OCTUPOLE CORRELATIONS AND DEFORMATION IN Ba, La AND Pr*

J.H. Hamilton[a], Y.X. Luo[a,b], J.K. Hwang[a], E.F. Jones[a]
A.V. Ramayya[a], S.H. Zhu[a,c,d], P.M. Gore[a], C.J. Beyer[a]
J. Kormicki[a], X.Q. Zhang[a], T.N. Ginter[a], M.G. Wang[d]
J.D. Cole[e], M.W. Drigert[e], W.C. Ma[f], P.G. Varmette[f]
G.M. Ter-Akopian [a,c,g] Yu.Ts. Oganessian[g], A.V. Daniel[g]
J. Kliman[g,h], J.O. Rasmussen[i], I.Y. Lee[i]
R. Donangelo[j], A.P. de Lima[k]

and GANDS95 Collaboration

[a]Department of Physics and Astronomy, Vanderbilt University
Nashville, TN 37235, USA
[b]Institute of Modern Physics, Lanzhou 730000, China
[c]Joint Institute for Heavy Ion Research, Oak Ridge, TN 37835, USA
[d]Physics Department, Tsinghua University, Beijing, China
[e]Idaho National Engineering and Environmental Lab., Idaho Falls, ID 83415, USA
[f]Department of Physics, Mississippi State University, MS 39762, USA
[g]Joint Institute for Nuclear Research, Dubna 141980, Russia
[h]Institute of Physics, Slovak Academy of Sciences, Bratislava, Slovakia
[i]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[j]Instituto Fisica, Universidade Federal, Rio de Janeiro, Brazil
[k]Physics Department, University of Coimbra, P-3000, Coimbra, Portugal

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Stable octupole deformation was predicted and subsequently found to occur centered around the reinforcing shell gaps at $Z = 56$ and $N = 88$ for $\beta_3 \simeq 0.15$. Evidence for stable octupole deformation is reviewed. New results in ^{145}Ba and ^{141}Ba are presented. Rotational enhancement of octupole deformation is found at intermittent spins in Ba and La nuclei and the quenching of such deformation at higher spins in ^{146}Ba but not in ^{144}Ba. Symmetric and asymmetric shapes coexist in ^{145}Ba and ^{145}La. Evidence for octupole correlation is found in ^{147}Pr but only $h_{11/2}$ bands are found in ^{149,151}Pr. The new ^{141}Ba levels have two sets of two intertwined bands of levels with the characteristics of octupole deformation as found in ^{143,145}Ba, however, a problem occurs with the assignment of parities in ^{141}Ba.

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1. Introduction

A new region of stable octupole deformation was proposed based on deformed shell model calculations which showed large shell gaps at $Z = 56$ and $N = 88$ for $\beta_3 \simeq 0.15$ [1,2]. The shell gaps at the same large β_3 for protons and neutrons reinforce each other to drive the nucleus to stable octupole deformation, another example of reinforcing shell gaps [3,4]. Static octupole deformation in nuclei occurs when the Fermi level lies between single particle orbitals with $\Delta N = 1, \Delta L = 3$ and $\Delta j = 3$. For $Z = 56$ and $N = 88$, these orbitals are $\pi d_{5/2}, h_{11/2}$ and $\nu f_{7/2}, i_{13/2}$.

The first evidence for octupole deformation in this region was reported in ^{144,146}Ba [5], ^{146}Ce [6] and then in ^{148}Nd [7]. Leander *et al.* [8] predicted ^{145}Ba to be a good candidate for octupole deformation. In decay [9] and spontaneous fission studies [10-12], however, no evidence for octupole deformation was found in ^{145}Ba. The first evidence for octupole deformation in an odd-A system was discovered in ^{143}Ba [10,13]. It was predicted theoretically [15] that rotation could enhance stable octupole deformation of intermediate spins and quench it at higher spins and both behaviors are observed [13]. Evidence for octupole correlations is observed in ^{139}Xe, ^{140,141,142}Ba and ^{144}Ce [10,12,14,16,17]. The odd-Z ^{145,147}La were reported to have octupole correlations [18]. Our recent extension of the levels in ^{145,147}La to higher spins gives evidence for rotational enhancement of stable octupole deformation [19].

We have found the first evidence of octupole deformation in ^{145}Ba and expanded information on ^{143}Ba [20]. A surprising new type of band structure with equal kinetic and dynamic moments of inertia, both equal to the rigid body value, is found in ^{145}Ba. In ^{145}La and ^{145}Ba we find evidence for the coexistence of symmetric and asymmetric shapes to confirm the long-standing theoretical predictions [21,22]. Recently we reinvestigated ^{141}Ba [23]. Two new bands are observed and the pairs of bands now appear to be like those expected for stable octupole deformation with $s = \pm i$ as found in ^{143,145}Ba. However, there is one problem with this interpretation. The levels in $Z = 59$ ^{147,149,151}Pr have been identified. In ^{147}Pr with $N = 88$, evidence for octupole correlations and/or deformation is found but not in ^{149,151}Pr [24].

