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Evolution of octupole correlations in ^{123}Ba

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High-spin states of ^{123}Ba have been studied via the ^{108}Cd(^{19}F,$3np$)^{123}Ba fusion-evaporation reaction at a beam energy of 90 MeV. Several $E1$ transitions linking the positive-parity $\nu(d_{5/2}+g_{7/2})$ band and negative-parity $\nu h_{11/2}$ band are observed in ^{123}Ba for the first time. Evidence for the existence of octupole correlations in ^{123}Ba is presented based on the systematic comparisons of the $B(E1)/B(E2)$ branching ratios and the energy displacements in odd-A Ba isotopes. The characteristics of octupole correlation in the odd-A ^{123,125}Ba are explained by the state-of-the-art multidimensionally-constrained relativistic mean-field model and cluster model based on the dinuclear system concept.

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As an extremely complicated finite quantum many-body system, the spatial distribution of an atomic nucleus exhibits a variety of intriguing geometrical shapes. Most nuclei have been found to have axially symmetric shapes. With the breaking of reflection symmetry in the intrinsic frame, some nuclei appear to have octupole deformations, i.e., pearlike shapes [1]. The occurrence of octupole deformations can be ascribed to the strong coupling between orbitals around the Fermi surface with $\Delta\ell = \Delta j = 3$. One of the well-known nuclear regions with the octupole deformation is around the double octupole-driving numbers $Z = 56$ and $N = 88$ where the experimental evidence of octupole deformation or correlations has been identified in many neutron-rich Ba isotopes [1–11]. For the neutron-deficient Ba isotopes, the experimental signatures of octupole correlations, such as the enhanced $E1$ transitions between the opposite-parity bands, strong $E3$ transitions, and parity doublet bands, etc. [1], have been reported in even-A $^{118,122–128}$Ba isotopes [12–17], which indicate octupole deformation or correlations also play an important role in the light Ba isotopes.

Although the rotational bands built on the different orbitals with different parities have been well established in the neutron-deficient odd-A Ba isotopes so far, the experimental evidence for octupole correlations especially the evidence concerning enhanced $E1$ transitions between the opposite-parity bands, has been observed only in ^{125}Ba [15,16]. Moreover, according to the empirical measurement of the strength of octupole correlations by the energy displacement between the opposite-parity states, these light Ba isotopes were found to have no static octupole deformation at low angular momenta, and rotation tends to drive these nuclei to static octupole deformation at medium angular momenta [17]. Due to the possible octupole deformation or correlation fluctuation at low angular momenta and the limited experimental information, to date the underlying reason of the evolution of octupole deformation or correlations with angular momentum in the $A \sim 130$ mass region still remains an open question. Thus, further searching for octupole correlations in the neutron-deficient odd-A Ba isotopes and investigation on the effect of rotation on the octupole correlations are very valuable for systematic understanding the evolution of octupole degrees of freedom along with the neutron number in the long Ba isotopic chain as well as with the angular momentum.

In this Rapid Communication, we report the new results on the level structure of ^{123}Ba. The observation of several new $E1$ transitions linking the positive-parity $\nu(d_{5/2}+g_{7/2})$ band and negative-parity $\nu h_{11/2}$ band provides evidence of octupole correlations in ^{123}Ba. The characteristics of octupole correlations in the odd-A Ba isotopes are discussed in terms of the state-of-the-art multidimensionally-constrained relativistic mean-field (MDC-RMF) model [18,19] and cluster model based on the dinuclear system (DNS) concept [20].

The experiment was performed at the HI-13 tandem facility of the China Institute of Atomic Energy (CIAE). The high-spin states of ^{123}Ba were populated through the ^{108}Cd(^{19}F,$3np$)^{123}Ba reaction at a beam energy of 90 MeV.

