Energy systematics of low-lying 0^+ states in neutron-deficient Ba nuclei

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Low-spin states in ^{124,126,128,130}Ba fed by the EC/β^+ decay of their La parents have been investigated by means of the γ-γ angular correlation measurement coupled with an isotope separator on-line. The spin of the first excited 0^+ states (0_2^+) were unambiguously established, and higher-excited 0^+ states were newly identified. The energy of the 0_2^+ state in ^{124}Ba previously assigned was revised upward. Resultingly, the level energy of the 0_2^+ state in neutron-deficient Ba nuclei takes a minimum at $N=72$ and then gradually increases toward neutron midshell ($N=66$), while the level energy of the 0_3^+ state rapidly decreases with decreasing neutron number. From an extrapolation of these 0^+ energies, it is highly expected that the energy relation between the 0_2^+ and 0_3^+ state would invert at ^{122}Ba or at more deformed Ba nuclei. This energy inversion is interpreted as the evolution of the 0_2^+ state in γ-soft nuclei toward the two-phonon γ-vibrational 0^+ state in axially-symmetric deformed nuclei, while the 0_3^+ state toward the β-vibrational 0^+ state.
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I. INTRODUCTION

The even-even Xe-Ba-Ce nuclei with $N<82$ lie in a typical transitional region on nuclear deformation. The structure of low-lying collective states in these nuclei exhibits a γ-soft character [1], especially in the Xe nuclei. In the Ba and Ce nuclei, although the γ-soft character is still dominant, a gradual shape change from a γ-soft nucleus near $N\approx78$ to an axially-symmetric nucleus occurs toward neutron midshell ($N=66$) [2]. This region gives us a good opportunity to study the evolution of nuclear deformation from a γ-soft nucleus to an axially-symmetric deformed nucleus, because the low-lying collective states in this region exhibit smooth and gradual changes against Z and N in contrast to other transitional regions such as the $Z>50$, $N>82$ region and the $Z<82$, $N<126$ region. The $Z>50$, $N>82$ nuclei show a sudden shape change between a spherical vibrational nucleus and a well-deformed nucleus around $Z\approx64$ and $N\approx90$ [3] due to the strong proton-neutron interaction between the $h_{11/2}$ protons and the $h_{9/2}$ neutrons. In the $Z<82$, $N<126$ nuclei, which also exhibit the shape change between a γ-soft nucleus and a well-deformed nucleus like the Xe-Ba-Ce nuclei, the systematic behavior of low-lying collective states is influenced by subshell effects [3] and the admixture of intruder configurations [4]. It is expected that there is no strong influence of subshell effects [3] and the admixture of intruder configurations in the Ba and Ce region.

During the past decade, experimental data of low-lying collective states in the Ba and Ce nuclei have been accumulated by means of in-beam γ-ray spectroscopy with heavy-ion fusion-evaporation reactions and through the EC/β^+ decay of precursor nuclides. Ground state bands and quasi-γ bands in these nuclei have been established from $N=78$ to $N=68$. The systematic behavior of these band structures indicates the shape evolution from a γ-soft nucleus to an axially-symmetric deformed nucleus. Especially, the energy systematics of the quasi-γ band in the Ce nuclei shows a clear indication of the evolution of the quasi-γ band in γ-soft nuclei toward the γ-band in well-deformed nuclei [2]. However, the nature of excited 0^+ states and their evolution are still unclear partly due to lack of experimental data. Although a number of excited 0^+ states have been established for the Xe nuclei and the stable ^{132,134}Ba nuclei, only the first excited 0^+ states (0_2^+) have been reported for $^{124-130}$Ba and $^{128-134}$Ce. Theoretical calculations such as the general collective model (GCM) [5] and the interacting boson model (IBM) [2,6,7] which reproduced many properties of the ground state band and the quasi-γ band failed to reproduce the excitation energies of the 0_2^+ band; the level spacings of the 0_2^+ band were calculated to be much larger than the experimental ones for most nuclei, and for some nuclei, particularly for Ba nuclei with $A<130$, the level energy of the 0_2^+ state was not reproduced well. In addition, the energy systematics of the 0_2^+ state in the Ba nuclei shows an unexpected irregularity. The level energy of the 0_2^+ state lowers with decreasing neutron number between ^{134}Ba and ^{128}Ba, and then slightly increases at ^{126}Ba and again slightly lowers at ^{124}Ba. Other collective states in the Xe-Ba-Ce nuclei do not show such an irregularity. It is not clear why this irregularity occurs.

Experimentally, since excited 0^+ states are scarcely populated with heavy-ion reaction, most of the excited 0^+ states in this region were observed through EC/β^+ decay and twonucleon transfer reaction. For the stable ^{132,134}Ba nuclei, a number of excited 0^+ states have been identified with the (p,t) reactions [8]. For $^{124-130}$Ba nuclei, only the first excited 0^+ states and their 2^+ band members (denoted as 2_3^+) have been reported, and no higher-excited 0^+ states have been observed. All these 0_2^+ and 2_3^+ states were populated by the EC/β^+ decay of their La parents. For ^{130}Ba, the spin of the 0_2^+ state was assigned from a γ-γ angular correlation measured at 90° and 180° [7]. For ^{128}Ba and ^{126}Ba, the spin assignment for the 0_2^+ states was merely due to the energy systematics [9,10]. For ^{124}Ba, the 0_2^+ state was assigned by observing an $E0$ transition to the 0_1^+ state with the conversion electron measurement [11].