The nuclei were studied in the spontaneous fission of ^{252}Cf. Prompt γ–γ–γ coincidence studies were carried out with Gamma sphere with 72 Compton-suppressed Ge detectors. A 28μCi ^{252}Cf source was placed at the center of Gamma sphere. Three-dimensional histograms (cubes) of the coincidence events were constructed from three separate runs in 1995 (for details see [10,13]).

2. Octupole deformation and correlations in Ba nuclei

The extended levels in ^{144,146}Ba shown in Fig. 1 exhibit the classic pattern of opposite parity levels connected by enhanced E1 transitions. Cranked shell model calculations for the Ba–Ce nuclei around $N = 88$ indicate that

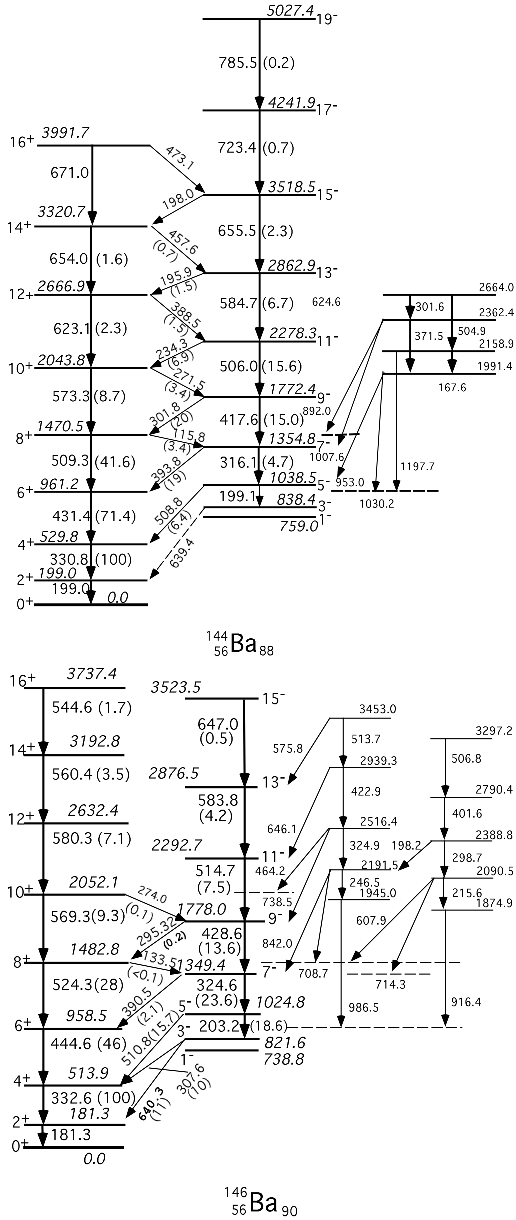

Fig. 1. Level schemes of ^{144,146}Ba.

at intermediate spins the octupole deformation increases and the octupole minima are much better separated. However, at higher spin and rotational frequency the octupole deformation is predicted to disappear. A transition to $\beta_3 = 0$ is expected above $\hbar\omega \approx 0.3$ MeV after the alignment of the $\nu i_{13/2}$ and $\pi h_{11/2}$ pairs [15]. For ^{144}Ba and ^{146}Ba, the ground bands are crossed (sharp upbends in J_1) above spin 12^+ and 10^+ in ^{144,146}Ba, respectively. Intertwined connecting transitions are not seen above 10^+ in ^{146}Ba but are seen to 16^+ in ^{144}Ba. The J_2 for the negative parity bands in ^{146}Ba has a sharp break at $\hbar\omega = 0.3$ while J_2 in ^{144}Ba is smooth to the highest spin (Fig. 2) [13]. The ^{146}Ba results are in agreement with the theoretical expectation of the vanishing of β_3 above $\hbar\omega = 0.3$ MeV but not ^{144}Ba. So the band crossings and quenching of octupole deformation at higher spins are different in ^{144,146}Ba.