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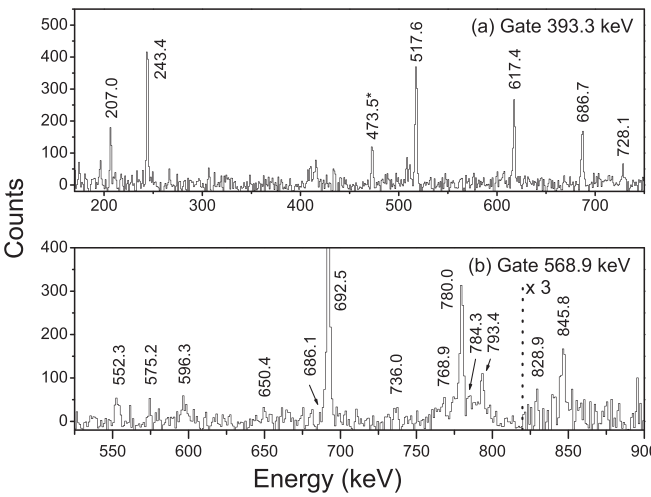

FIG. 1. Coincident γ-ray spectra with gating on (a) 393.3-keV transition in band 1 and (b) 568.9-keV transition in band 3. The peaks marked with stars are known contaminants from other nuclei.

The target was ^{108}Cd with a thickness of 1.1 mg/cm^2. It was on a 14.0-mg/cm^2 Pb backing, which served to stop the recoil nuclei. The deexcited γ rays emitted from the stopped recoil nuclei were detected by a γ-detector array of 11 high-purity germanium (HPGe) detectors with bismuth germanate anti-Compton suppressors. Two additional planar HPGe detectors were used to detect low-energy γ rays. The energy resolutions of these detectors were 2.0–3.0 keV at 1.33 MeV.

A total of 6.1×10^7 coincident events were collected from which a symmetric γ-γ matrix was built. The level scheme analysis was performed using the RADWARE software [21]. The γ-ray spectra gated on the known γ-ray transitions in ^{123}Ba are shown in Fig. 1. In order to obtain the directional correlations of γ rays deexciting oriented states (DCO) intensity ratios to determine the multipolarities of γ-ray transitions, the detectors around 90.0° with respect to the beam direction were sorted against the detectors around 40.0° to produce a two-dimensional angular correlation matrix. To get clean DCO values for transitions in ^{123}Ba, gates were set on the uncontaminated stretched $E2$ transitions. In general, the stretched quadrupole transitions were adopted if the DCO ratios were larger than 1.0, and the stretched dipole transitions were assumed if the DCO ratios were less than 0.8. The DCO values obtained in the present measurement for previously assigned transitions in ^{123}Ba were found to be consistent with the expected values.

The structure of ^{123}Ba has been previously studied by many experiments, such as ^{94}Mo(^{32}S$,n2p$)^{123}Ba, ^{74}Se(^{52}Cr$,n2p$)^{123}Ba, and ^{114}Sn(^{12}C$,3n$)^{123}Ba fusion-evaporation reactions [22,23], and ^{123}La β decay [24]. The partial level scheme of ^{123}Ba, deduced from the present Rapid Communication, is shown in Fig. 2. It was constructed from the γ-γ coincidence relationships, intensity balances, and DCO analyses. The present analysis confirms most of the transitions found in the previous studies [22–24].

Band 1 built on the $1/2^+$ isomeric state of 120.9 keV has been identified up to $11/2^+$ in the β-decay study of ^{123}La [24] and is suggested to be a rotational sequence based on the $\nu s_{1/2}$ orbital. As shown in Fig. 1(a), by requiring coincidence with the known γ-ray transitions under spin $11/2^+$ of band 1, four new coincident γ-ray transitions of 517.6, 617.4, 686.7, and 728.1 keV are observed. The DCO ratio analyses suggest that all these γ-ray transitions except the 728.1-keV transition have quadrupole transition characters. The γ-ray decay of 728.1 keV, whose DCO ratio could not be extracted, is also assumed to be a stretched $E2$ transition.

