Unexpected 5/2^{−} spin of the ground state in ^{147}Ba: No octupole deformation in ground states of odd-A Ba isotopes

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Unexpected $5/2^-$ spin of the ground state in ^{147}Ba. No octupole deformation in ground states of odd-A Ba isotopes.

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The ^{147}Ba nucleus has been studied in prompt γ-ray spectroscopy using the EUROGAM2 Ge array. Spin and parity of the ground state has been determined to be $5/2^-$. The unexpected, $5/2^-$ ground state results from interaction with other negative-parity configurations. A new ground-state band has been established in ^{147}Ba and some previously reported levels have been arranged into a $3/2^-$ band, which may correspond to the $3/2^-[532]$ configuration. The new spin assignments in ^{147}Ba suggest that the theoretical predictions of static octupole deformation in the ground state of ^{147}Ba, may not be be valid. No candidates for parity doublets have been found in ^{147}Ba. Instead, an octupole band built on the ground state has been proposed.

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Usually in nuclei with strong octupole correlations pronounced $E1$ transitions are present, which have $B(E1)$ rates up to three orders of magnitude higher than the average value of 10^{-5} W.u. observed in heavy nuclei [1]. Two effects, the single-particle coupling and the volume effect contribute to the $E1$ strength. Remarkably, the two contributions may cancel [2]. Consequently, in nuclei with octupole deformation $B(E1)$ rates could be low. Such low $B(E1)$ rates observed in ^{146}Ba [3–5] are believed to indicate an octupole deformation in this nucleus, predicted there by calculations [6]. It may be expected that the ^{147}Ba nucleus, with one neutron outside the ^{146}Ba core, should also have octupole deformation and, therefore exhibit parity-doublet bands, predicted by theory in odd-A nuclei with octupole deformation [2]. Therefore, studying the band structure of ^{147}Ba, one could test the presence of octupole deformation in these nuclei.

In a reflection-asymmetric potential positions of single-particle orbitals are changed as compared to their positions in a reflection-symmetric potential. A specific prediction for ^{147}Ba is that due to octupole interactions the ground state of ^{147}Ba should have spin and parity of $3/2^-$ [6]. In a β-decay study of ^{147}Ba [7] a $(3/2^-)$ spin and parity for the ground state in ^{147}Ba has been assumed based on systematics (see Fig.5 of Ref. [7], indicating the $3/2^-[532]$ neutron configuration for the ground state of ^{147}Ba). In subsequent fission works, first spin and parity $3/2^+$ has been proposed for the ground state in ^{147}Ba [8], but later spin and parity $7/2^-$ has been assigned to this level and some unspecified, low-energy levels were introduced [9]. Later fission work [5] has assigned again spin and parity $(3/2^-)$ to the ground state of ^{147}Ba. In a recent β-decay work [10], significant changes of multipolarities of transitions have been reported. Several E1 transitions from Ref. [7], which suggested parity doublets, were shown to be M1+E2 in character. Although in Ref. [10] an octupole deformation was predicted for an Ω=5/2 configuration, the ground state was reported with a tentative spin and parity of $3/2^-$. As summarized in Ref. [10], the spin of the ground state in ^{147}Ba is uncertain and spins of other levels remain unknown.

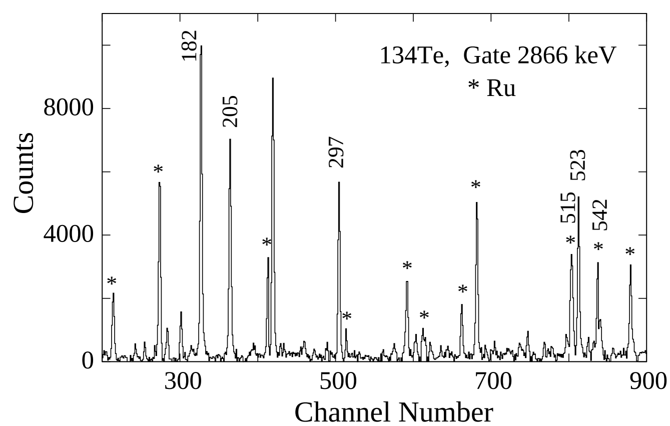

FIG. 1: γ spectrum gated on the 2866-keV line of ^{134}Te. Lines are labeled with their energies in keV.