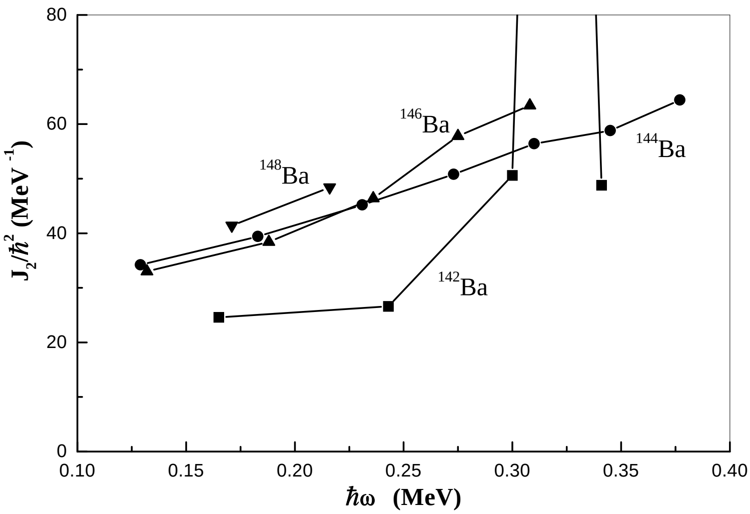

Fig. 2. Negative parity band moments of inertia J_2 as a function of $\hbar\omega$ for even–even Ba nuclei.

In ^{143}Ba we reported the first evidence for M1 and E1 transitions between these $s = \pm i$ doublets, to test their purity. Fig. 3 gives the new level scheme for ^{145}Ba including 28 new transitions and 15 new levels. In ^{145}Ba, two new collective bands, band -1 beginning at 671.1 keV and band -5 at 1463.1 keV, were found. Between bands -1 and -2, and between -4 and -5, two sets of intertwined, crossing transitions were assigned as E1 from systematics and the measured total conversion coefficient of the 126.5 keV transition which is in agreement with an E1 value. The ground band is a strong coupled band based on a symmetric rotor shape. Based on systematic comparison with neighboring nuclei ^{143,144,145}Ba and intertwined strong crossing transitions

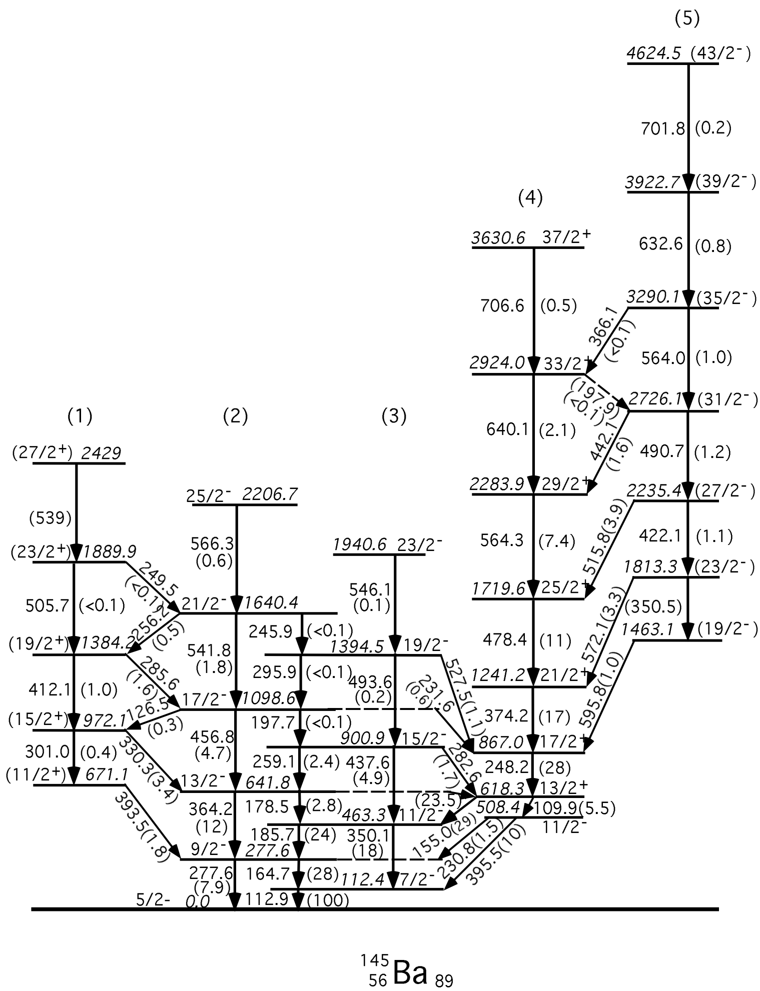

Fig. 3. Level scheme of ^{145}Ba.

