Eur. Phys. J. A **30**, 347–350 (2006)
DOI 10.1140/epja/i2006-10146-1

**THE EUROPEAN PHYSICAL JOURNAL A**

*Letter*

# High-spin levels based on the $11/2^-$ isomer in $^{135}$Ba

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Received: 18 September 2006 / Revised: 30 October 2006 /
Published online: 27 November 2006 – 
Communicated by R. Krücken

**Abstract.** High-spin states in the $^{135}$Ba nucleus have been studied with the reaction $^{130}$Te($^9$Be, 4n) at a beam energy of 45 MeV. The level scheme based on the $h_{11/2}$ isomer has been expanded with spins up to 35/2 $\hbar$. At low spins, the yrast collective structure built on the $\nu h^{-1}_{11/2}$ multiplet may show a transitional shape with $\gamma > 30°$ according to the systematical behavior observed in neighboring nuclei as well as the calculations of the triaxial rotor-plus-particle model. The configurations for several high-spin states have been discussed from a systematical comparison with neighboring isotones.

**PACS.** 23.20.Lv $\gamma$ transitions and level energies – 21.60.Ev Collective models – 27.60.+j $90 \leq A \leq 149$

The odd-$A$ $^{135}$Ba nucleus with $Z = 56$ and $N = 79$ lies in the $A = 135$ transitional region with the neutron number approaching the closed shell at $N = 82$. In this region, the nuclei have a small quadrupole deformation parameter $\varepsilon_2$ and a soft $\gamma$-deformation. Their level structures should exhibit complex characteristics as the existence of a competition between the collective motion and the single-particle motion. In previous publications, the high-spin levels of many nuclei in this region, such as in $^{133}$Ba [1], $^{135}$La [2], $^{136}$La [3], $^{137}$La [4], $^{135}$Ce [5], $^{136}$Ce [6], $^{137}$Ce [7] and $^{138}$Ce [8], have been extensively researched. Several interesting phenomena, for example, the shape coexistence of prolate and oblate deformations, the oblate rotational bands, the high-spin structures based on isomers and the excitation levels with multi-quasiparticle configurations were observed. The odd-$A$ $^{135}$Ba nucleus like other $N = 79$ isotones in this region is expected to have a stronger single-particle property and a weaker collectivity than those of $N < 79$ isotopes as its neutron number is closer to the closed shell at $N = 82$. Previous experimental studies of the other $N = 79$ odd-$A$ isotones in $^{137}$Ce [7], $^{139}$Nd [9], $^{141}$Sm [10] and $^{143}$Gd [10] showed the existence of a sequence of levels with weak collectivity based on the $11/2^-$ isomer state at low-spin states from which a prolate-oblate transition in each isotope can be determined. At high-spin states, some systematical levels with multi-quasiparticle configurations [7,10] have been assigned and an oblate collective rotational band has been observed [7]. In order to systematically understand the nuclear structural character in this region, it is interesting to study of the high-spin states of $^{135}$Ba. In previous works, some lower-spin levels have been reported by the ($^9$Be, $x$n) reaction [11], the $\beta$-decay [12] and the (n, $\gamma$) reaction [12]. In this letter, we briefly report on the experimental investigation of new high-spin levels above the $11/2^-$ isomer in $^{135}$Ba.

High-spin states in $^{135}$Ba were populated via the $^{130}$Te ( $^9$Be, 4n) fusion-evaporation reaction. An isotopically enriched $^{130}$Te target of thickness 2.34 mg/cm$^2$ evaporated on a natural aurum backing of 20 mg/cm$^2$ was bombarded by a beam of $^9$Be ions accelerated by the HI-13 accelerator at the China Institute of Atomic Energy (CIAE). An array of fourteen Compton-suppressed Ge detectors was employed to measure the in-beam $\gamma$-rays. The resolutions of the Ge detectors are between 1.8 and 2.2 keV at 1.333 MeV $\gamma$-ray energy. The $\gamma$-$\gamma$ coincidence data were measured at a beam energy of 45 MeV. Approximately $7.7 \times 10^7$ coincidence events were collected, from which a $\gamma$-$\gamma$ coincidence matrix was built. The $\gamma$-ray energies and efficiencies were calibrated with $^{152}$Eu source. In order to determine the multipolarity of $\gamma$-ray transitions, four detectors near 90° with respect to the beam axis were sorted against the other ten detectors at 45° (four), 55° (one), 125° (one) and 135° (four) to produce a two-dimensional