The measurement of prompt γ rays following spontaneous fission of ^{248}Cm, has been performed using the EUROGAM2 array of Anti-Compton Spectrometers [11] and four low-energy photon spectrometers (LEPS). In this work we reinvestigated the ^{147}Ba nucleus using the same data as in Ref. [5] but applying now better analysis techniques [12]. The new sorting programs produced 2D and 3D histograms with higher dispersion (more channels on each axis). The constant-peak-width compression of the spectra, allowed to extend the energy range up to 4.5 MeV, maintaining the resolution. Gain matching of the individual detectors of the Eurogam array has been improved by applying more accurate calibration procedures. We also applied the so called add-back of signals in Clover detectors, which has significantly improved peak-

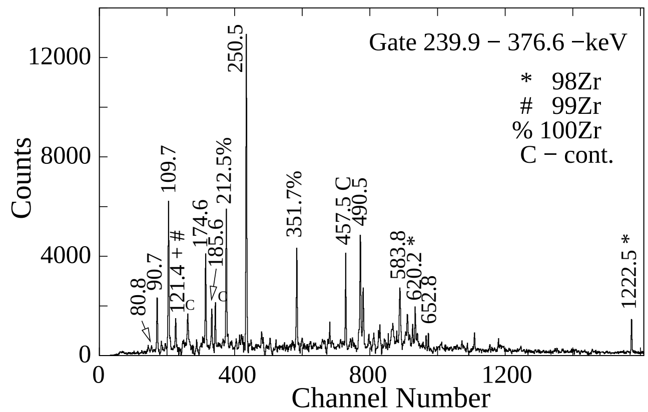

FIG. 2: γ spectrum doubly-gated on the 239.9- and 376.7-keV lines of ^{147}Ba. Label 'C' marks unknown contamination lines.

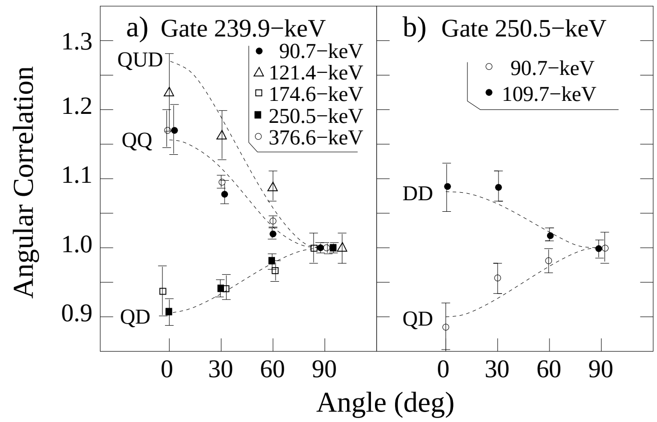

FIG. 3: Angular correlations for γ cascades in ^{147}Ba, as observed in this work. Symbols QQ, QD, QUD and DD mark predicted angular correlations for cascades of stretched quadrupole(Q), stretched dipole(D) or unstretched, unmixed dipole (UD), respectively.

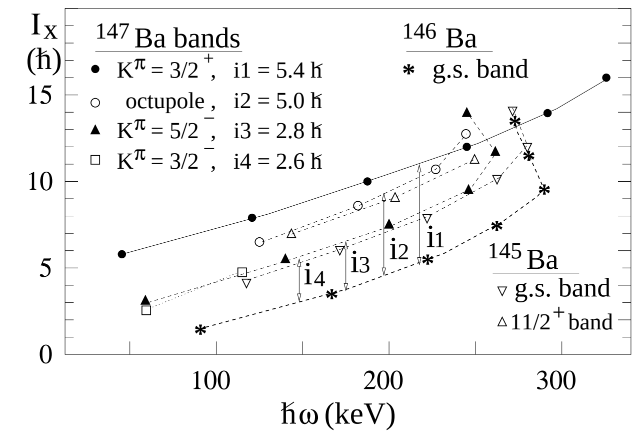

FIG. 4: Aligned angular momentum in bands of ^{147}Ba. Bands in ^{147}Ba: K^{π}=3/2^{+} - on top of the 360.2-keV level, K^{π}=5/2^{-} - on to of the 238.6-keV level (with the 153.4-keV transition included), K^{π}=3/2^{-} - on top of the 46.0-keV level, octupole - on 573.0-keV level (here I_x was calculated taking K=5/2). Alignments in bands of ^{145}Ba and ^{146}Ba are shown to help the discussion.