between bands 1 and 2 and bands 4 and 5 with $B(\mathrm{E1})/B(\mathrm{E2})$ ratios similar to ^{143}Ba, the J_π of the 671.1 keV head of band 1 was assigned as $(11/2^+)$, and J_π of the 1463.1 keV head of band 5 was assigned as $(19/2^-)$. The error weighted average $B(\mathrm{E1})/B(\mathrm{E2})$ values in ^{143}Ba are $0.64(4) \times 10^{-6}$ fm^{-2} for $s = -i$ and $0.33(5) \times 10^{-6}$ fm^{-2} for $s = +i$, respectively, and for ^{145}Ba $0.55(6) \times 10^{-6}$ fm^{-2} for $s = -i$ and $0.36(5) \times 10^{-6}$ fm^{-2} for $s = +i$. These compare favorably with the average in ^{144}Ba of $0.88(8) \times 10^{-6}$ fm^{-2} excluding the low value for the 7^- state. The similarity of these data support the ^{145}Ba spin and parity assignments. These data indicate that the octupole correlations are very strong and lead to stable octupole deformation in both ^{143,145}Ba.

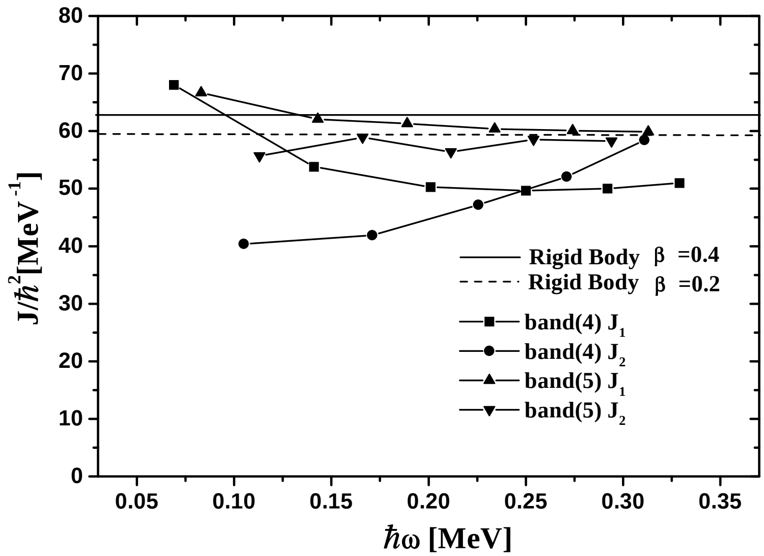

Fig. 4. Moments of inertia (J_1 and J_2) in ^{145}Ba.

Their bands 1 and 2, 4 and 5 form a typical octupole deformation structures similar to the $s = \pm i$ bands in ^{143,144,146}Ba. The moments of inertia J_1 and J_2 vs $\hbar\omega$ for band 4 and 5 in ^{145}Ba are shown in Fig. 4. For the $i_{13/2}$ band 4, the J_1 is very large at low rotational frequency and smoothly reduces as $\hbar\omega$ increases, but J_2 smoothly increases as $\hbar\omega$ increases. The J_1 and J_2 of band 5 are very large and are essentially constant and equal with increasing rotational frequency. Surprising, they essentially have a rigid body moment of inertia, the first such band observed in neutron rich nuclei. This could be the first example of a pairing-free rotational band in this region. On the other hand, it may be related to the same phenomenon that occurs in superdeformed bands in the light Hg–Pb region where octupole deformation plays a role in the SD bands. Indeed the large, constant, and essentially equal J_1 and J_2 for band 5 are very similar to the large, constant, and essentially equal J_1 and J_2 in the first superdeformed band in ^{152}Dy [25]. This rigid body band in ^{145}Ba definitely offers a new challenge for theory.

Shown in Fig. 5 is the new level scheme of ^{141}Ba established in the present work [23]. The band 1, previously assigned to be negative parity and a $\nu(\mathrm{f}_7/2)^3$ multiplet in ^{141}Ba, is confirmed up to $(19/2^-)$ but not the earlier reported 814.0 keV transition was not confirmed. Instead the 835.7 keV transition and tentatively assigned 770 keV transition are placed on the top of this band. Band 2 and 3 are extended to one level higher. The first four enhanced E1 transitions between negative parity band 1 and positive parity band 2 are confirmed and two additional crossing transitions are seen.