Band 2 built on the $\nu(d_{5/2} + g_{7/2})$ orbital has been established in Ref. [22]. The present analysis confirms the low-energy parts of states up to spins $17/2^+$ and $23/2^+$ for the positive and negative signature sequences, respectively. In Ref. [22], the excitation energy 2106 keV was assigned to the $21/2^+$ state, although it was found to decay to the $17/2^+$ state at 1482 keV via the 674-keV transition. In the present Rapid Communication, the transition with an energy of 673.5 keV is observed in coincidence with known γ-ray transitions under spin $17/2^+$ of band 2. Thus, the previous 2106-keV excitation energy of the $21/2^+$ state is modified to 2154.3 keV. Consequently, the 2816-keV excitation energy of the $25/2^+$ state is modified to 2863.7 keV. In Ref. [22], the excitation energies of the $27/2^+$ and $29/2^+$ states are tentative because of their weak deexcited transitions to the $23/2^+$ and $25/2^+$ states, respectively. In the present Rapid Communication, a new 673.4-keV transition is observed in coincidence with the known γ-ray transitions under spin $23/2^+$ of band 2. The DCO ratio analyses suggest that this γ-ray transition has quadrupole transition character. Therefore, the spin-parity $27/2^+$ is assigned to the 3189.4-keV level.

Band 3 built on the $\nu h_{11/2}$ orbital has been established up to $67/2^-$ in Ref. [22]. In the present Rapid Communication, band 3 is identified up to spins $35/2^-$. The obtained DCO values support the spin and parity assignments in Ref. [22]. More interestingly, six new interband transitions linking the positive-parity band (band 2) and negative-parity band (band 3) are observed for the first time. The observation of these interband transitions further confirms the validity of the present transition sequence in band 2.

One of the most important experimental evidences for octupole correlations is the observation of the enhanced $E1$ transitions between the opposite-parity bands. Here, these new observed $E1$ transitions between bands 2 and 3 imply that the octupole correlations may exist in ^{123}Ba. To investigate the octupole correlations in ^{123}Ba, the experimental $B(E1)/B(E2)$ branching ratios in ^{123}Ba are extracted and compared with those in the neighboring isotope ^{125}Ba [15] as well as those in the octupole-deformed isotope ^{145}Ba [8] in Fig. 3. It can be seen that the deduced $B(E1)/B(E2)$ ratios in ^{123}Ba are very similar to those in ^{125}Ba but smaller than those in ^{145}Ba at low angular momenta. With the increase in angular momentum, the $B(E1)/B(E2)$ ratios in ^{123}Ba increase and become comparable with those in ^{145}Ba around $27/2\hbar$. The enhanced $E1$ transitions observed in ^{123}Ba suggest the occurrence of octupole correlations in this nucleus.

To evaluate the stability of the octupole deformations with spin variation, the energy displacements $\delta E(I) = E(I^-) - [(I+1)E(I-1)^+ + IE(I+1)^+]/(2I+1)$ between the opposite-parity bands in ^{123,125,145}Ba are plotted in Fig. 4(a). In the limit of stable octupole deformation, the

