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Octupole correlations in neutron-rich ^{143,145}Ba and a type of superdeformed band in ^{145}Ba

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High spin states in neutron-rich odd-Z ^{143,145}Ba nuclei have been investigated from the study of prompt γ rays in the spontaneous fission of ^{252}Cf by using γ-γ- and γ-γ-γ- coincidence techniques. Alternating parity bands are identified for the first time in ^{145}Ba and extended in ^{143}Ba. A new side band, with equal, constant dynamic, and kinetic moments of inertia equal to the rigid body value, as found in superdeformed bands, is discovered in ^{145}Ba. Enhanced $E1$ transitions between the negative- and positive-parity bands in these nuclei give evidence for strong octupole deformation in ^{143}Ba and in ^{145}Ba. These collective bands show competition and coexistence between symmetric and asymmetric shapes in ^{145}Ba. Evidence is found for crossing $M1$ and $E1$ transitions between the $s=+i$ and $s=-i$ doublets in ^{143}Ba. [S0556-2813(99)50810-8]

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Theoretical calculations in the deformed shell model suggested the existence of an island of stable octupole deformed nuclei around $Z=56$ and $N=88$ [1,2]. Leander *et al.* [3] predicted that the odd-N ^{145}Ba is a good candidate for octupole deformation. Searches for octupole deformation in ^{145}Ba, including β-decay work [4] and spontaneous fission studies found some collective bands [5–7] but no evidence for octupole deformation. The first evidence for octupole deformation in this region was reported in ^{144,146}Ba [8], ^{146}Ce [9], and then in ^{148}Nd [10]. The first evidence for octupole deformation in an odd-A system in this region was discovered in ^{143}Ba [5,11]. Both $s=\pm i$ parity doublets were then reported in ^{143}Ba [6] and confirmed in our work [12]. Evidence for octupole correlations and deformation is also observed in ^{139}Xe, ^{140,141,142}Ba, and ^{144}Ce [5,7,11–14]. The odd-Z ^{145,147}La also are reported to have strong octupole correlations [15] with the evidence significantly extended in our work [16]. Thus, an island of stable octupole deformation around the $Z=56$, $N=88$ region is established. However, evidence for octupole deformation was not found in ^{145}Ba as was predicted to occur [3].

Here we report the first evidence of octupole deformation in ^{145}Ba and expanded level structures in ^{143}Ba. A surprising new type of band structure with equal kinetic and dynamic moments of inertia and equal to the rigid body is found in ^{145}Ba. These properties are characteristic of the superdeformed bands first observed in ^{152}Dy [17]. Also, we find the first evidence of crossing transitions between the $s=\pm i$ parity doublets in ^{143}Ba. These transitions test the purity of these doublets.

The ^{143}Ba and ^{145}Ba nuclei were studied in the spontaneous fission of ^{252}Cf. Prompt γ-γ-γ-coincidence studies were carried out with Gammasphere with 72 Compton-suppressed Ge detectors. A 25 μCi ^{252}Cf source was covered by a $11.3\ \mathrm{mg/cm^2}$ Ni foil and $13.7\ \mathrm{mg/cm^2}$ Al foil on both sides and placed at the center of the Gammasphere. Three-dimensional histograms (cubes) of the 2.9×10^{10} coincidence events were constructed. Details of the experimental techniques are described elsewhere [5,7,11].

The new level schemes for ^{143}Ba and ^{145}Ba are shown in Figs. 1 and 2. The bands connected by stretched $E2$ γ transitions inside the band are numbered. All previously reported transitions in [5,6,11] were confirmed. Many new transitions

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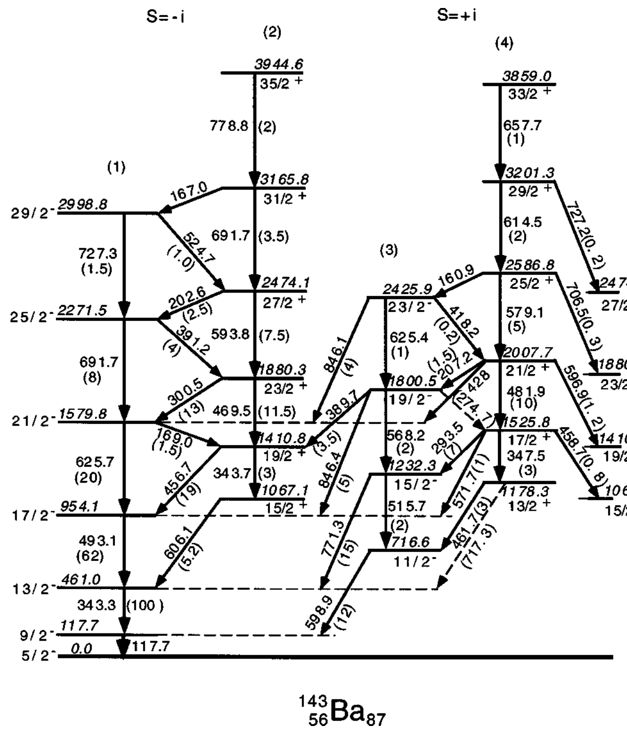