The aim of the present work is to establish the 0_2^+ states and higher-excited 0^+ states in ^{124,126,128,130}Ba populated via the EC/β^+ decay of mass-separated La nuclei, and to clarify the nature of the excited 0^+ states and their evolution from a γ-soft nucleus to an axially-symmetric deformed nucleus. In order to assign the spin of the excited 0^+ states unambiguously, γ-γ angular correlation measurements are performed using an efficient five-HPGe detector system [12]. From the energy systematics of the 0_2^+ and 0_3^+ states, the nature of these 0^+ states and their evolution in this transitional region are discussed.

II. EXPERIMENTS

The $^{124-130}$La nuclei were produced by heavy-ion fusion-evaporation reactions at the TIARA-ISOL [13] connected with the JAERI AVF cyclotron. The 195 MeV ^{36}Ar beam with an intensity of about 120 particle nA was delivered to a 3 mg/cm^2 ^{nat}Mo target for producing ^{128}La and ^{130}La, and to an isotopically enriched ^{92}Mo and ^{94}Mo target for ^{124}La and ^{126}La respectively. Reaction products were ionized with a thermal ion source, and accelerated with 40 kV. In the present ion source, La and Ce isotopes are efficiently ionized as a monoxide ion rather than as an elemental ion [14], so that the monoxide ion was mass-separated for the subsequent spectroscopic measurements. This method has another advantage of reducing contaminants of Cs and Ba isobars which are not obtained as a monoxide ion but efficiently ionized as an elemental ion. In the present reaction systems, Pr isotopes are weakly produced. Since the Pr isotopes are also ionized as a monoxide ion, the radioactivities of ^{128}Pr and ^{130}Pr were weakly observed. After mass-separation with a resolution of about 1500, the separated ions were transported to a low-background measuring area and collected on an aluminized Mylar tape in a tape transport system. The source was periodically transported to the measuring position at time intervals of 324 s, 100 s, and 52 s for ^{128}La, ^{126}La, and ^{124}La, respectively.

The measuring position was equipped with five n-type coaxial HPGe detectors for γ-γ angular correlation measurements. Each of the detectors has a relative efficiency of about 30%, and was placed 60 mm from the source position. The detectors were configured at fixed angles of 0°, 60°, 150°, 200°, and 250° with respect to the source position, which provides ten correlation angles of 90°, 100°, 110°, 120°, 130°, 130°, 140°, 150°, 160°, and 170° simultaneously. Singles γ-ray, γ-$\gamma(\theta)$ coincidence and multispectrum scaling measurements were carried out. Detailed description of the system and data analysis is given in Ref. [12].

For $A=130$ nuclei, the measurement was performed without the tape transport system in order to measure the decay of ^{130}La as efficiently as possible. In this method, the radioactivity of ^{130}La ($T_{1/2}=8.7$ m) was accumulated from the decay of ^{130}Ce ($T_{1/2}=22.9$ m), which were produced much more than ^{130}La in the present reaction system. The accumulation of ^{130}Ba, the daughter of ^{130}La, gives no problems to the measurement of ^{130}La, because ^{130}Ba is stable. In addition, data of the decay of ^{130}Pr ($T_{1/2}=40$ s) were obtained simultaneously. The separated ions were continuously collected on an aluminized Mylar foil mounted at the center of a collection chamber around which the five HPGe detectors were placed at the same geometry as that described above.

The beam intensities of $2-3\times10^4$ ions/s were obtained for the mass-separated $^{124-130}$LaO$^+$ ions at the collecting position. About 3.8×10^8, 3.0×10^8, 3.7×10^8, and 4.0×10^8 coincidence events were accumulated during a period of 42, 57, 60 and 51 h for $A=124$, 126, 128, and 130, respectively.

III. RESULTS

A. γ-γ angular correlations

Generally, the γ-γ angular correlation function $W(\theta)$ is described as

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta),$$

where θ is the angle, A_2 and A_4 are the angular correlation coefficients, and $P_2(\cos\theta)$ and $P_4(\cos\theta)$ are the Legendre polynomials. In the case of measurements using a multiple-detector system, coincidence counts obtained by different detector pairs have to be normalized with corresponding detector efficiencies. In the present analysis, the coincidence count N_{ij}^{mn} obtained for the cascade between γ rays i and j detected with detectors m and n, respectively, was normalized by using the corresponding singles counts S_i^m and S_j^n obtained in the same experimental run instead of the detector efficiencies themselves [12]. Considering the attenuation arising from finite solid angle of detectors, the fitting equation to deduce the A_2 and A_4 values is rewritten as