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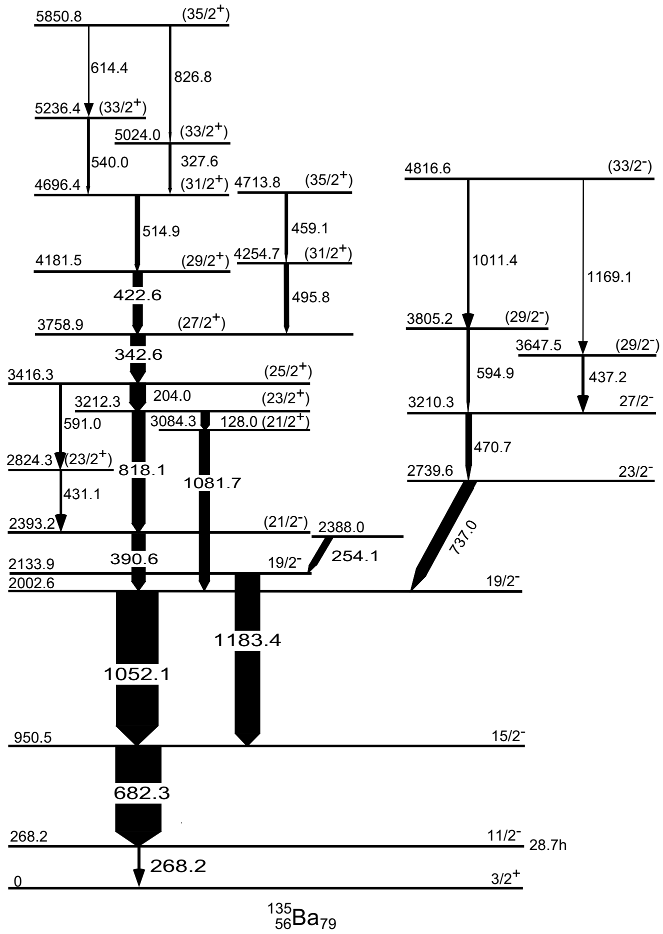


**Fig. 1.** Level scheme of $^{135}$Ba.

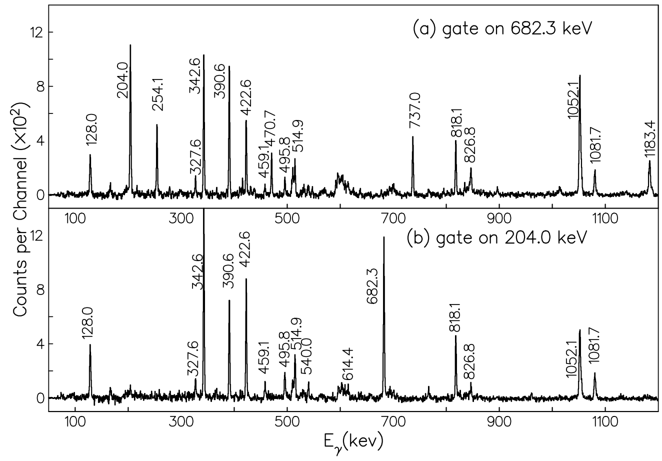


**Fig. 2.** Coincidence spectra obtained (a) by gating on the 682.3 keV, (b) by gating on the 204.0 keV in $^{135}$Ba.

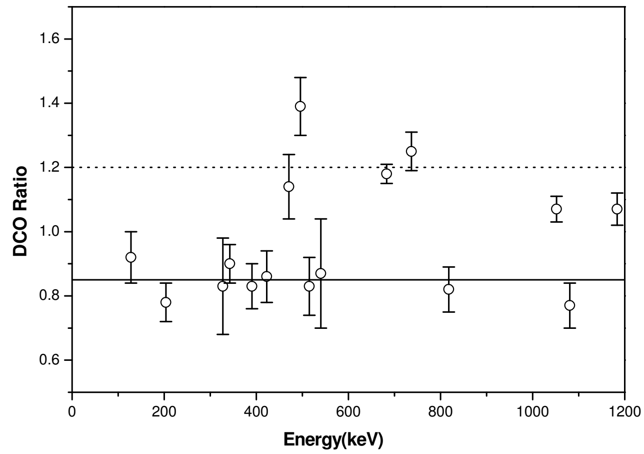


**Fig. 3.** DCO ratio *versus* $\gamma$-ray for several transitions in $^{135}$Ba. The dashed line is drawn to indicate the reference value for $\Delta I = 2$ transitions. The solid line corresponds to the reference value for $\Delta I = 1$ transitions.

angular-correlation matrix from which it was possible to extract the average directional correlation of the oriented-state (DCO) intensity ratios. The $\gamma$-$\gamma$ coincidence data were analyzed with the Radware software package [13].