FIG. 1. Level scheme of ^{143}Ba.

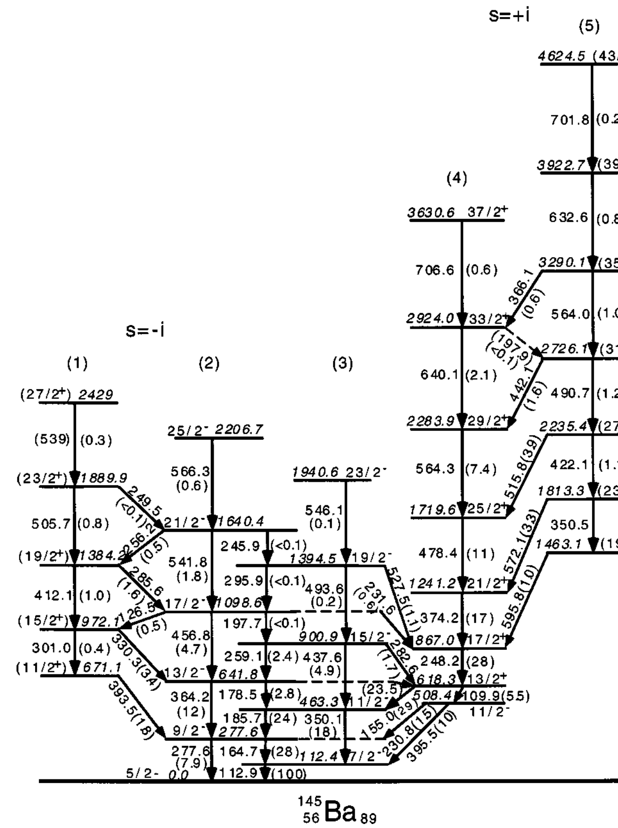

FIG. 2. Level scheme of ^{145}Ba.

and levels are observed. In ^{143}Ba, a new level at 2425.9 keV was added to band (3). New $E1$ crossover transitions, 207.2, 418.2, and 160.9 keV, between bands (3) and (4), along with a tentative one at 274.7 keV, were found. Other new transitions of ($E1$) 389.7 and ($M1$) 846.1 keV between the $s=+i$ band (3) and $s=-i$ bands (2) and (1), and $M1$ transitions of 458.7, 596.9, 706.5, and 727.2 keV and $E1$ transitions of 428, 571.7, and tentatively 717.3 keV between the $s=+i$ band (4) and the $s=-i$ bands (2) and (1), respectively, were also found. $B(M1)/B(E2)$ values between bands (1) and (3) range from $2-4\times10^{-5}$ $\mu_N^2/e^2\text{fm}^4$ and between bands (2) and (4) are of the order of 1×10^{-6} $\mu_N^2/e^2\text{fm}^4$.

In ^{145}Ba, two new collective bands, (1) with 671.1, 972.1, 1384.2, 1889.9, and 2429 keV levels and (5) with 1463.1, 1813.3, 2235.4, 2726.1, 3290.1, 3922.7, and 4624.5 keV levels, were discovered. Two sets of intertwined, crossing transitions of 393.5, 330.3, 126.5, 285.6, 256.2, and 249.5 keV between bands (1) and (2), and of 595.8, 572.1, 515.8, 442.1, (197.9), and 366.1 keV between bands (4) and (5) were also observed and assigned as $E1$ based on systematics and the measured total conversion coefficient of the 126.5 keV transition [0.08(20)], which agrees with an $E1$ value (0.11) but cannot definitely exclude an $M1$ value (0.53). This internal-conversion coefficient was extracted from the 301.0 – 505.7 keV double gated spectrum by comparing the γ-ray intensities of the intermediate 126.5 and 285.6 keV cascade transitions. A new level is added to bands (2), (3), and (4). Three new $E1$ side transitions, 23.5 and 231.6 keV between bands (2) and (4) and 282.6 keV between bands (3) and (4) are also found. A total of 28 new transitions and 15 new levels were found in ^{145}Ba.

