Coexistence of Reflection Asymmetric and Symmetric Shapes in ^{144}Ba

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Phys. Rev. Lett. **124**, 032501 — Published 24 January 2020

DOI: 10.1103/PhysRevLett.124.032501

Coexistence of Reflection Asymmetric and Symmetric Shapes in ^{144}Ba

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Level structures in neutron-rich ^{144}Ba nucleus have been reinvestigated by measuring prompt γ rays in the spontaneous fission of ^{252}Cf. The previous $s = +1$ octupole band structure with reflection asymmetric shape has been expanded, and a side quadrupole band structure based on 3^+ state with reflection symmetric shape is identified. Thus, the results show coexistence of reflection asymmetric and symmetric shapes in ^{144}Ba. This is a first identification of such shape coexistence structure in nuclear structure. The other structural characteristics are discussed.

PACS numbers: 21.10.Re, 23.20.Lv, 27.60.+j, 25.85.Ca

A nucleus with octupole deformation has a reflection asymmetric shape. Theoretical calculations predicted the existence of an octupole deformation island in the $Z = 56$ and $N = 88$ neutron-rich nuclear region [1–3]. In such nuclei, the level structures were expected to show two sets of parity doublet bands characterized with the simplex quantum numbers $s = \pm1$ for even-even nuclei and $s = \pm i$ for odd-A nuclei [3]. So far, the octupole band structures have been experimentally identified in many nuclei in this region, for examples, in Xe ($Z = 54$) [4–6], Cs ($Z = 55$) [7–9], Ba ($Z = 56$) [1, 10–17], La ($Z = 57$) [18, 19], and Ce ($Z = 58$) [11, 17, 20–26] isotopes. Among them, most of the observed octupole bands belong to single simplex with $s = +1$ in even-even nuclei, and $s = +i$ or $s = -i$ in odd-A nuclei. The two sets of parity doublet bands were only reported in few nuclei, for examples, in odd-A ^{141}Xe [4, 6] and ^{143}Ba [14] (with $s = \pm i$), and in even-even ^{140}Xe [5] and ^{148}Ce [24] (with $s = \pm1$).

On the other hand, shape coexistence has been an important issue of nuclear structure. It has been reported in many nuclear region, including light nuclei, medium-heavy nuclei and heavy nuclei [27–33]. However, almost all of the shape coexistence were discovered between spherical, prolate, oblate and triaxial deformations with reflection symmetric shapes. Search for the coexistence between reflection asymmetric and symmetric shapes in a nucleus is a very significant topic. Recently, the coexistence of octupole bands and γ vibration bands in ^{142}Ba and ^{146}Ce [17] and the multiple chiral doublet bands with octupole correlations [34] have been reported, but no shape coexistence of stable octupole deformation and well deformed quadrupole deformation is observed.

The ^{144}Ba nucleus is located at the center of the $Z = 56$, $N = 88$ octupole deformation island, and is predicted to have the strongest octupole deformation in this region. In previous reports, the s = +1 octupole band structure has been studied in Ref. [10–13, 15]. Here we reinvestigate the high spin states of ^{144}Ba, and the results show the shape coexistence of stable octupole deformation and well deformed quadrupole deformation in this nucleus.

The high-spin states of ^{144}Ba were investigated by measuring the prompt γ rays at ^{252}Cf spontaneous fission. The experiment was carried out at the Lawrence Berkeley National Laboratory. The Gammasphere detector array consisting of 101 Compton-suppressed Ge detectors was used to detect the γ rays. A γ-γ-γ coincidence matrix (cube) was constructed. Detailed information of the experiment can be found in Refs. [5, 11, 23]. By carefully analyzing the data, a new partial level scheme of ^{144}Ba has been established as shown in Fig. 1. The $\triangle I = 2$ collective bands are labeled on the top of the scheme.