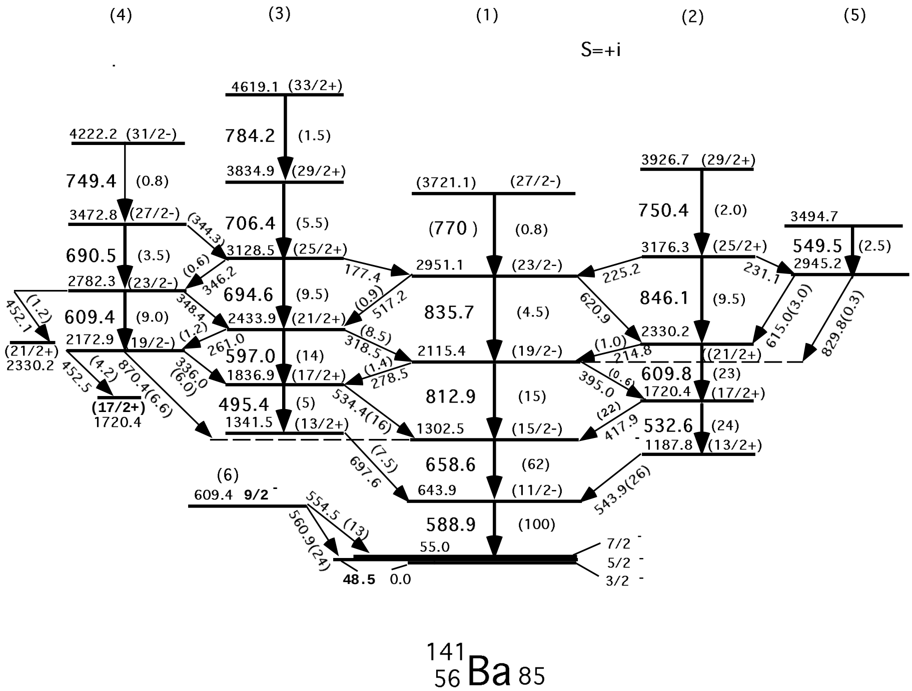

Fig. 5. Level scheme of ^{141}Ba.

New connecting transitions (E1) between band 1 and 3 were observed. Two new bands, band 4 and 5, were identified for the first time. Of particular interest is the observation of the new band 4. Five intertwined transitions were found between band 4 and 3. A new, strong intensity crossover transition of 870.4 keV was observed, connecting the bottom of band 4 with the 1302.5 keV level of band 1.

The 336.0 keV linking transition between band 4 and 3 supports a spin of 19/2 for the 2172.9 keV level of band 4. The strong 870.4 keV crossover transition connecting the 1302.5 keV ($15/2^-$) level and the 2172.9 keV level suggests that the 870.4 keV transition is most likely an $E2$ transition, and thus the two levels have the same parity (M2 multipolarity assignement to this 870.4 keV transition would seem unlikely). So negative parity should be assigned to the newly found band 4. Now three pairs of opposite parity bands are observed in ^{141}Ba, but with only simplex quantum number $s = +i$ assigned to the pair consisting of band 1 and 2, in contrast with ^{143,145}Ba (20), where two parity doublet bands are observed with $s = \pm i$. B(E1)/B(E2) ratios for opposite parity pairs bands 1 and 2, bands 3 and 4, and bands 1 and 3, range from 0.18 (3) to 1.18(4)($\times 10^{-6}$ fm^{-2}) with an average value of 0.51(4) $\times$ 10^{-6} fm^{-2}. These are compatible with those in

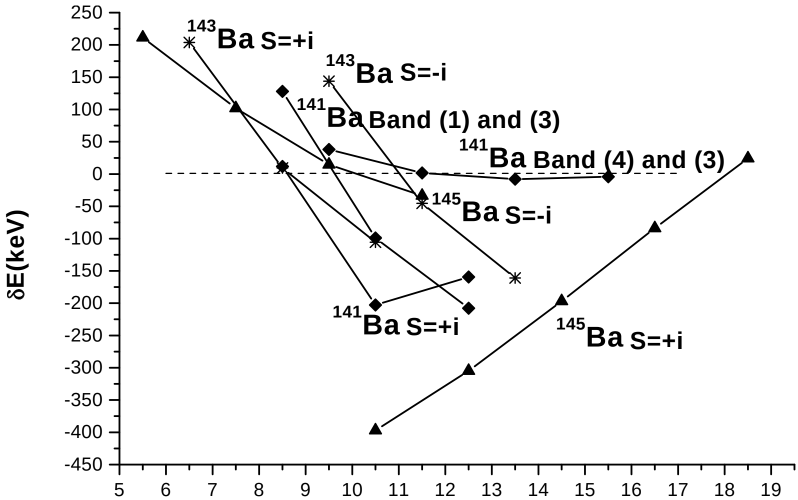

Fig. 6. Plot of ΔE vs spin I in ^{141}Ba.