Some double gated spectra in ^{145}Ba are shown in Fig. 3. When we gate on the 164.7 and 330.3 keV transitions, the transitions 112.9, 364.2, 412.1, and 505.7 keV in bands (1) and (2), and the partner transitions in ^{103,104,105}Mo are seen. In Fig. 3, the 185.7 keV transition is much stronger than the 178.5 keV and 155.0 keV transitions. These intensity differences provide evidence for the existence of a 23.5 keV transition between the 641.8 and 618.3 keV levels. Gating on the 112.9 and 301.0 keV transitions in the lower panel of Fig. 3, the 506 keV transition is a doublet because of a strong 506.0-301.8-115.8 keV cascade in ^{144}Ba. In this gate, one sees 164.7, 393.5, 412.1, and 505.7 keV transitions in ^{145}Ba along with Mo partner peaks. When gating on the 490.7, 564.0 keV and 478.4, 515.8 keV transitions in bands (4) and (5) as shown in Fig. 4, one sees many new transitions in ^{145}Ba, including several in band (5), along with those belonging to partners.

Spins and parities (J^π) for each band in ^{143}Ba have been assigned in previous papers [5,6] based on systematics and some angular correlation, as well as internal conversion coefficient measurements. From Fig. 1, one can see that in ^{143}Ba, two sets of opposite parity bands, bands (1) and (2) and bands (3) and (4), each set with intertwined, strongly enhanced $E1$ crossing transitions, form structures characteristic of octupole deformation with the simplex quantum number $s=-i$ and $s=+i$, respectively. Here evidence of $M1$ and $E1$ transitions between the $s=+i$ and $s=-i$ structures is reported. These new data in ^{143}Ba provide an important test of the purity of the simplex quantum numbers $s=\pm i$.

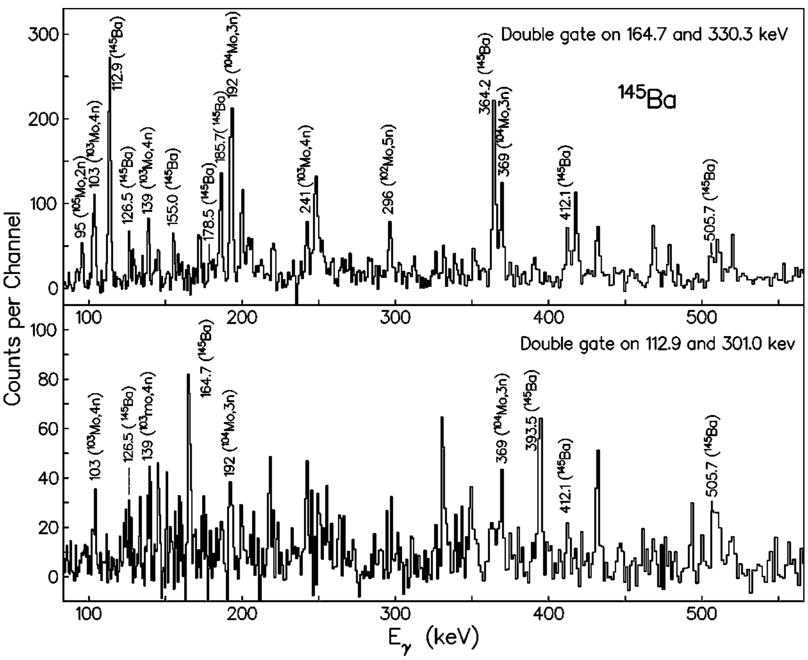

FIG. 3. Spectra obtained by summing the double gate on 164.7 and 330.3 keV (upper) and 112.9 and 301.0 keV transitions (bottom) in ^{145}Ba.

In ^{145}Ba, the spins and parities of bands (2), (3), and (4) also have been assigned based on systematics and some angular correlations, as well as internal conversion measurements [6]. Based on systematic comparison with neighboring nuclei, ^{143}Ba, ^{144}Ba, and ^{146}Ba, and intertwined strong crossing transitions between bands (1) and (2) and bands (4) and (5) with $B(E1)/B(E2)$ 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 $(19/2^{-})$. Bands (1) and (2) with $\Delta I=2$ transitions in each band and intertwined $E1$ transitions between the bands form a typical octupole deformation structure similar to that in ^{143,144,146}Ba with simplex quantum number $s=-i$. Bands (4) and (5) with similar structural characteristics to bands (1) and (2) form the octupole deformation structure with $s=+i$. Thus, these data indicate the two sets of parity doublets with $s=\pm i$ expected for octupole deformation at higher spins.