Comparing previous results in Refs. [10–13], we confirmed and expanded the bands (1) and (2), as seen in Fig. 1. Bands (3) and (4) are updated and reconstructed in our work. In Ref. [13], six levels, 1992.3, 2363.6, 2903.3 keV in band (3), and 1881.8, 2160.2, 2664.8 keV in band (4) along with some linking transitions were reported. We confirm most of these levels and transitions, but the 2903.3 keV level does not belong to band (3). We add six new levels, 1805.7, 2926.1, 3585.5 keV in band (3) and 1769.1, 3280.1, 3926.8 keV in band (4), along with some new transitions to the level scheme, as seen in Fig. 1. As examples, Figs. 2 and 3 present some summing double gating coincidence γ ray spectra in ^{144}Ba. Most of the corresponding γ peaks can be seen, including the previously observed, the new identified and some Mo partner ones.

The positive parity band (1) and negative parity band (2) with $\Delta I = 2$ transitions in each one and linking $E1$ transitions between the bands form an octupole band structure with simplex quantum number $s = +1$ in ^{144}Ba [10]. The characteristics of the strong octupole deformation have been discussed in Refs. [10–13, 15].

In Ref. [13], the spin and parity for 1992.7 and 2363.6

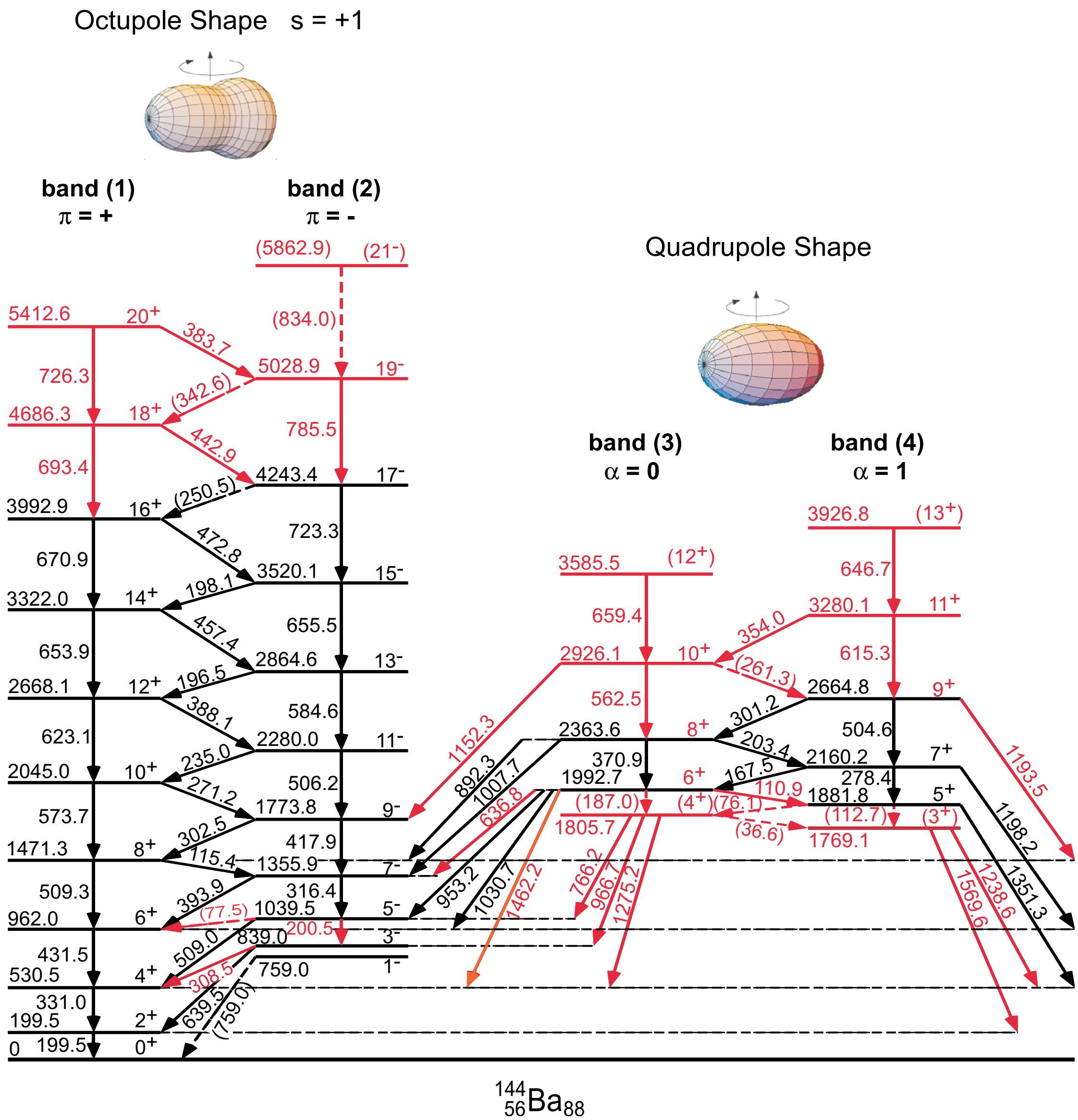

FIG. 1: The partial level scheme of ^{144}Ba identified in the present work. New levels and transitions are labeled with red.

keV levels in band (3) were tentatively assigned as (6^-) and (8^-), and other two levels at 1881.8 and 2160.2 keV in band (4) were tentatively assigned as (5^+) and (7^+) respectively. Thus the the bands (3) and (4) in ^{144}Ba likely formed a s = -1 octupole band structure. In this work, according to our analyzing (seeing following discussion), we assign both the bands (3) and (4) as positive parity bands as showing in Fig. 1. Thus, the band (3) with signature $\alpha = 0$ and band (4) with signature $\alpha =$ 1 form a quadrupole deformed band structure based on the 1769.1 keV (3^+) level.