the neighboring Ba isotopes given above. To study the static or dynamic properties of the octupole deformation, the energy displacement δE between the opposite parity bands

$$\delta E = E(I^+) - \tfrac{1}{2}\left[E(I+1)^- + E(I-1)^+\right]$$

and the corresponding rotational frequency ratios

$$\frac{\omega^+(I)}{\omega^-(I)} = \frac{2\left[E(I+1)^+ - E(I-1)^+\right]}{\left[E(I+2)^- - E(I-2)^-\right]}\,,$$

were calculated and are shown in Figs. 6 and 7, respectively, with comparison to those of ^{143,145}Ba. In the limit of stable octupole deformation δE and $\omega^+(I)/\omega^-(I)$ should approach zero and unity, respectively [2]. From Figs. 6 and 7 it can be seen that except for the $s=+i$ doublet of ^{145}Ba, δE and also $\omega^+(I)/\omega^-(I)$ show the same down-sloping and up-sloping variations with increasing spins, respectively. Of particular interest is the pronounced behavior of the newly found opposite parity band 4 and 3 in ^{141}Ba, with δE approaching zero line and the $\omega^+(I)/\omega^-(I)$ remaining near unity over almost all the observed spin range, indicating possible stable octupole deformation. If the 870.4 keV transitions were not present, bands 4 and 3 with positive and negative parity would have all the characteristics of the $s=-i$ band with the same spins and opposite parities to those of the $s=+i$ bands 1 and 2 as expected for stable octupole deformation. It is not clear which parities are correct for bands 3 and 4. All the data but the 870.4 keV

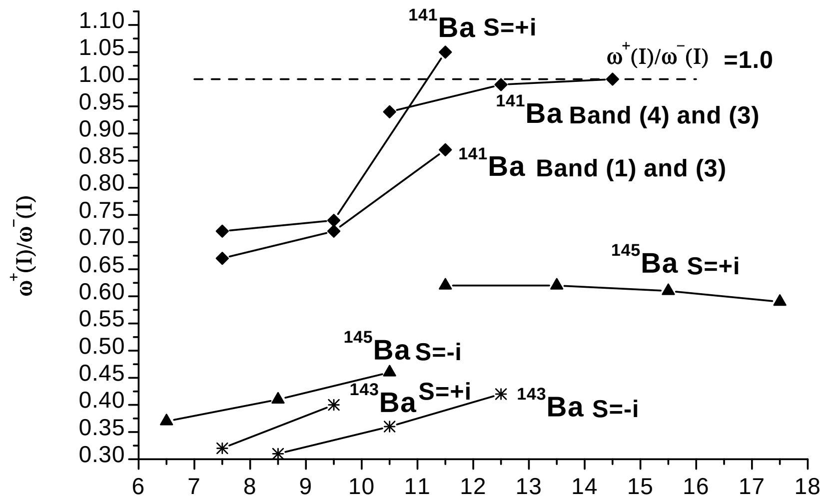

Fig. 7. Rotational frequency ratios vs spin I in ^{141}Ba.

transition strongly favor their being the $s = -i$ bands. The 870.4 keV M2 transition would have half life of the order of 10^{-9}s. Such a transition at the bottom of a band might compete with an E1 transition which is typically hindered by 10^2–10^5. So the parities of bands 3 and 4 are open. In summary, the previously reported opposite parity bands 1 and 2, 1 and 3 and the newly observed opposite parity bands 4 and 3 in ^{141}Ba connected by enhanced E1 transitions, are characteristic of octupole deformations and/or correlations.

3. Octupole deformation and correlations in ^{145,147}La

In Fig. 8 are shown 11 new levels and 22 new transitions in ^{145}La $Z = 57$, $N = 88$ mostly at high spin [19] beyond those reported in [18]. The measured conversion coefficient verifies the parity change between bands −4 and −5. A new high-spin band −2 beginning at 2186.0 keV has intertwined crossing transitions to band −1. In ^{147}La, six new levels and 9 new transitions to high spins were seen beyond [18].

Ground bands −2, −3 in ^{145}Ba and −3, −4 in ^{145}La to $19/2^-$ are similar and likely originate from Coriolis-mixed $\nu h_{9/2}$ and $\nu f_{7/2}$ orbitals in ^{145}Ba and $\pi g_{7/2}$ and $\pi d_{5/2}$ orbitals in ^{145}La built on a well-deformed symmetric rotor shape. The $\Delta I = 2$ and $\Delta I = 1$ transitions are collectively coupled with signature splitting.

Bands −1 (presumably originating from an $h_{11/2}$ excitation) and −2 in ^{145,147}La are similar with enhanced crossing E1 transitions and suggest static octupole deformation assigned $s = +i$ with asymmetric shape.

