Eur. Phys. J. A **20**, 207–210 (2004)
DOI 10.1140/epja/i2003-10163-6

THE EUROPEAN PHYSICAL JOURNAL A

Letter

A new isomer in ^{136}Ba populated by deep inelastic collisions

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Received: 22 September 2003 / Revised version: 11 November 2003 /
Published online: 6 April 2004 –
Communicated by D. Schwalm

Abstract. Excited states in ^{136}Ba, populated in deep inelastic collisions by the interaction of 450 MeV ^{82}Se ions with a ^{139}La target, have been studied by means of in-beam γ-ray spectroscopy. A new isomer with $I^\pi = (10^+)$ has been identified at an excitation energy $E_x = 3.357$ MeV. The half-life was determined as $T_{1/2} = 94 \pm 10$ ns. The extracted $B(E2)$ value is much smaller than those in ^{132}Te and ^{134}Xe. This hindrance is investigated by a shell model calculation.

PACS. 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.60.+j $90 \leq A \leq 149$

The $^{136}_{56}$Ba$_{80}$ nucleus lies near the neutron shell closure at $N = 82$ and in the proton mid-shell between $Z = 50$ and 64 shell closures. In this region, an interplay of quadrupole collectivity and single-particle degrees of freedom could exist even in the relatively low-lying states. The yrast 10^+ isomers have been observed in the $N = 80$ isotones ^{132}Te [1,2], ^{134}Xe [2] and ^{138}Ce [3]. The $\nu(h_{11/2})^{-2}$ configuration is expected to be dominant for these isomers. On the other hand, because of the quadrupole collectivity, other configurations can significantly mix in the low-spin yrast states including the states which the 10^+ isomers decay into. The decay rates as well as the excitation energies of the isomers are therefore important measures in understanding the nuclear structure in this region.

Since the yrast 10^+ isomers are known for ^{132}Te, ^{134}Xe and ^{138}Ce, a similar 10^+ isomer is expected for the $N = 80$ isotone of ^{136}Ba. However, no evidence for such a state has been reported so far, primarily due to experimental difficulties to access higher-spin states in this nucleus. In this paper we report on the first identification of the 10^+ isomer in ^{136}Ba, which was done by a deep-inelastic-collision experiment. The half-life of the isomer was measured by use of the γ-γ coincidence method. A remarkable hindrance of the $E2$ transition strength compared with those for the neighboring nuclei of ^{132}Te and ^{134}Xe is found and will be discussed based on a shell model calculation.

During the process of this work, we have noticed an independent study on ^{136}Ba [4], where consistent results to this work were obtained.

In the present experiment, excited states in ^{136}Ba have been produced in deep inelastic collisions (DIC) of ^{82}Se ions with a ^{139}La target. The 450 MeV ^{82}Se beam was supplied by the tandem accelerator at the Japan Atomic Energy Research Institute (JAERI). The thick self-supporting target with a thickness of 100 mg/cm^2 was used to stop recoiled residuals inside the target material. Emitted γ-rays were detected by the GEMINI detector array, consisting of 12 Compton-suppressed HP-Ge detectors. The detectors were positioned at angles of 32° (2 detectors), 58° (2), 90° (4), 122° (2) and 148° (2) relative to the beam direction. A typical energy resolution of the Ge detectors was 2.4 keV at 1.33 MeV of ^{60}Co. Energies and a relative time of γ-rays were recorded on magnetic tapes when two or more Ge detectors were detected in coincidence. The coincidence time window was set to 200 ns so that half-lives of less than ~100 ns could be extracted. A total of 3×10^7 γ-γ events were collected. The energy calibration was made by using ^{133}Ba and ^{152}Eu standard sources. Two-dimensional γ-γ matrices of both prompt-prompt and prompt-delayed coincidences were created to construct the level scheme.

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Table 1. Energies, level assignments, relative intensities, and DCO ratios for the γ-ray transitions in ^{136}Ba.