In order to confirm the I^π's assignments in ^{144}Ba, $\gamma \rightarrow \gamma(\theta)$ angular correlation measurements have been carried out by dividing the data set into angular bins [35]. Here we only obtained several angular correlation values in ^{144}Ba as most of the non-yrast transitions in ^{144}Ba are very weak. Our experimental $\gamma \rightarrow \gamma(\theta)$ results and extracted mixing ratio (δ) values for some cascades and comparison with theoretical values obtained in Ref. [36] are given in Table I. One can see that if both bands (3) and (4) are assigned with positive parity, all the angular correlation results support our assignments. However, if the band (3) is assigned with negative parity, the experiment values for the 1037.7-431.5 keV cascade are not agree with the theoretical values for the $6^-(E1)6^+(E2)4^+$ assignment, although for 1.5 σ on A_2 for the 892.3-509.3 keV cascade, both the $8^+(M1/E2)8^+(E2)6^+$ and $8^-(E1)8^+(E2)6^+$ assignments are possible. These data give the evidences for the I^π assignments of ^{144}Ba in the present work.

To give more information for the I^π's assignments of bands (3) and (4) in ^{144}Ba, we have measured a to-

TABLE I: Angular correlations for some cascade transitions and the spin and parity assignments for the levels as well as the mixing ratios for some $M1/E2$ transitions in ^{144}Ba.

Cascade (keV)	$A_2^{expt.}$	$A_4^{expt.}$	$A_2^{theor.}$	$A_4^{theor.}$	$\delta(E2/M1)$	Assignment	Yes or No
655.5-584.6	0.11 (1)	0.04(2)	0.10	0.01		$15^-(E2)13^-(E2)11^-$	Yes
1198.2-431.5	-0.27(3)	-0.10(5)	-0.27	-0.01	-0.35	$7^+(M1/E2)6^+(E2)4^+$	Yes
			or [-0.27	-0.05	-3.5]		
1351.3-331.0	-0.28(2)	-0.03(3)	-0.28	-0.01	-0.32	$5^+(M1/E2)4^+(E2)2^+$	Yes
			or [-0.28	-0.06	-4.2]		
1030.7-431.5	0.15(4)	0.08(7)	0.15	0.05	-0.83	$6^+(M1/E2)6^+(E2)4^+$	Yes
			if [0.18	0.00		$6^-(E1)6^+(E2)4^+$]	No
892.3-509.3	0.17(4)	0.07(6)	0.17	0.02	-0.50	$8^+(M1/E2)8^+(E2)6^+$	Yes
			if [0.17	0.00		$8^-(E1)8^+(E2)6^+$]	Yes