to-background ratio. An example is shown in Fig. 1, which should be compared with the analogous spectrum, shown in Fig. 1 (a) of Ref. [13], obtained from the same data set but without add-back. Counts in lines are significantly higher in Fig. 1, as compared to Fig. 1 (a) of Ref. [13], which is primarily due to the restoration of counts in the 2866-keV gated line, thanks to the add-back. All the improvements mentioned above allowed the observation of weaker lines and the improvement of angular correlations. Further details about the experiment and data analysis can be found in Ref. [14].

Figure 2 shows a γ spectrum doubly gated on the 239.9- and 376.6-keV lines of the yrast cascade in ^{147}Ba [5]. Present are all the lines reported in Ref. [5]. Interestingly, the 90.7-keV transition follows smoothly the energy trend of quadrupole transitions in the cascade. We can see additional transitions in this cascade with energies 583.8 and 652.8 keV. The 352- and 428-keV transitions reported in [8, 9] are not observed in ^{147}Ba in fission of ^{248}Cm, as already mentioned in Ref. [5] .

In Fig. 3(a) we show angular correlations for the 239.9-376.6- and 239.9-90.7-keV cascades. Both cascades are clearly consistent with quadrupole-quadrupole (QQ) solution. The DCO ratios reported in Ref.[5] were not conclusive about the multipolarity of the 90.7-keV transition, though the α_K and α_{tot} conversion coefficients were in favor of an E2 assignment to this transition. Angular correlation results and the α_K=2.4(4) value reevaluated in this work indicate a stretched E2 multipolarity for the 90.7-keV transition. The observed properties of the 90.7-keV transition indicate that this transition is a member of the yrast quadrupole cascade.

Very similar yrast bands of stretched E2 transitions, observed in the neighboring nuclei ^{145}Ba [15] and ^{149}Ce [16], have been interpreted as the 3/2^{+}[651] neutron configuration. In Fig. 4 we show the aligned angular momentum in the discussed yrast band in ^{147}Ba, relative to the alignment in the ground-state band of ^{146}Ba. We have assumed that the spin of the 450.8-keV level in ^{147}Ba is 13/2. The observed alignment of 5.4$\hbar$, is only consistent with a configuration originating from the neutron $i_{13/2}$ orbital. This alignment is nearly identical with the alignment in the 3/2^{+}[651] band of ^{149}Ce and supports spin and parity 13/2^{+} for the 450.8-keV level in ^{147}Ba. Consequently, considering the spontaneous fission populates predominantly yrast levels [17], and that the 90.7-keV transition is a stretched E2, the spin and parity of the 360.2-keV level in ^{147}Ba is 9/2^{+}.

Angular correlations for the 239.9-250.5-keV cascade, shown in Fig. 3(a) are consistent with the 250.5-keV transition being a stretched dipole (the intermediate, stretched 90.7-keV transition, does not influence angular correlations of the 239.9-250.5-keV cascade). This is confirmed by the angular correlation for the 90.7-250.5-keV cascade, shown in Fig. 3(b), which is consistent with the stretched quadrupole-dipole(QD) solution. With a stretched dipole multipolarity of the 250.5-keV transition the spin of the 109.7-keV level in ^{147}Ba is 7/2.