E_γ (keV)	E_i (keV)	J_i^π	→	J_f^π	I_γ	DCO
66.9(1)	2207.1	6^+	→	5^-	11(1)	
86.3(1)	2140.2	5^-	→	4^+	6(1)	
153.2(1)	2207.1	6^+	→	4^+	7(1)	0.7(1)
163.9(1)	2030.4	7^-	→	4^+	12(1)	0.6(1)
176.9(1)	2207.1	6^+	→	7^-	16(1)	0.7(1)
273.6(1)	2140.2	5^-	→	4^+	13(1)	0.8(1)
340.5(1)	2207.1	6^+	→	4^+	48(2)	0.9(1)
349.2(2)	3706.0		→	$10^{(+)}$	70(2)	
362.7(1)	3356.8	$10^{(+)}$	→	$8^{(+)}$	46(2)	0.9(1)
508.9(1)	4214.9				40(2)	
787.0(1)	2994.1	$8^{(+)}$	→	6^+	85(3)	0.9(1)
818.5(1)	818.5	2^+	→	0^+	100(3)	1.2(1)
963.6(1)	2994.1	$8^{(+)}$	→	7^-	8(1)	
1048.1(1)	1866.6	4^+	→	2^+	75(3)	1.0(1)
1235.4(1)	2053.9	4^+	→	2^+	25(2)	1.0(1)

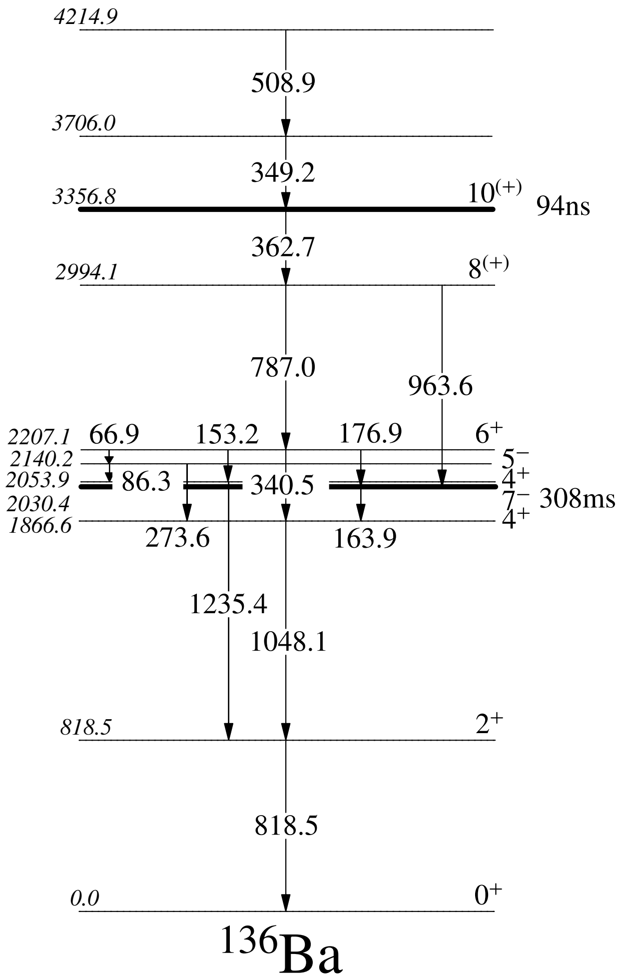

Fig. 1. A proposed level scheme of ^{136}Ba.

The directional correlations of γ-rays de-exciting oriented states (DCO) ratio [5,6] defined below was used to deduce transition multipole orders:

$$R_{\mathrm{DCO}} = \frac{I_\gamma \text{ at } 32^\circ (\text{or } 148^\circ) \text{ gated on } \gamma_{\mathrm{G}} \text{ at } 90^\circ}{I_\gamma \text{ at } 90^\circ \text{ gated on } \gamma_{\mathrm{G}} \text{ at } 32^\circ (\text{or } 148^\circ)}.$$

Since the angle of 148° is equivalent to that of 32° [6], the corresponding events were summed in the DCO matrices to increase the statistics. In the DCO analysis, stretched $\Delta I = 2$ transitions close to the γ-ray of interest are generally used as gates (γ_G). In this case, the DCO ratios fall into unity for stretched quadrupole ($\Delta I = 2$) and unstretched dipole ($\Delta I = 0$) transitions, while the values are ~ 0.6 for stretched dipole ($\Delta I = 1$) transitions. For mixed $\Delta I = 1$ transitions, the DCO ratios depend on the the mixing ratio δ.