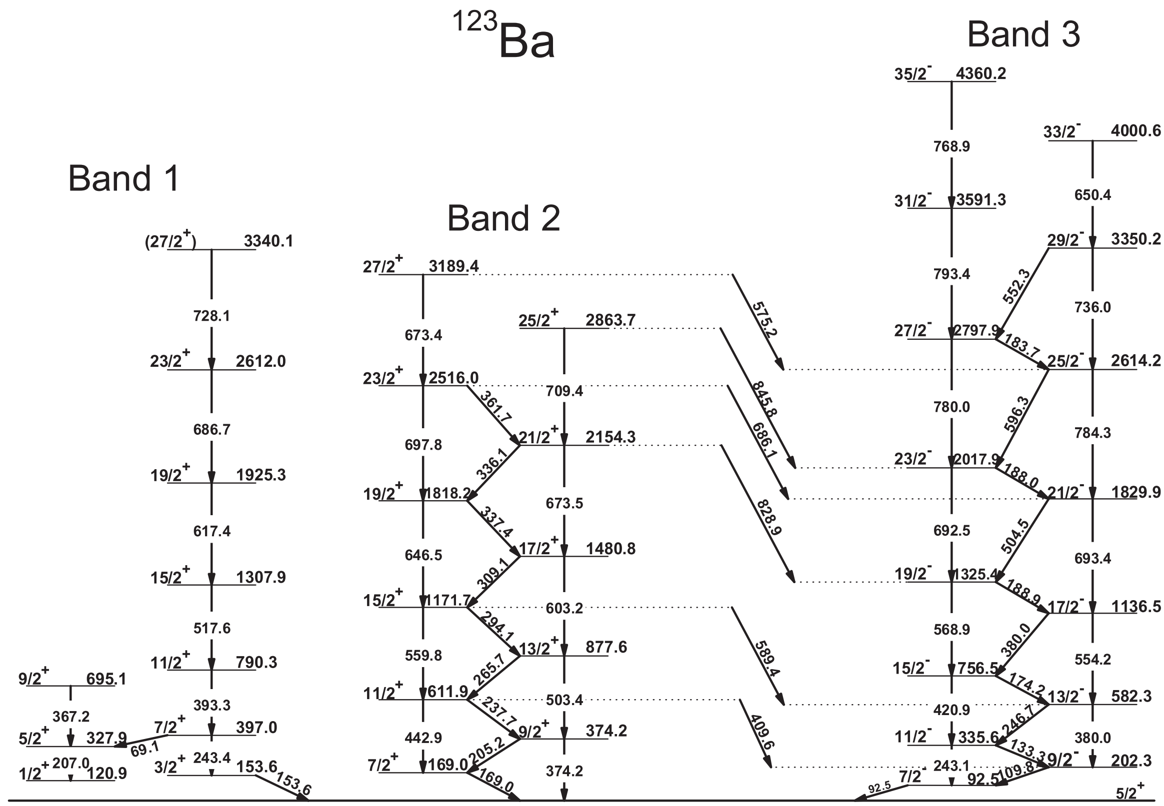

FIG. 2. Partial level scheme of ^{123}Ba. Energies are in keV.

energy displacement δE is close to zero [17,25]. As shown in Fig. 4(a), ^{123}Ba has a similar energy displacement pattern as ^{125}Ba. In contrast to a more regular trend of the energy displacements to zero in ^{145}Ba with increasing spin, both energy displacements in ^{123}Ba and ^{125}Ba first slowly decrease until $19/2\hbar$, then increase and tend toward to zero.

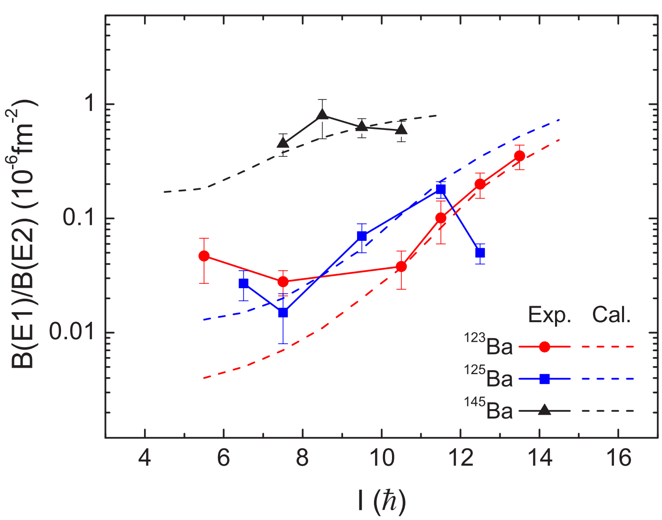

FIG. 3. The experimental $B(E1)/B(E2)$ ratios of ^{123,125,145}Ba isotopes in comparison with the cluster model calculations. The experimental data of ^{125}Ba are taken from Ref. [15], and the data of ^{145}Ba are taken from Ref. [8].