In Ref. [10] a M1+E2 multipolarity has been reported for the 109.7-keV transition, which is consistent with α_K=1.1(2) conversion coefficient obtained in this work for this transition. This indicates the same parity for the ground state and the 109.7-keV level. If the spin of the ground state were also the same as that of the 109.7-keV level then one would expect a decay from the 360.2-keV level to the ground state. In Fig. 2 this decay is not observed and the limit for the intensity of this branch is lower than 0.007 fraction of the intensity of the 250.5-keV transition. Therefore we concluded that the spin of the ground state is 5/2. This spin is supported by the angular correlation for the 109.7-250.5-keV cascade, shown in Fig. 3(b), which is consistent with both transitions being stretched dipoles. This result excludes spin 3/2 for the ground state. The non-observation of the 360.2-keV decay to the ground state indicates that, most likely, the parity of the ground state is opposite to the parity of the 360.2-keV level. Consequently, we propose spin and parity $5/2^-$ for the ground state in ^{147}Ba. We note here that in a recent compilation [18] a strong decay branch from the 360.1-keV level to the ground state is reported, with a remark that this decay is uncertain. The present data exclude such a branch.

We observe a new, 121.4-keV decay branch from the 360.1-keV level, as seen in In Fig. 5, which displays the level scheme of ^{147}Ba as observed in this work (the properties of γ lines are listed in Table I). Angular correlation for the 121.4-239.9-keV cascade is consistent with the 121.4-keV transition being an unstretched dipole (QUD in Fig. 3). This result indicates spin and parity $9/2^-$ for the 238.6-keV level, considering the negative parity of the ground state and the presence of the 238.6-keV prompt decay, observed also in Ref. [10].

The M1 multipolarity of the 85.2-keV transition, reported in Ref. [10] indicates negative parity for the 85.2-keV level, while the absence of any decay from the 360.2-keV level to the 85.2-keV level suggests spin 5/2 for the 85.2-keV level. Such spin is consistent with angular correlations for the 308.7-153.4-keV cascade, shown in Fig. 3(a). The prompt character of the 153.4-keV decay supports further the negative parity for the 85.2-keV level.

We observe the 174.6-keV decay of the 360.2-keV level, reported previously [5, 10]. The angular correlation for the 239.9-174.6-keV cascade, shown in Fig. 3(a) is consistent with a stretched-dipole character of the 174.6-keV transition, indicating spin 7/2 for the 185.5-keV level. We also observe a new 53.0-keV decay from the 238.6-keV level to the 185.5-keV level. This, together with the 100.4-keV decay of the 185.5-keV level supports spin 7/2 for the 185.5-keV level.

Spin 3/2 or 5/2 can be proposed for the 46-keV level, based on the observed branchings. The 3/2 solution is preferred because this “band” is weakly populated in fission, which suggests its non-yrast character. With the

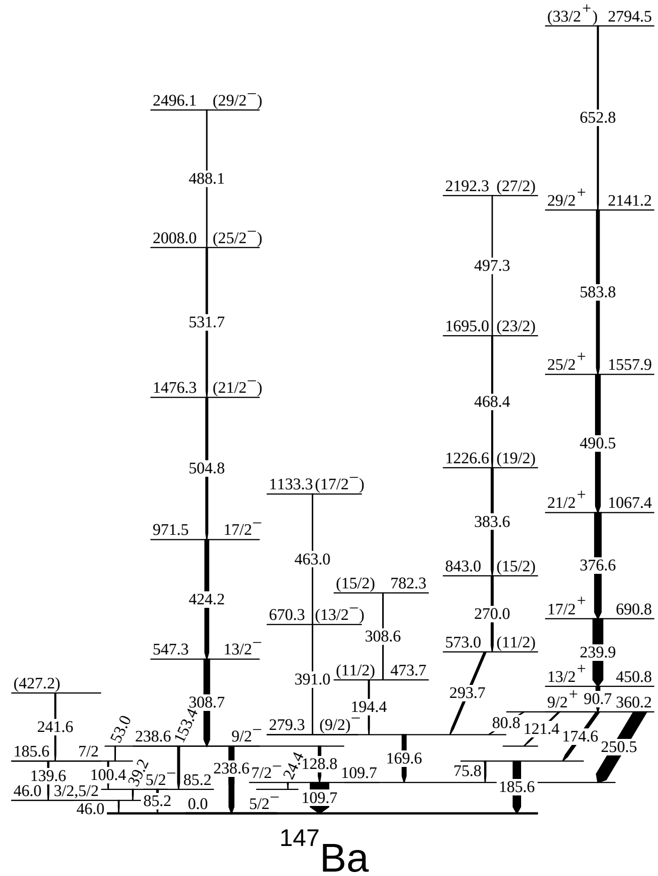

FIG. 5: Level scheme of ^{147}Ba, as observed in this work.