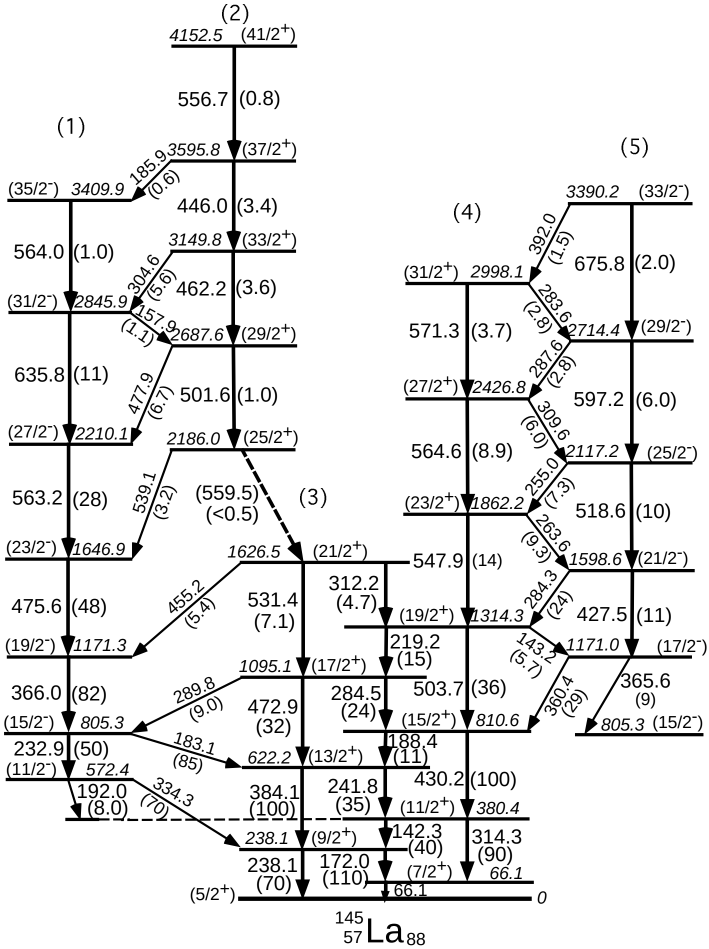

Fig. 8. Level scheme of ^{145}La.

From the $23/2^+ \to 19/2^+$ transition, J_1 unbends sharply in band -4 but not in band -5, suggesting the $19/2^+$ (or $23/2^+$) to $31/2^+$ levels are not a continuation of band -4. The $B(\mathrm{E1})/B(\mathrm{E2})$ values of the $s = -i$ doublet (bands $-4, -5$) in ^{145}La, above $19/2^+$ are constant and comparable to or larger than those in ^{144}Ba, suggesting octupole deformation (or correlation) from rotation enhancement above $19/2^+$ and a shift from symmetric to asymmetric shape.

Below $I^\pi = (21/2^+)$ in the $s = +i$ doublet of ^{145}La, low $B(\mathrm{E1})/B(\mathrm{E2})$ values for bands -1 and -3 suggest weak octupole correlations. The E2 strengths around the band crossings are much reduced. Bands $-1, -2$ and bands -4 (at higher spins), -5 form the two sets of parity doublets seen in stable octupole deformation.

In summary, the new high spin states in ^{145,147}La and ^{143,145}Ba support the existence of stable octupole deformation or at least strong octupole correlations in these nuclei. These new data confirm the long-standing theoretical prediction [3] of stable octupole deformation in ^{145}Ba. The strong-coupling ground band and octupole deformation structures in ^{145}La and ^{145}Ba show competition and coexistence between symmetric and asymmetric shapes to confirm the long standing theoretical predications that such coexistence could occur for certain single particle orbitals [21,22]. A new band with rigid body moments of inertia in ^{145}Ba may be the first example in neutron rich nuclei of a pairing-free structure or of a type of superdeformed band. This new structure offers a challenge for theory.

4. Octupole correlations in ^{147}Pr and $\pi h_{11/2}$ bands in ^{149,151}Pr

New transitions in ^{147,149,151}Pr were discovered by gating on transitions in the appropriate partner Y fragments and on a few low energy transitions known from ^{149,151}Ce beta decay to ^{149,151}Pr. The level schemes of these three isotopes are shown in Fig. 9 [24].