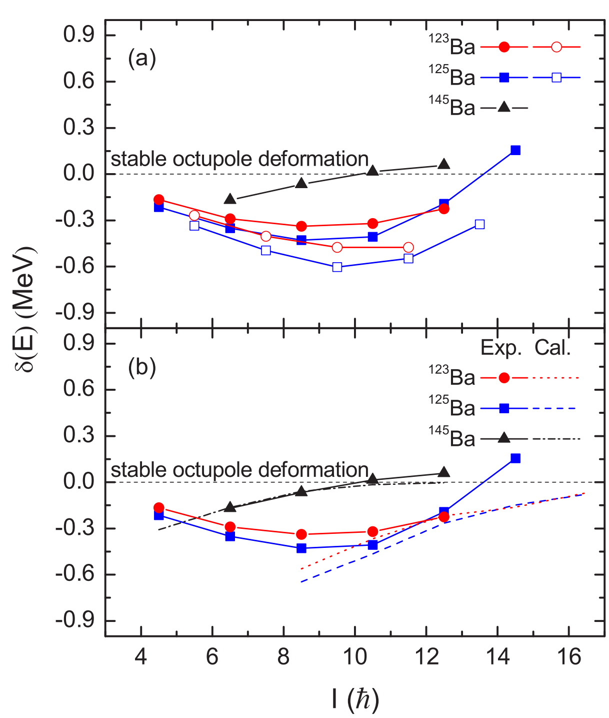

FIG. 4. (a) Experimental energy displacements $\delta E(I)$ between the opposite-parity bands as a function of spin in ^{123,125,145}Ba. (b) Comparison of experimental and calculated energy displacements $\delta E(I)$ for the simplex quantum number $s = -i$ band structures of ^{123}Ba, ^{125}Ba [15], and ^{145}Ba [8].

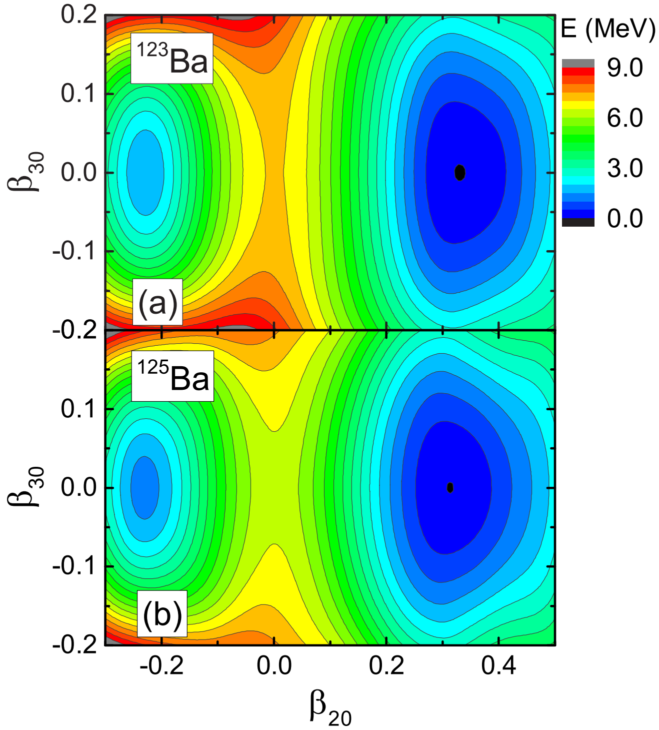

FIG. 5. The potential-energy surfaces for (a) ^{123}Ba and (b) ^{125}Ba calculated by the MDC-RMF model. The energies are normalized with respect to the ground state. The contour separation is 0.5 MeV.

To further illustrate the octupole correlations and the effect of rotation on the octupole correlations in the odd-A Ba isotopes, calculations based on the state-of-the-art microscopic MDC-RMF model and cluster model have been performed. The MDC-RMF model [18,19,26,27] and cluster model based on the DNS concept [20,28,29] have been successfully applied to describe the properties of octupole deformation or correlations in actinides, lanthanides, and some medium mass nuclei. Recently, the MDC-RMF model has been used to describe the potential-energy surface of ^{78}Br in which, for the first time, the evidence for octupole correlations in multiple chiral doublet bands was observed [30] and the value of the transitional octupole moment for ^{144}Ba predicted by the cluster model [28] has also been confirmed in the experiment [11].