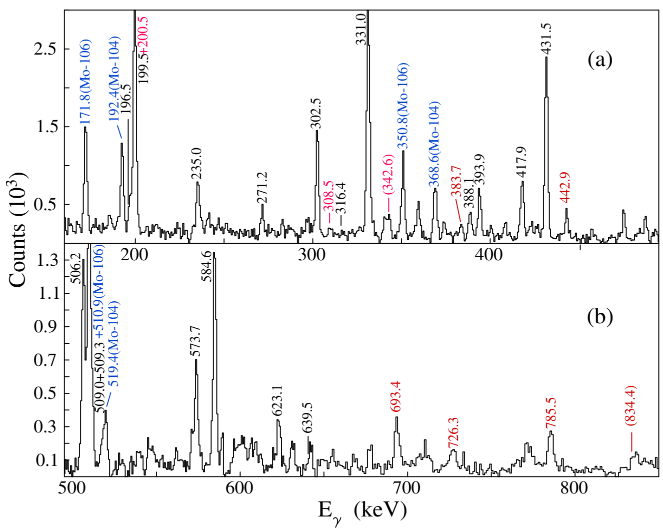

FIG. 2: Portion of γ ray spectrum by summing double gating on 653.9 and 670.9 keV, and 655.5 and 723.3 keV γ transitions in ^{144}Ba. The energy range is (a) from 160 to 495 keV, and (b) from 495 to 850 keV. New transitions in ^{144}Ba are labeled in red, and the Mo partner ones are labeled in blue.

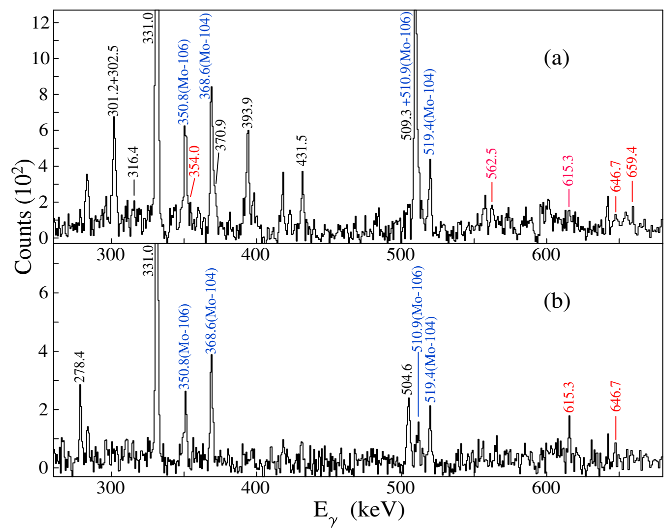

FIG. 3: Portion of γ ray spectra (a) by summing double gating on 431.5 and 1030.7 keV, 431.5 and 892.3 keV, and 417.9 and 1152.3 keV γ transitions, and (b) by summing double gating on 278.4 and 1351.3 keV, and 504.6 and 1351.3 keV γ transitions in ^{144}Ba. New transitions in ^{144}Ba are labeled in red, and the Mo partner ones are labeled in blue.

tal internal conversion coefficient (α_T) of the low-energy crossing transition 167.5 keV from the 2160.2 keV level in band (4) to the 1992.7 keV level in band (3). The method has been used in ^{148}Ce [22]. The 167.5 keV α_T value in ^{144}Ba is obtained by double gating on the 504.6 and 1030.7 keV transitions. In this gate spectrum, the difference in relative intensities of the 431.5 and 167.5 keV γ peaks is equal to the internal conversion electron intensity of the 167.5 keV γ transition. Obtained experimental α_T value of the 167.5 keV γ transition is 0.26(3). The theoretical values are 0.055 for an $E1$ transition, 0.24 for an $M1$ one and 0.33 for an $E2$ one. So the 167.5 keV transition in ^{144}Ba is an *M1/E2* transition and bands (3) and (4) should have the same parity according to the transition rule. This result also supports our I^π assignments of even parity for both bands (3) and (4).