The level scheme of $^{135}$Ba deduced from the present study is shown in fig. 1. It was constructed from the $\gamma$-$\gamma$ coincidence, the relative transition intensities, and the DCO ratio analysis. The transition intensities are represented by the width of the arrows. Four yrast levels at 0, 268.2, 950.5 and 2002.6 keV along with two linking transitions, 682.3 and 1052.1 keV, reported in ref. [11], were confirmed. We did not observe the 268.2 keV $\gamma$-transition from the 268.2 keV level to the ground state as it belongs to an $M4(E5)$ transition and is too weak to be observed. All the other levels and transitions in fig. 1 were newly identified in our work, including 20 levels and 24 transitions. As example, fig. 2 shows two representative coincidence $\gamma$-ray spectra by gating on the 682.3 keV (a), and the 204.0 keV (b) $\gamma$-transitions, respectively, from which the stronger coincidence $\gamma$-peaks in $^{135}$Ba can been seen.

The spin and parity ($I^\pi$) assignments for the levels are based on the previous works [11,12], the DCO ratios and the systematical comparison with the levels of neighboring $N = 79$ isotones $^{137}$Ce [7], $^{141}$Sm [10] and $^{143}$Gd [10]. Figure 3 shows a plot of the observed DCO ratios for some transitions of $^{135}$Ba in the present work. The DCO ratios for some weak transitions cannot be obtained because of the poor statistics of the $\gamma$-peaks. Generally, a quadrupole ($\Delta I = 2, E2$) transition is adopted if a DCO ratio is around 1.2, and a dipole ($\Delta I = 1$) transition is assumed if a DCO ratio is around 0.85. However, in a dipole ($\Delta I = 1$) transition, one cannot distinguish between $E1$ and $M1$ transitions using this method. The $I^\pi$ of the ground state of $^{135}$Ba has been assigned as $3/2^+$ and the 268.2 keV level was assigned as $11/2^-$ [11,12] with a long half-life of $T_{1/2} = 28.7$ h [12]. In ref. [11], the $I^\pi$ of 950.5 and 2002.6 keV levels was tentatively assigned as $15/2^-$ and $19/2^-$, respectively. From our DCO ratio values, we confirmed these assignments because both the 682.3 and 1052.1 keV $\gamma$-transitions belong to the $E2$ multipolarity. According to the observed DCO ratios and the systematical comparison with neighboring nuclei, we assigned or tentatively assigned the $I^\pi$'s of other high-spin levels, as shown in fig. 1. At the lower-spin states from $11/2^-$ at 268.2 keV to $19/2^-$ at 2133.9 keV, there are

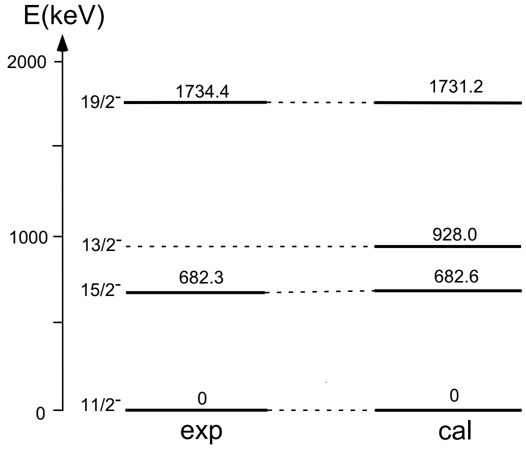


**Fig. 4.** Calculated levels of some members of the $\nu h_{11/2}^{-1}$ level family and comparison to the experiment for $^{135}$Ba. The energies of the $11/2^-$ levels are taken as zero.