In the MDC-RMF model [18], all shape degrees of freedom $\beta_{\lambda\mu}$ with even μ are included self-consistently. The potential-energy surfaces on the (β_{20},β_{30}) plane for ^{123,125}Ba calculated by the MDC-RMF with the PC-PK1 parametrization [31] are shown in Fig. 5. It can be seen that, although the minimum of the nuclear potential energy corresponds to the reflection symmetric shape, both potential-energy surfaces of ^{123,125}Ba are very soft with respect to the shape degree of freedom β_{30}, which further support the existence of octupole correlations in ^{123,125}Ba.

The cluster model is based on the assumption that cluster-type shapes are produced by the motion of the nuclear system in the mass-asymmetry coordinate [20]. The intrinsic nuclear wave function is thought as a superposition of the mononucleus and various cluster configurations. It was found that among the cluster components most contribution comes from the dinuclear system with the α particle as a light cluster. At low angular momenta the weight of the α-cluster DNS is small. However, due to the fact that the moment of inertia of the α-cluster DNS is larger than that of the mononucleus, the nuclear potential energy as a function of mass asymmetry becomes softer with the increase in angular momentum, and at a certain critical value I_{crit}, the α DNS is developed and consequently the reflection asymmetric minimum occurs. Thus, the nucleus can be characterized by the critical value I_{crit} which describes the phase transition from a reflection-symmetry to a reflection-asymmetry shape. According to the calculations by the cluster model, the values of I_{crit} for ^{123,125}Ba isotopes are $13\hbar$ and $12\hbar$, respectively. These values are consistent with the observed spin region where the $B(E1)/B(E2)$ values of ^{123,125}Ba remarkably increase and the energy displacements tend to zero. For the values of angular momenta close to or larger than I_{crit}, the DNS cluster model is capable of describing the peculiarities of alternate-parity bands. However, at low angular momenta, the parity splitting is mainly from the energy difference between single-particle orbitals of opposite parities, and at present, such effects are not included in this model.

In Figs. 3 and 4(b), the $B(E1)/B(E2)$ ratios and energy displacements calculated by the cluster model are compared with the experimental data for ^{123,125,145}Ba, respectively. It can be seen that the overall agreements are good, especially for the $B(E1)/B(E2)$ ratios. As is explained above, at low angular momenta, the deviations of the theoretical results from experimental data for ^{123,125}Ba are large. At medium angular momenta, the agreements between the experimental data and the theoretical results are rather good which further indicates that as the consequence of rotation, the static octupole deformation develops in ^{123,125}Ba.

To summarize, high-spin states in ^{123}Ba have been studied via the ^{108}Cd(^{19}F$,3np$)^{123}Ba fusion-evaporation reaction at a beam energy of 90 MeV. The previously known band 1 built on the $\nu s_{1/2}$ orbital is extended up to higher-spin states, while the high-spin levels of band 2 built on the $\nu(d_{5/2}+g_{7/2})$ orbital are modified. Several $E1$ transitions linking the positive-parity $\nu(d_{5/2}+g_{7/2})$ band and negative-parity $\nu h_{11/2}$ band are observed for the first time. Systematic comparisons of the $B(E1)/B(E2)$ branching ratios and the energy displacements between the opposite-parity bands in ^{123,125,145}Ba give evidence for the existence of octupole correlations in ^{123}Ba. According to the calculations by the MDC-RMF model and the cluster model based on the DNS concept, the odd-A ^{123,125}Ba at low angular momenta are very soft with respect to the reflection-asymmetric shape degree of freedom. With the increase in angular momentum, the reflection-asymmetry minima are predicted to develop around $13\hbar$ and $12\hbar$ for ^{123}Ba and ^{125}Ba, respectively. The characteristics of octupole correlations in the odd-A Ba isotopes are explained by the theoretical calculations.

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