Figure 1 shows a level scheme of ^{136}Ba resulting from the present work. The transition energies, γ-ray intensities and DCO ratios are also summarized in table 1. The transitions below the 2207 keV state were previously known [7]. A 787 keV γ-ray seen in fig. 2(a) which is obtained by gating on the 1048 keV $4^+ \to 2^+$ transition connects the 2207 keV and 2994 keV level [8]. In the present work, a 964 keV crossover transition depopulating the 2994 keV level was newly observed. In addition, three new transitions with energies of 349, 363 and 509 keV were found in coincidence with the lower-lying transitions in ^{136}Ba. From the analysis of the prompt-delayed coincidence spectra (figs. 2(b) and (c)), a new isomer was identified at $E_x = 3357$ keV, decaying to the 2994 keV level via the 363 keV transition. The transitions below the isomer can be seen in the delayed spectrum (fig. 2(b)). Above the isomer, the 349 and 509 keV transitions were also observed (fig. 2(c)). The DCO ratios for the 363 and 787 keV transitions are consistent with $\Delta I = 2$, resulting in assignments of $I = 8$ for the 2994 keV state and $I = 10$ for the 3357 isomeric state. The positive-parity assignments are preferred by the systematic behavior of the yrast 8^+ and 10^+ energy levels in the region.

For the determination of the half-life of the 10^+ isomer, a γ-ray time difference spectrum has been analyzed. Figure 3 shows a decay curve of the isomer. By

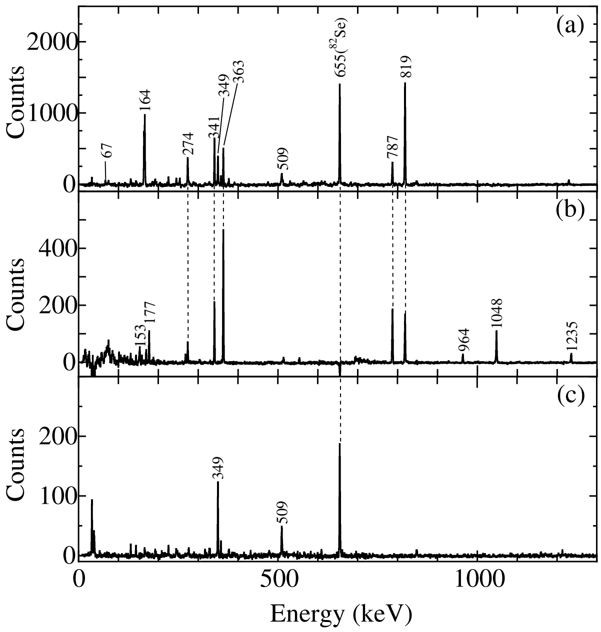

Fig. 2. (a) A prompt coincidence spectrum gated on the 1048 keV transition. A delayed γ-ray spectrum gated on the 349 keV transition, showing γ-rays below the 10^+ isomer is also drawn in panel (b), while an early γ-ray spectrum gated on the 819 and 1048 keV transitions, showing the transitions above the 10^+ isomer, is drawn in panel (c).

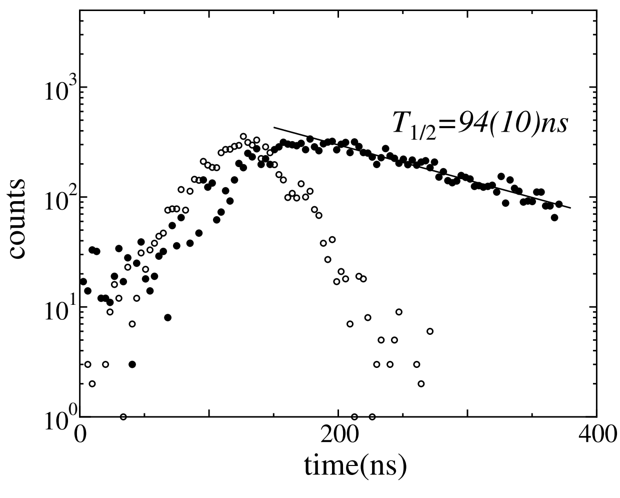

Fig. 3. A time difference spectrum between the 349 keV transition and the 340, 363, 787, 819, 1048 keV transitions, showing the decay curve for the isomer. The time difference spectrum in prompt coincidence is also shown with open circles.