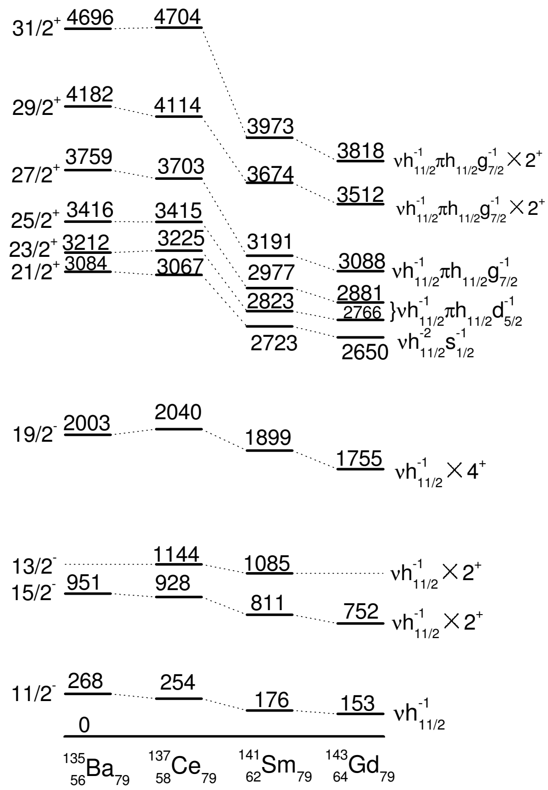


**Fig. 5.** The possible configurations suggested for some states in $^{135}$Ba compared to those in $^{137}$Ce, $^{141}$Sm and $^{143}$Gd.

odd-parity levels connected by the quadrupole transitions. Above the $21/2^-$ state, the levels divide into two groups of even-parity states (left part) and odd-parity states (right part) connected mainly by the dipole transitions. At high spins, we did not observe a collective oblate rotational band in $^{135}$Ba, as reported in $^{137}$Ce [7]. The reason may be that a higher incident energy beam is needed in order to populate higher-spin states.

The level structure of $^{135}$Ba exhibits complex characteristics. It is difficult to determine all the level configurations. However, some important features can been discussed based on the systematics and model calculations. At lower-spin states, the $11/2^-$ isomer state at 268.2 keV can be explained by the $h_{11/2}$ neutron hole coupled to the even-even nucleus core. The $15/2^-$ state at 950.5 keV may belong to a member of the $\nu h_{11/2}^{-1} \times 2^+$ multiplet and the $19/2^-$ state at 2002.6 keV may belong to a member of the $\nu h_{11/2}^{-1} \times 4^+$ multiplet. Another $13/2^-$ state of the member of the $\nu h_{11/2}^{-1} \times 2^+$ multiplet was not observed in the present work. This $\nu h_{11/2}^{-1}$ level family has been systematically observed in the neighboring isotones $^{137}$Ce [7], $^{139}$Nd [9], $^{141}$Sm [10] and $^{143}$Gd [10] also.

Shape transition is a very interesting phenomenon in the $A = 135$ transitional region. The prolate-oblate shape transition at low-spin states was reported in the neighboring Ce [7,14] and Nd [9] isotopes between $N = 77$ and $N = 79$. That is, in an isotopic chain the nucleus has a prolate shape with $\gamma < 30°$ at $N \leq 77$ and it has an oblate shape with $\gamma \geq 30°$ at $N \geq 79$. It indicated that the sequence of the $13/2^-$ and $15^-$ levels of the $\nu h_{11/2}^{-1}$ multiplet is a signature of a prolate or an oblate shape: when the $15^-$ state lies up on the $13/2^-$ state, the nucleus has a prolate shape, whereas when the level inversion of the $13/2^-$ state and $15/2^-$ state occurs, the nucleus has an oblate shape. Although the $13/2^-$ state member in $^{135}$Ba has not been identified in the present work, we still strongly suggest that at low-spin states $^{135}$Ba has a triaxial shape with $\gamma > 30°$ in the oblate side based on the systematic behavior observed in the neighboring nuclei. As in $^{133}$Ba [1] the $h_{11/2}$ collective structure is expected to have a prolate deformation, the prolate-oblate transition may occur between $N = 77$ and $N = 79$ in Ba isotopes also. In order to further understand the structural characteristics at the low-spin states in $^{135}$Ba, we have performed calculations using the triaxial rotor-plus-particle model with a variable moment of inertia (VMI) [15–17]. In the calculations, the adjustable parameters are $\varepsilon_2$, $\gamma$ and the Coriolis attenuation factor $\chi$. By varying the $\varepsilon_2$, $\gamma$ and $\chi$ values, and by carefully comparing the calculated levels with the corresponding experimental ones, we determined these values used in the calculations as follows: $\varepsilon_2 = 0.09$, $\varepsilon_4 = 0.0$, $\gamma = 33.6°$ and $\chi = 0.73$. Other parameters were taken as standard. The results of our calculations and a comparison with experimental data are shown in fig. 4. Generally, the agreement between the theoretical and experimental results is quite good. The calculations predict that the $13/2^-$ state should lie above the $15/2^-$ state. One needs to observe it in further experiments. As expected, the calculations indicate that the $^{135}$Ba nucleus at low spins has a triaxial shape with $\gamma > 30°$. This might give a support to our above suggestion of the prolate-oblate shape transition in Ba isotopes.