The ground bands (2) and (3) at lower spins, linked by $M1$ transitions in ^{145}Ba, form a strong coupled collective structure with signature splitting. Above the 463.3 keV $(11/2^{-})$ level, the transition intensities are very weak as the levels become nonyrast. This strong-coupled collective structure represents a well-deformed symmetric rotor shape in ^{145}Ba and also is observed in ^{145}La [16]. It probably originates mainly from Coriolis-mixed $\nu h_{9/2}$ and $\nu f_{7/2}$ orbitals.

The $B(E1)/B(E2)$ values in ^{143}Ba and ^{145}Ba in our investigation are listed in Table I. The similarity of these data

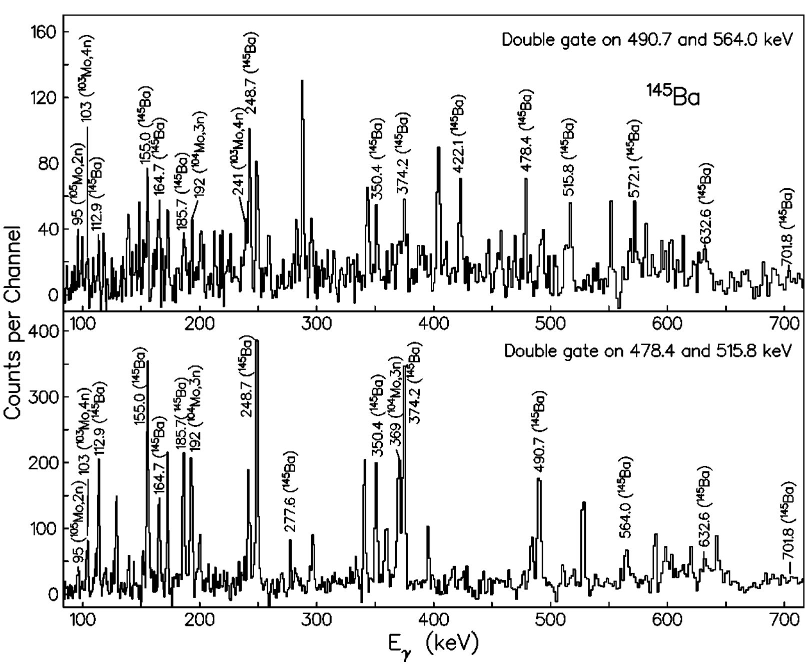

FIG. 4. Spectra obtained by summing the double gate on 490.7 and 564.0 keV (upper) and 478.4 and 515.8 keV transitions (bottom) in ^{145}Ba.

TABLE I. $B(E1)/B(E2)$ ratios in ^{143,145}Ba.

$I_i^\pi \rightarrow I_f^\pi$	$B(E1)/B(E2)(10^{-6}\ \mathrm{fm}^{-2})$	$I_i^\pi \rightarrow I_f^\pi$	$B(E1)/B(E2)(10^{-6}\ \mathrm{fm}^{-2})$
^{143}Ba, $s=-i$,			
bands (1) and (2)			
$19/2^+ \rightarrow 15/2^+$	0.25(7)	$25/2^- \rightarrow 21/2^-$	1.0(1)
$19/2^+ \rightarrow 17/2^-$		$25/2^- \rightarrow 23/2^+$	
$21/2^- \rightarrow 17/2^-$	1.2(2)	$27/2^+ \rightarrow 23/2^+$	2.3(6)
$21/2^- \rightarrow 19/2^+$		$27/2^+ \rightarrow 25/2^-$	
$23/2^+ \rightarrow 19/2^+$	0.73(6)	$29/2^- \rightarrow 25/2^-$	0.7(3)
$23/2^+ \rightarrow 21/2^-$		$29/2^- \rightarrow 27/2^+$	
^{143}Ba, $s=+i$,			
bands (3) and (4)			
$17/2^+ \rightarrow 13/2^+$	0.36(6)	$23/2^- \rightarrow 19/2^-$	0.20(15)
$17/2^+ \rightarrow 15/2^-$		$23/2^- \rightarrow 21/2^+$	
$21/2^+ \rightarrow 17/2^+$	0.3(1)		
$21/2^+ \rightarrow 19/2^-$			
^{145}Ba, $s=-i$,			
bands (1) and (2)			
$15/2^+ \rightarrow 11/2^+$	0.45(10)	$19/2^+ \rightarrow 15/2^+$	0.63(12)
$15/2^+ \rightarrow 13/2^-$		$19/2^+ \rightarrow 17/2^-$	
$17/2^- \rightarrow 13/2^-$	0.8(3)	$21/2^- \rightarrow 17/2^-$	0.59(12)
$17/2^- \rightarrow 15/2^+$		$21/2^- \rightarrow 19/2^+$	
^{145}Ba, $s=+i$,			
bands (4) and (5)			
$27/2^- \rightarrow 23/2^-$	0.35(7)	$35/2^- \rightarrow 31/2^-$	0.50(15)
$27/2^- \rightarrow 25/2^+$		$35/2^- \rightarrow 33/2^+$	
$31/2^- \rightarrow 27/2^-$	0.34(7)		
$31/2^- \rightarrow 29/2^+$			