In this work, we have observed the 1462.2 keV transi-

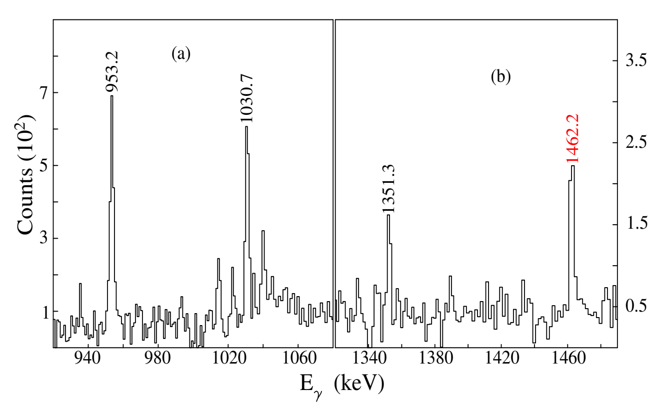

FIG. 4: Portion of γ ray spectrum obtained by double gating on 167.5 and 331.0 keV γ transitions in ^{144}Ba, ranging from (a) 920 to 1080 keV, and (b) 1320 to 1490 keV.

tion from the 1992.7 keV level in band (3) to the 530.5 keV one in band (1). Fig. 4 shows a γ ray spectrum by double gating on 167.5 and 331.0 keV γ transitions. The new 1462.2 keV γ peak can be clearly seen. Obtained the relative intensities of the 953.2, 1030.7 and 1462.2 transitions, which decayed from the 1992.7 keV level, are 100(12), 84(2) and 59(9), respectively. These data have the same order of the intensity magnitude. If band(3) is assigned with negative parity, the 1462.2 keV transition should have $M2/E3$ multipolarities, for which the transition intensity should be too weak to be observed. On the other hand, if band(3) has positive parity, the 1462.2 keV transition should have an $E2$ multipolarity as supported by our data.

Examining the the level character in bands (3) and (4) in ^{144}Ba, the energy of the bandhead ($I^{\pi} = 3^{+}$) is 1769.1 keV. The identified energies of the 3^{+} levels for s = -1 octupole band structures in even-even ^{140}Xe and ^{148}Ce are 1304.4 and 1117.6 keV, and the energies of the $11/2^{-}$ levels for $s = +i$ odd-A ^{141}Xe and ^{143}Ba are 553.0 and 716.6 keV, respectively. So if bands (3) and (4) in ^{144}Ba belong to the $s = -1$ octupole band structure, energies of the levels may be too high to be possible.

When we assign the band (3) with positive parity, we also can exclude the γ vibrational band structure for bands (3) and (4). Firstly, the energies of levels of the γ vibrational bands in ^{142}Ba and ^{144}Ce [17] are about 200 keV lower than that in bands (3) and (4) in ^{144}Ba. Then, in the γ vibrational band structure, a decay from the γ band to the ground state rotational band is expected to be pure quadrupole transitions [37]. In a recent report [38], the transition admixtures are at least 90% E2, many with small M1 from the observed mixing ratios (δ(E2/M1)) in $\triangle I$ = 0, 1 γ vibrational band to ground band decays in various nuclei. In Table I, the δ(E2/M1) value for the 1037.7 keV transition from the $6^{+} - 6^{+} - 4^{+}$ $\gamma \rightarrow \gamma(\theta)$ is -0.83 to give the transition probability ratio 60%(M1)/40%(E2), and the δ(E2/M1) value for the 892.3 keV transition from the $8^{+} - 8^{+} - 6^{+}$ $\gamma \rightarrow \gamma(\theta)$ is -0.50 to give the transition probability ratio 80%(M1)/20%(E2). These large M1 admixtures can exclude the γ vibrational band assignment for bands (3) and (4). On the other hand, the paring energy gap in this region is about 1.5 MeV [39], which is lower than the 1769.7 keV of the bandhead energy of band (4) in ^{144}Ba. So it is reasonable to assign the bands (3) and (4) in ^{144}Ba as two quasiparticle positive parity band structure.