fitting the decay slope, the half-life was determined as $T_{1/2} = 94(10)$ ns. Assuming that the 363 keV transition has a pure $E2$ character, the reduced $E2$ transition probability is extracted as $B(E2) = 0.96(10)\ e^2\mathrm{fm}^4$. This value is much smaller than those for the neighboring nuclei of ^{132}Te, $B(E2) = 42(1)\ e^2\mathrm{fm}^4$ and ^{134}Xe, $B(E2) = 26(5)\ e^2\mathrm{fm}^4$ [2]. The energy levels and the $E2$ strength of the 10^+ isomers will be discussed in the next section based on a shell model calculation.

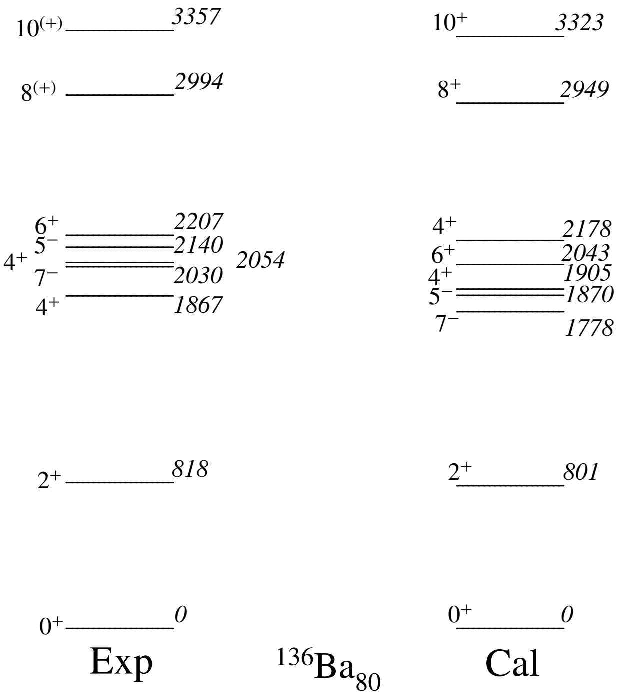

Fig. 4. Comparison of experimental and calculated energy levels of ^{136}Ba.

In order to investigate the $E2$ strength of the 10^+ isomer observed in ^{136}Ba, a shell model calculation has been carried out. We take the $(0g_{7/2}1d_{5/2}2s_{1/2}0h_{11/2}1d_{3/2})$ orbits for protons and $(2s_{1/2}0h_{11/2}1d_{3/2})$ for neutron holes, on top of the ^{132}Sn inert core. For protons, the excitation out of $(0g_{7/2}1d_{5/2})$ is restricted up to 4 particles with the total seniority $v \leq 4$. We adopt the surface delta-interaction (SDI) for the pp and nn interaction, whose strengths as well as the single-particle energies are fitted to the observed levels of ^{134}Te and ^{130}Sn. The quadrupole-quadrupole interaction is used for the pn interaction. The excitation energies of the 8^+ and 10^+ states are rather sensitive to the single-hole energy of $n0h_{11/2}$ in this region. Although the attractive monopole pn interaction plays a certain role, the present schematic interaction may not treat this effect properly. We therefore introduce a slight Z-dependence of the single-hole energy so as to reproduce the levels of the neighboring $N = 81$ nuclei. Note that this shift of the single-hole energy does not influence significantly the $E2$ strengths of the 10^+ isomers shown below. The calculated energy levels of ^{136}Ba are presented in fig. 4. The energy levels up to the 10^+ isomer are well reproduced.