TABLE I: Properties of γ transitions in ^{147}Ba, populated spontaneous fission of ^{248}Cm, as observed in the present work. Intensities of γ lines are in relative units. Transitions of 24.4-, 39.2- and 46.0-keV, shown in the level scheme have been taken from Ref. [10].

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)	$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)	$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)
53.0(3)	8(3)	174.6(1)	20(2)	383.6(2)	4(1)
75.8(2)	7(2)	185.6(1)	40(3)	391.0(2)	5(2)
80.8(2)	3(1)	194.4(2)	5(1)	424.2(1)	20(3)
85.2(1)	6(2)	238.6(2)	26(4)	463.0(3)	2(1)
90.7(1)	25(2)	239.9(1)	53(3)	468.4(2)	3(1)
100.4(2)	2(1)	241.6(3)	2(1)	488.1(3)	3(1)
109.7(1)	100(4)	250.5(1)	61(4)	490.5(2)	14(2)
121.4(2)	7(1)	270.0(1)	8(1)	497.3(3)	1.3(5)
128.8(2)	13(2)	293.7(1)	9(1)	504.8(2)	13(2)
139.6(3)	3(1)	308.6(3)	2(1)	531.7(3)	9(2)
153.4(2)	10(3)	308.7(1)	40(5)	583.8(3)	8(2)
169.6(1)	21(2)	376.6(1)	34(3)	652.8(3)	0.8(3)

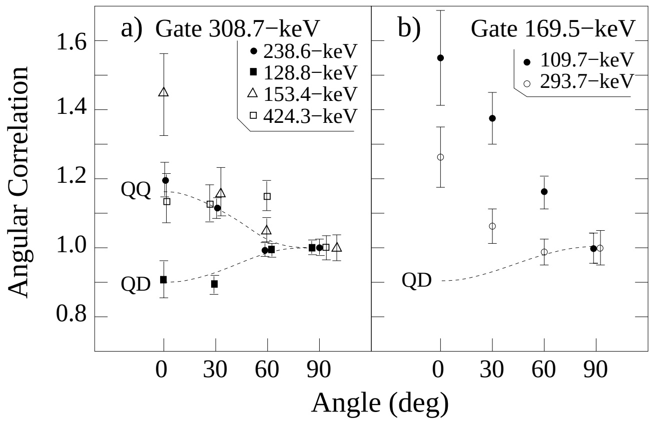

FIG. 6: Angular correlations for γ cascades in ^{147}Ba, as observed in this work. Symbols QQ, QD, QUD and DD mark predicted angular correlations for cascades of stretched quadrupole(Q), stretched dipole(D) or unstretched, unmixed dipole (UD), respectively.

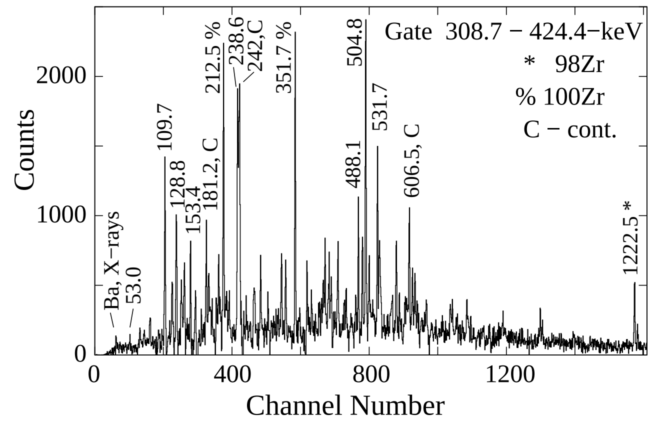

FIG. 7: γ spectrum doubly-gated on the 308.7- and 424.2-keV lines of ^{147}Ba. Label 'C' marks unknown contamination lines.