The two new higher spin bands discovered in ^{149,151}Pr resemble the ground state rotational bands in ^{148,150}Ce as seen by comparing their transition energies. A proton $h_{11/2}$ decoupled band was discovered in ^{147}La with $N = 90$ [18,19]. Therefore the bands in ^{149,151}Pr can be understood as coupling of a $h_{11/2}$ proton to the ^{148,150}Ce cores. The $h_{11/2}$ band in ^{149}Pr shows back bending at $\hbar\omega \approx 0.27$ MeV, the same as in the proton $h_{11/2}$ band in ^{147}La. Cranked shell model calculations [18] suggest this backbending at $\hbar\omega \approx 0.27$ MeV originates from alignment of the neutron $\mathrm{i}_{13/2}$ pair, not of the proton $h_{11/2}$ pair which occurs at $\hbar\omega \approx 0.40$ MeV [19]. The $B(\mathrm{E1})/B(\mathrm{E2})$ ratios of $0.33 \times 10^{-6}\mathrm{fm}^{-2}$ for the 288.2(E1) and 381.6(E2) keV and $0.60 \times 10^{-6}\mathrm{fm}^{-2}$ for 335.2(E1) and 453.7(E2) keV transitions in ^{147}Pr were extracted from coincidence spectra. The four $B(\mathrm{E1})/B(\mathrm{E2})$ ratios for ^{146}Ce go from 0.70 to 2.1 with average about 0.90×10^{-6} fm^{-2}. The $B(\mathrm{E1})/B(\mathrm{E2})$ ratios in ^{147}Pr are smaller than those in ^{146}Ce but still show definite enhancement of the E1 transitions.

The absence of parity doublets in ^{147}Ce with $N = 89$ [26] but seen in ^{146}Ce indicates that the addition of an odd neutron blocks the octupole correlations in ^{147}Ce. The addition of a proton to ^{146}Ce does not change the degree of octupole correlation in ^{147}Pr. The level scheme of ^{147}Pr with $N = 88$ is very similar to that observed in ^{145}La with $N = 88$ where octupole correlations are observed. The absence of parity doublets in ^{149,151}Pr is expected because their core nuclei, ^{148,150}Ce do not show octupole correlations. Instead, in ^{149,151}Pr, $h_{11/2}$ decoupled bands are observed.

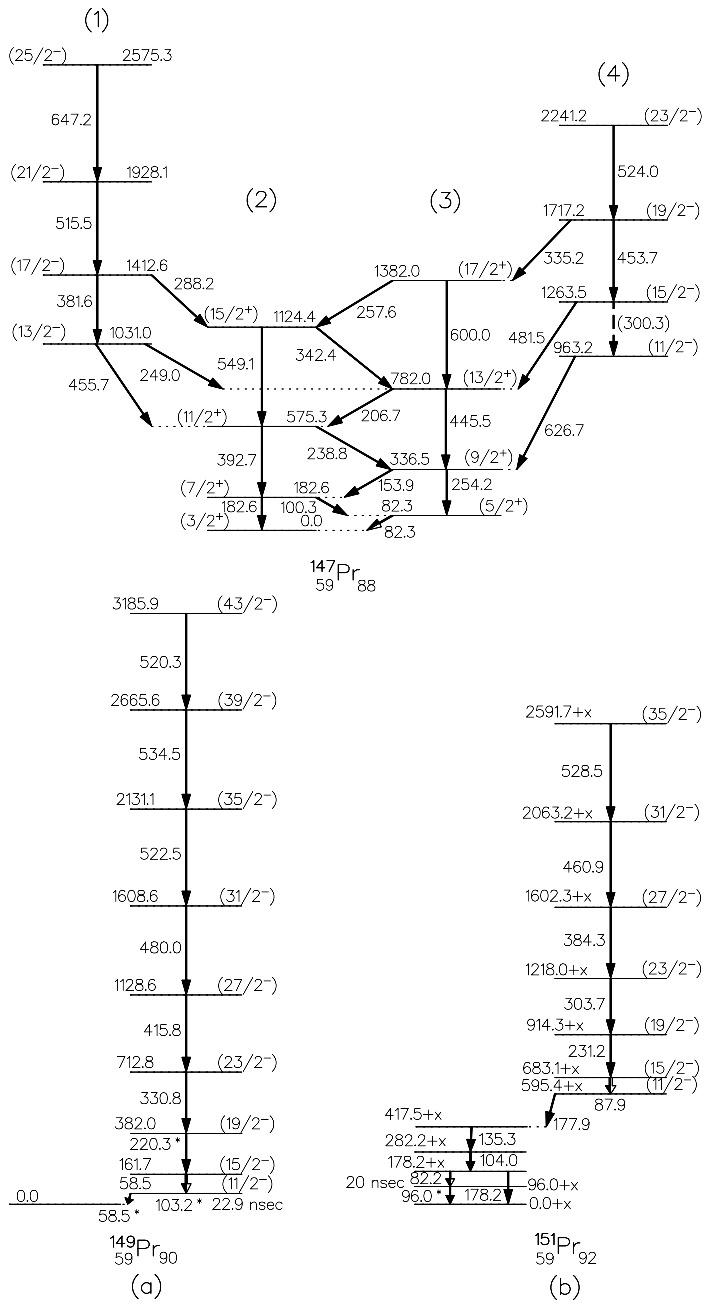

Fig. 9. Level schemes of ^{147,149,151}Pr.

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