Plots of the kinetic moments of inertia (J_1) versus rotational frequency ($\hbar\omega$) for s = +1 octuple band structure of ^{144}Ba and bands (3) and (4) of ^{144}Ba, and s = $\pm$ 1 octupole band structures of ^{148}Ce [24] are shown in Fig. 5. One can see that in the octupole band structures, the J_1's behaviors in positive parity (π = +) bands with the $\hbar\omega$ increasing are different from that in the negative parity (π = -) bands. But in the bands (3) and (4)

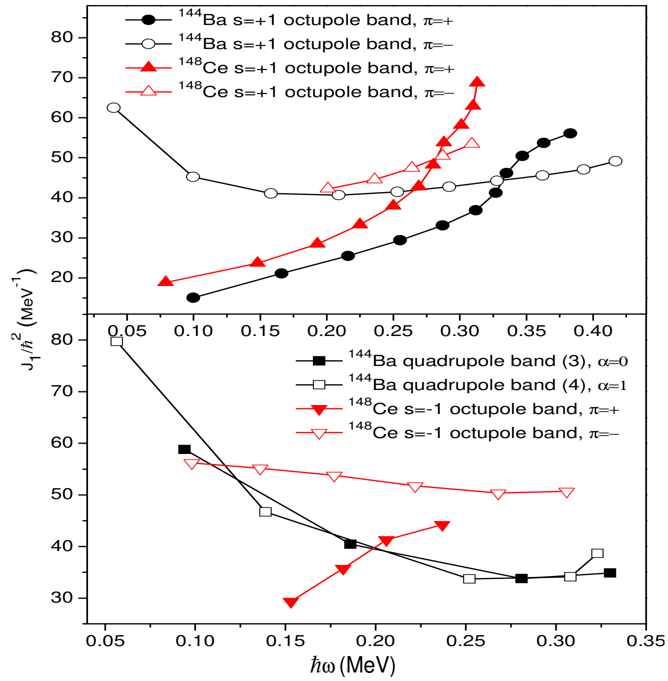

FIG. 5: Plots of moment of inertia (J_1) as a function of rotational frequency ($\hbar\omega$) in s = +1 octupole band structure of ^{144}Ba and bands (3) and (4) of ^{144}Ba in comparison to that in s = $\pm$1 octupole band structures of ^{148}Ce.

of ^{144}Ba, they have the same behaviors and show the quadrupole rotational character.

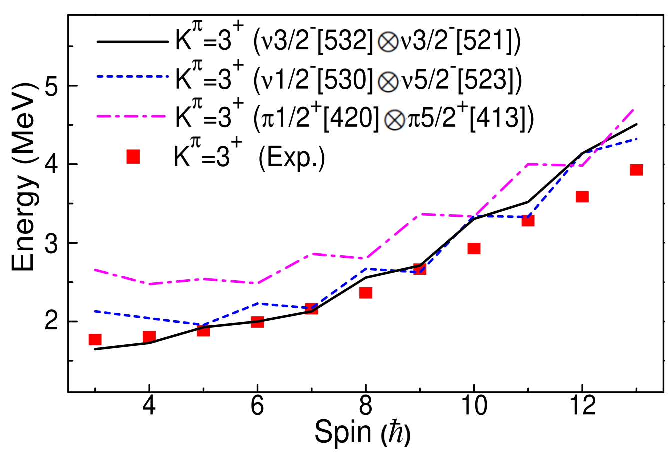

FIG. 6: projected shell model calculation of the $K^{\pi} = 3^{+}$ band structures with different configurations in ^{144}Ba, compared with the experimental data. The deformation parameters in calculation are: $\varepsilon_2 = 0.150$, $\varepsilon_4 = 0.013$.