241.6-keV transition on top of the 185.5-keV level, the 46.0-185.5-427.1-keV band resembles the $3/2^-$ ground-state band in ^{149}Ce. The alignment, $i4 = 2.6\hbar$, seen in this band in Fig. 4, is similar to the alignment in the $3/2^-$ ground-state band of ^{149}Ce.

In a γ spectrum doubly gated on the 169.6- and 239.9-keV lines, the total intensity of the 90.7- and 80.8-keV transitions should be the same, while γ intensities may differ due to the internal conversion. Indeed, γ intensity of the 80.8-keV line, which is 28(4) in arbitrary units, is much higher than γ intensity of the 90.7-keV line, which yields 10.0(2.6) in these units. Considering the E2 multipolarity of the 90.7-keV transition (with the total conversion coefficient of 2.71 [19]), this observation is only consistent with the E1 multipolarity of the 80.8-keV transition (the total conversion coefficients are 0.41, 1.81 and 4.13 for the E1, M1 and E2 multipolarities, respectively [19]). Thus the parity of the 279.3-keV level is negative.

The cascade of 109.7-169.3-293.6-270.0-keV transitions in ^{147}Ba, reported in Ref. [5] is confirmed and extended in this work by 383.6, 468.4- and 497.3-keV transitions. In Fig. 6(b) we show angular correlation for the 169.6-109.7-keV cascade. The strong positive anisotropy observed for this cascade, which is characteristic of two mixed, M1+E2 transitions in a cascade, excludes the quadrupole-dipole (QD) solution. Thus the 169.6-keV transition is of dipole character. Similarly, the QD solution can be excluded for the 169.6-293.7-keV cascade, indicating a dipole character for the 293.7-keV transition. We propose spin 9/2 rather than 7/2 for the 279.3-keV level and, consequently, spin 11/2 for the 573.0-keV level. Otherwise the band on top of 573.0-keV level would be very non-yrast, contradicting its rather strong population in fission. The absence of any decay from the 279.3-keV level to the ground state, further favors spin 9/2 over 7/2 for this level. A similar, second $9/2^-$ level has been recently proposed in ^{143}Xe [21] and ^{145}Ba [15].

In this work we have found a cascade of five transitions on top of the 238.6-keV level, as shown in Fig. 5. A spectrum doubly-gated on the 308.7- and 424.2-keV lines from this new cascade is shown in Fig.7. In the spectrum there are new lines at 504.8-, 531.7- and 488.1-keV and known lines of ^{147}Ba at 53.0-, 153.4- and 238.6-keV as well as X-rays of Ba. There are also known lines from more than one of the complementary Zr isotope, which indicates that the new cascade belongs to a Ba isotope. Angular correlations shown in Fig. 6(a) are consistent with the quadrupole character of the 308.7- and 424.2-keV transitions. Due to their prompt character they are assumed to be E2 transitions. The 504.8- and 531.7-keV transitions which follow the regular trend of in-band transition energies, are also assumed to have an E2 multipolarity.

The alignment of $2.8\hbar$ in the band on top of the 238.6-keV level, seen in Fig. 4, is similar to the alignment in the ground-state band of ^{145}Ba (also shown in Fig.4) interpreted as the $5/2^-[523]$ neutron configuration [15]. Moreover, the plot for the 238.6-keV band shows a back-bending at similar rotational frequency $h\omega \approx 270$ keV. It is then likely that the band on top of the 238.6-keV level corresponds to the $5/2^-[523]$ neutron configuration, seen also in the Sm,Gd,Dy and Er, N=91 isotones [22–25].

The 238.6-keV level decays to both $5/2^-$ levels, the ground state and the 85.2-keV level. However, none of them fits the excitation energy of 65 keV, anticipated for the band head from the regular rotational pattern of the band on top of the 238.6-keV level. The intensity of the 153.4-keV, E2 transition, when corrected for its energy, is factor 3.5 larger than the intensity of the 238.6-keV, E2 transition.Thus, the 85.2-keV level is a likely candidate for the bandhead.