Although determining the configurations of all the levels observed in $^{135}$Ba is difficult, the configurations for some levels may be discussed based on a systematical comparison with neighboring isotopes and isotones. The

$19/2^-$ state at 2133.9 keV lies up on the $19/2^-$ state at 2002.6 keV. It may originate from the $\nu h_{11/2}^{-1} \times 4_2^+$ configuration as the $4_2^+$ state at 2050.9 keV in $^{136}$Ba [18] lies up on the $4^+$ state at 1866.6 keV. The $21/2^-$ state at 2393.2 keV may have a $\nu h_{11/2}^{-1} \times 6^+$ configuration. These levels can be seen in the neighboring nuclei $^{137}$Ce [7] also. Now we discuss the even-parity levels at the high-spin states in fig. 1. By systematically comparing with the assigned configurations of some levels in the nuclei $^{137}$Ce [7], $^{141}$Sm [10] and $^{143}$Gd [10], three-quasiparticle configurations for some states may be suggested as shown in fig. 5. The $21/2^+$ state at 3084 keV may originate from the $\nu h_{11/2}^{-2} s_{1/2}^{-1}$ configuration. Both the $23/2^+$ and $25/2^+$ levels at 3212 and 3416 keV may belong to the members of the $\nu h_{11/2}^{-1} \pi h_{11/2} d_{5/2}^{-1}$ configuration, and the $27/2^+$ level at 3759 keV may originate from the $\nu h_{11/2}^{-1} \pi h_{11/2} g_{7/2}^{-1}$ configuration. The $29/2^+$ state at 4182 keV and the $31/2^+$ state at 4696 keV may be two members of the $\nu h_{11/2}^{-1} \pi h_{11/2} g_{7/2}^{-1} \times 2^+$ multiplet. From fig. 5 one can see that the level energies of these three-quasiparticle states are quite similar in $^{135}$Ba and $^{137}$Ce, and generally decrease with increasing $Z$ number. The high-spin even-parity levels above the $31/2^+$ state at 4696 keV, may have five-quasiparticle configurations, and the odd-parity levels above the $23/2^-$ state at 2740 keV at the right side in fig. 1 may have tree-quasiparticle configurations also. But detailed configurations for these levels cannot be determined by the present work.

In summary, high-spin states in the $^{135}$Ba nucleus have been studied. The level scheme based on the $h_{11/2}$ isomer has been expanded with spins up to $35/2\ \hbar$. At low spins, the yrast collective structure built on the $\nu h_{11/2}^{-1}$ multiplet shows a transitional shape with $\gamma > 30°$ according to the systematical comparison with neighboring nuclei and the calculations of the triaxial rotor-plus-particle model. The prolate-oblate transition may occur between $N = 77$ and $N = 79$ in Ba isotopes. The configurations for several high-spin states have been discussed from a systematical comparison with neighboring nuclei. The identification of the proper configurations of the high-spin states in $^{135}$Ba needs more experimental and theoretical work, in particular, on electromagnetic transition probabilities.

The work at Tsinghua University was supported by the National Natural Science Foundation of China under Grant Nos. 10575057, 10375032, the Special Program of Higher Education Science Foundation under Grant No. 20030003090. The authors wish to thank the staff of the in-beam $\gamma$-ray group and the tandem accelerator group at CIAE for their help and hospitality during the experiment and for providing the heavy-ion beam and the target.

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