supports the ^{145}Ba spin and parity assignments. For ^{143}Ba, the error weighted average values are $0.64(4)\times10^{-6}\ \mathrm{fm}^{-2}$ for $s=-i$ and $0.33(5)\times10^{-6}\ \mathrm{fm}^{-2}$ for $s=+i$, respectively. For ^{145}Ba, the same average values are $0.55(6)\times10^{-6}\ \mathrm{fm}^{-2}$ for $s=-i$ and $0.36(5)\times10^{-6}\ \mathrm{fm}^{-2}$ for $s=+i$. These compare favorably with the average in ^{144}Ba of $0.36(2)\times10^{-6}\ \mathrm{fm}^{-2}$. These data indicate that the octupole correlations are very strong leading to stable octupole deformation in ^{143,145}Ba.

Band (4) in ^{145}Ba based on the $13/2^+$ level becomes the yrast band and has the strongest transition intensities. It most probably originates from a $\nu i_{13/2}$ single-particle orbital coupling. The fact that the average $B(E1)/B(E2)$ value is less than in the $s=-i$ band may indicate that the $i_{13/2}$ neutron single orbital coupling reduces the octupole correlations.

Plots of the moments of inertia J_1 and J_2 against $\hbar\omega$ for bands (4) and (5) are shown in Fig. 5. For the $i_{13/2}$ band (4), the J_1 is very large at low rotational frequency ($\hbar\omega$) 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. Quite surprisingly, they essentially have a rigid body moment of inertia. This is the first such band observed in neutron rich nuclei. This could indicate a pairing-free rotational band and, if so, is the first such example observed 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 standard deviation 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

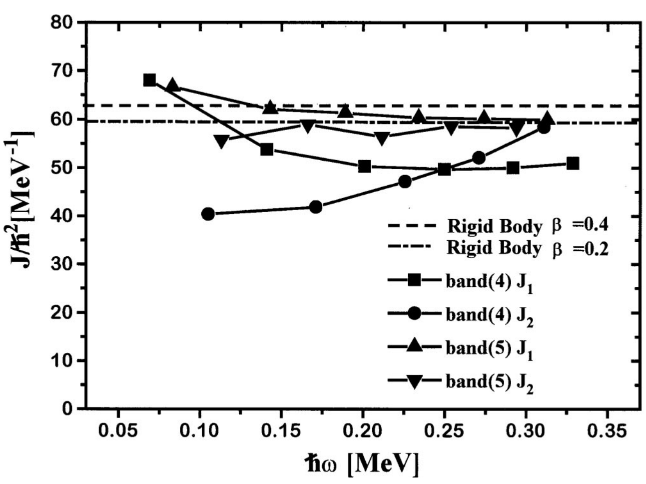

FIG. 5. Plots of the moments of inertia J_1 and J_2 as a function of rotational frequency in bands (4) and (5) of ^{145}Ba.

superdeformed band in ^{152}Dy [17]. The origin of this rigid body band in ^{145}Ba is not clear but definitely offers a new challenge for theory.

In summary, new high spin states in ^{143}Ba and ^{145}Ba have been investigated. Stable octupole deformation or at least strong octupole correlations are observed in these nuclei. These new data confirm the long-standing theoretical prediction [3] of stable octupole deformation in ^{145}Ba. 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. The strong-coupling ground band and octupole deformation structures in ^{145}Ba show competition and coexistence between symmetric and asymmetric shapes. The first evidence of crossing $M1$ and $E1$ transitions between the $s = \pm i$ doublets in ^{143}Ba was obtained.

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