In the calculation of the $E2$ strengths, we use the effective charges $e_p^{\mathrm{eff}} = 2.8e$ and $e_n^{\mathrm{eff}} = 0.4e$, which are fitted to $B(E2; 2^+ \to 0^+)$ of the $N = 82$ and 80 nuclei, as shown in table 2. The value of e_p^{eff} is somewhat larger than other shell model calculations in this region [9]. This may be ascribed to the truncation of the model space. With the effective charges fixed by the low-lying states, the $E2$ decay strengths of the 10^+ isomers in the $N = 80$ nuclei tend to be overestimated. However, the overall trend of

Table 2. Calculated $B(E2; 2_1^+ \rightarrow 0_1^+)$ values ($e^2\mathrm{fm}^4$) of $N = 82$ and 80 nuclei. Experimental data are taken from refs. [10,11].

Nucleus	Experimental	Calculated
${}^{134}_{52}\mathrm{Te}_{82}$	–	209
${}^{136}_{54}\mathrm{Xe}_{82}$	402 ± 16	357
${}^{138}_{56}\mathrm{Ba}_{82}$	460 ± 18	436
${}^{132}_{54}\mathrm{Te}_{80}$	–	316
${}^{134}_{54}\mathrm{Xe}_{80}$	680 ± 120	600
${}^{136}_{56}\mathrm{Ba}_{80}$	820 ± 16	818

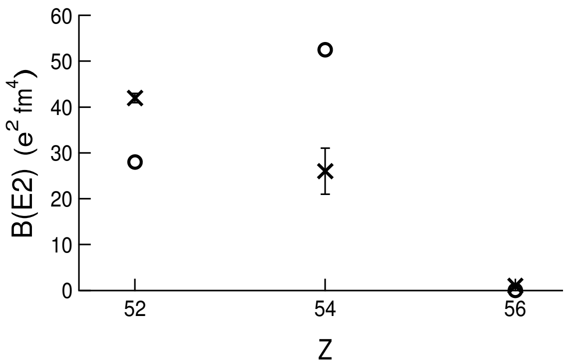

Fig. 5. $B(E2)$ values from the 10^+ isomers for the $N = 80$ isotones. The experimental values are shown by crosses with error bars, whereas the shell model values (scaled by 1/2) are shown by circles.

the $B(E2)$ values, particularly the Z-dependence, is well reproduced. The measured and calculated $E2$ strengths of the 10^+ isomers are depicted in fig. 5, where the calculated $E2$ strengths are scaled by 1/2.

Whereas it is not easy to reproduce accurately the $B(E2)$ values of non-collective $E2$ transitions, such as those of the 10^+ isomers, their Z-dependence seems to carry valuable information of nuclear structure [12]. The $E2$ decay strength of 10^+ is remarkably hindered in ^{136}Ba from those in ^{132}Te and ^{134}Xe. In analyzing the shell model results, it is found that this hindrance originates from different characters of the wave functions between the 10^+ and 8^+ states. The 10^+ state is dominated by the $J_p = 0$, $J_n = 10$ component, while the 8^+ state by the $J_p = 2$, $J_n = 6$ component, and the $E2$ transition matrix element between these components vanishes. Thus, the mismatch of configuration in the yrast states seems to account for the large retardation of the $E2$ transition from the 10^+ isomer observed in ^{136}Ba.

We have firstly identified a 10^+ isomer in ^{136}Ba. The half-life of the isomer was measured as 94(10) ns corresponding to $B(E2) = 0.96(10)$ $e^2\mathrm{fm}^4$ for the $10^+ \rightarrow 8^+$ transition. A shell model calculation has been carried out to investigate the $E2$ strength of the 10^+ isomers in ^{136}Ba and its neighbours. The hindrance for the isomeric transition in ^{136}Ba has been attributed to the different characters of the wave functions of the 10^+ and 8^+ states.

We would like to thank the staff of the JAERI tandem accelerator for providing the ion beam. This work is supported by STA Exchange Program and by NSFC-19705011, NSFC-19905012.

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