Strong E2 decay branches from the 238.6-keV level to the 85.2-keV level and the ground state suggest a substantial mixing between the two $5/2^-$ levels. Their interaction has probably pushed up the 85.2-keV level by about 20 keV from its unperturbed position. In this picture the the $5/2^-$ ground state was pushed down by the same amount. Therefore, its original position, still 26 keV below the proposed $3/2^-$ level at 46.0 keV, makes it an unlikely member of the $3/2^-$ band. Also its association with the band on top of the 279.3-keV level is unlikely, due to the absence of any decay of this level to the ground state. Thus, the nature of the ground state in ^{147}Ba remains unknown.

In calculation for ^{145}Ba [15] we have shown that negative-parity excitations in ^{145}Ba result from a complex mixing of four neutron orbitals, 1/2[541], 1/2[530], 3/2[532] and 3/2[521], present near the Fermi surface. In this ensemble there should be four close-lying $5/2^-$ levels. It is known that if more levels of the same spin can mix, they will produce one solution of that spin, which is pushed well down in energy while other solutions for this spin are pushed up [26]. The ground states in ^{147}Ba and ^{145}Ba might correspond to such a solution. The extra lowering could be the reason for the unexpected $5/2^-$ spin of the ground state in ^{147}Ba, which otherwise would have spin $3/2^-$, as proposed in Ref. [6]. It would be very interesting to search for the remaining two $5/2^-$ levels expected at low energies in ^{147}Ba (one of them should correspond to the $3/2^-$[532] configuration).

Although the above scenario for the ground state in ^{147}Ba is likely, one might still ask whether the observed lowering of the $5/2^-$ level is rather due to an octupole deformation. In the single-particle neutron diagram calculated in Ref. [6] this would correspond to a sizable octupole deformation parameter $\beta_3 > 0.1$ and, consequently, the presence of parity doublets in ^{147}Ba. In the limit of static octupole deformation the splitting between parity doublets is small. It grows when the potential barrier between the two octupole minima drops [2]. In the limit of octupole vibration (zero barrier) one observes an octupole band with the band head at an energy of the octupole-phonon vibration.

In the present work we did not identify any candidate for a low-energy parity doublet to the $5/2^-$ ground state in ^{147}Ba. The lowest possible candidate for an octupole excitation is the 573.0-keV level with a tentative 11/2 spin assignment. The large alignment of $5.0\hbar$ in the band on top of this level is difficult to explain with the available negative-parity neutron configurations. One might think that this band is the unfavored branch of the $3/2^+$[651] neutron configuration. However, there is a clear upbend in this band, while in the favored branch, α=+1/2, of the $3/2^+$[651] configuration no backbending is seen. Thus, the α=-1/2, $3/2^+$[651] assignment may be questioned. We note that the backbending frequency in the band on top of the 573.0-keV level is similar to the backbending frequency in the band on top of the 238.6-keV level while the alignment is by $2.2\hbar$ higher than in the 238.6-keV band. This closely resembles the properties of the $11/2^+$ band in ^{145}Ba [15], shown in Fig. 4 for comparison. Therefore, we propose that the 573.0-keV level corresponds to an octupole vibration coupled to either the ground state or the 85.2-keV level.

Summarizing, in both ^{145}Ba and ^{147}Ba one sees octupole vibrations coupled to a low-lying $5/2^-$ level. Energies of the 3^- octupole vibration in the even-even core nuclei ^{144}Ba and ^{146}Ba, which are 838.0- and 775.0-keV, respectively, are higher than excitation energies of the proposed $11/2^+$ octupole vibration in ^{145}Ba and ^{147}Ba, which are 670.3- and 573.0-keV, respectively. This suggests an admixture of parity doublets, i.e. a small barrier in an octupole potential, which lowers energies of octupole excitations. Nevertheless, one can conclude that the dominating mode of octupole correlations in ^{145}Ba and ^{147}Ba are octupole vibrations and there is no static octupole deformation in these nuclei. It is possible, that nuclear rotation helps developing octupole deformation at medium spins, as seen in ^{150}Sm [20], and ^{145}Ba [27].

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