. If the above interpretation is correct, ^{147}La should exhibit the same weak octupole correlations as seen in the ^{146}Ba core. In particular, as can be seen from Fig. 3, $B(E1)/B(E2)$ branching ratios for bands 1 and

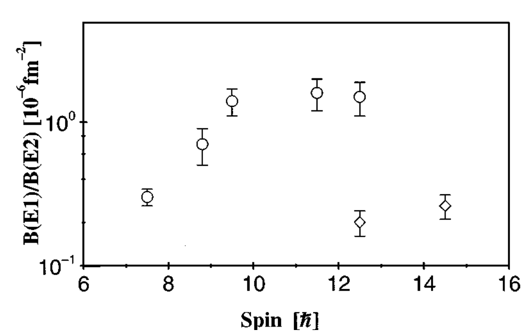

FIG. 3. $B(E1)/B(E2)$ branching ratios in ^{145}La (circles) and ^{147}La (diamonds) nuclei.

2 in ^{147}La are an order of magnitude smaller than in ^{145}La, probably due to the small electric dipole moment in the core nucleus ^{146}Ba [4,16]. It is worth noting that, as shown in Fig. 2, band 1 displays a pronounced backbending, similar to that in the ground-state band of ^{146}Ba (blocking arguments suggest that the backbending is due to alignment of a pair of neutrons in the $i_{13/2}$ orbital). The presence of such a pronounced backbending indicates that octupole correlations are weak in ^{147}La.

The new information obtained in this work for ^{145}La and ^{147}La suggests that octupole correlations in the neutron-rich La isotopes are similar in strength to those observed in their Ba core nuclei. It appears that the addition of a proton does not change the degree of octupole correlation effects. This is in contradiction to the theoretical predictions [1] that proton shell structure should lead to weaker octupole effects in $Z=57$ nuclei as compared to $Z=55$ or $Z=56$ nuclei. In fact, the experimental data suggest stronger octupole effects in lanthanum than in cesium isotopes. The observed decrease of $E1$ strength in ^{147}La as compared to ^{145}La resembles the similar effect observed in the ^{144}Ba and ^{146}Ba core nuclei, in accordance with calculations which assume the presence of octupole deformation in these nuclei. However, since the structure observed in ^{145}La does not exhibit the full characteristics of a parity doublet, the presence of stable octupole deformation in lanthanum nuclei remains an open question. Further experiments are required to resolve this problem. The new data obtained in this work provide an important test for theoretical models predicting stable octupole deformation in the region. One may hope that new calculations could answer the central question about its presence. Despite a growing body of experimental data, it is still not clear whether lanthanide nuclei have a stable octupole deformation. This is in fact a general problem, concerning all regions where enhanced octupole effects have been observed, since in no odd-A or odd-odd nucleus has one seen the complete set of features characteristic of stable octupole deformation in a nucleus, including both electric *and* magnetic properties of γ transitions.

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