For the quadrupole bands (3) and (4) in ^{144}Ba, they show the regular $\triangle$I = 2 and $\triangle$I = 1 transitions inside the bands, and have very small signature splitting between bands (3) and (4). Based on the level character, we propose that they have the prolate deformation. It has the $K^\pi = 3^+$ band head and is expected to have two proton or two neutron configurations. To understand the characteristics of the bands (3) and (4) in ^{144}Ba, we have performed projected shell model (PSM) [40] calculations. The PSM uses a Nilsson potential having axial deformation to build model basis. In the present work, the axial deformation parameters $\varepsilon_2 = 0.150$, $\varepsilon_4 = 0.013$ are adjusted around the value taken from Ref. [41] to obtain suitable deformation bases. The monopole-pairing strength is taken to be $G_M = [G_1\text{-}G_2(\text{N-Z})/\text{A}]/\text{A}$ for neutrons and $G_M = G_1/\text{A}$ for protons with $G_1 = 20.82$, $G_2 = 13.58$ being the coupling constants. This choice of G_M is appropriate for the single-particle space employed in the PSM, where three major shells are used for each type of nucleon (N=3, 4, 5 for neutrons and protons). The quadrupole-pairing strength G_Q is assumed to be proportional to G_M with the proportionality constant being fixed to be 0.18. For the bands (3) and (4) with $K^\pi = 3^+$ in ^{144}Ba, the possible configurations are $\nu 3/2^-[532]\bigotimes\nu 3/2^-[521]$, $\nu 1/2^-[530]\bigotimes\nu 5/2^-[523]$ and $\pi 1/2^+[420]\bigotimes\pi 5/2^+[413]$, respectively. The calculated results of the excited energies with the spin variation and compared with the experimental results are given in Fig. 6. It can be seen that the calculated results for the $\nu 3/2^-[532]\bigotimes\nu 3/2^-[521]$ configuration are better in agreement with the experimental results than the other configurations up to medium spin states. So the bands (3) and (4) in ^{144}Ba can be proposed with $\nu 3/2^-[532]\bigotimes\nu 3/2^-[521]$ two neutron configuration with $\varepsilon_2 = 0.150$, and it shows the prolate deformation with the reflection symmetric shape.

In conclusion, the high-spin states in neutron-rich ^{144}Ba nucleus have been reinvestigated from the study of the prompt γ rays in spontaneous fission of ^{252}Cf. The $s = +1$ octupole band structure with reflection asymmetric shape has been expanded, and a side quadrupole band structure with reflection symmetric shape has been identified. This quadrupole band structure is proposed with $\nu 3/2^-[532]\bigotimes\nu 3/2^-[521]$ two neutron configurations based on the projected shell model calculation. The experimental evidences for the quadrupole band structure have been discussed. The results show coexistence of reflection asymmetric and symmetric shapes in ^{144}Ba, which is a first identification of such well deformed shape coexistence structure.

The work at Tsinghua University was supported by the National Natural Science Foundation of China under Grants No. 11175095, and No. 11875174. The work at Vanderbilt University, Lawrence Berkeley National Laboratory was supported by U. S. Department of Energy under Grant No. DE-FG05-88ER40407 and Contract No. DE-AC03-76SF00098. The work at Huzhou University was supported by the National Natural Science Foundation of China under Grants No. U1832139, and No. 11847315. The work at JINR was partly supported by the Russian Foundation for Basic Research Grant No. 08-02-00089 and by the INTAS Grant No. 2003-51-4496.

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