$$\frac{N_{ij}^{mn}}{S_i^m S_j^n}=A_0[1+Q_2^m(i)Q_2^n(j)A_2P_2(\cos\theta_{mn}) + Q_4^m(i)Q_4^n(j)A_4P_4(\cos\theta_{mn})],$$

where θ_{mn} is the angle between the detectors m and n, A_0 is a fitting coefficient together with the A_2 and A_4, and $Q_2^m(i)$ and $Q_4^m(i)$ are the geometrical correction factors. The Q_2 and Q_4 were determined by the collimated source method [15] as a function of γ-ray energy using a 150 mm thick lead collimator with a hole of 2 mm inner diameter and strong γ-ray sources of ^{152}Eu, ^{133}Ba and ^{241}Am. Figure 1 shows results of the γ-γ angular correlations for $0^+-2^+-0^+$ cascades observed in $^{124-130}$Ba and ^{130}Ce. The results of the A_2 and A_4 values were plotted in Fig. 2 together with theoretical values for possible spin sequences. Here, it is assumed that

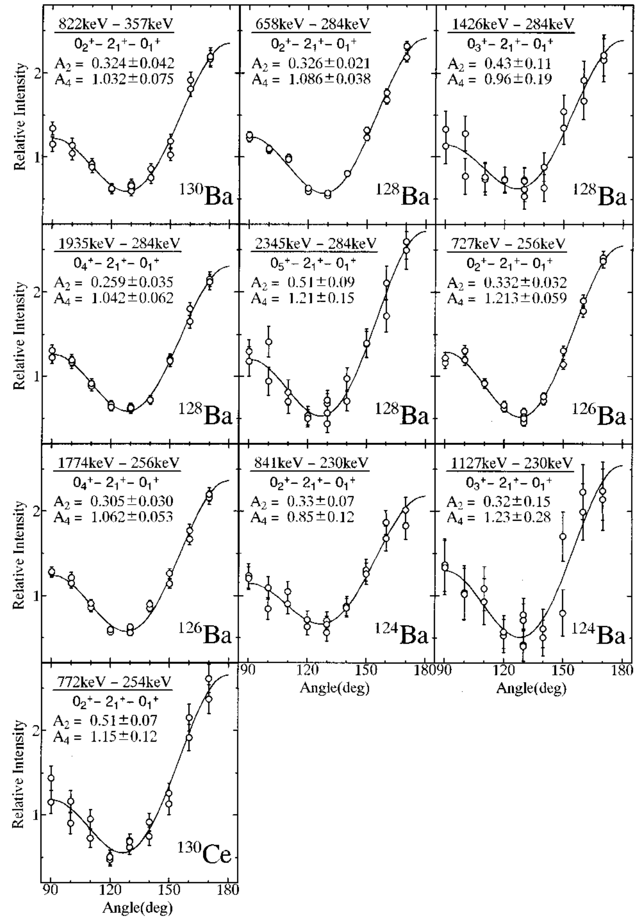

FIG. 1. Results of the γ-γ angular correlations for $0^+-2^+-0^+$ spin sequences observed in $^{124-130}$Ba and ^{130}Ce.

possible γ-ray transitions are limited to only $E1$, $M1$, and $E2$ transitions. All the results are in reasonable agreement with the theoretical angular correlation of the 0-2-0 spin sequence, being far from the other spin sequences.

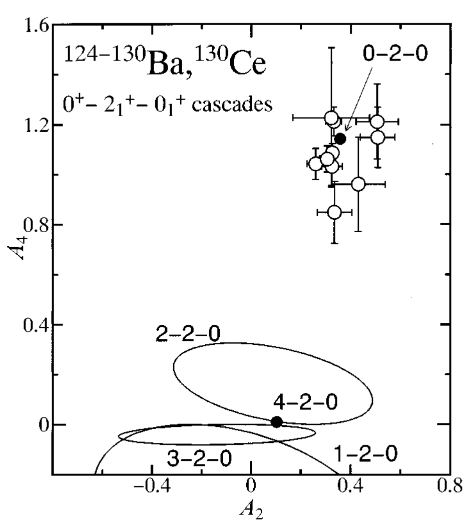

FIG. 2. Parametric plots of the angular correlation coefficients A_2 and A_4 for the results of $0^+-2^+-0^+$ cascades in $^{124-130}$Ba and ^{130}Ce.

B. Excited 0^+ states

The observation of a number of excited 0^+ states in the present experiments was due to the population of β-decaying low-spin isomers of the La nuclei. It has been suggested that there exist two β-decaying isomers with high spin and low spin in ^{124,126,128}La [9,11,16]. It is not known for these nuclides which isomeric state is the ground state. Based on β-branching intensities to Ba levels, the spin of the high-spin isomers was estimated to be 7 or 8 for ^{124}La and 5 or 6 for ^{126,128}La [9,16]. These high-spin isomers decay to high-spin states in Ba nuclei but not to 0^+ states. On the other hand, the spin of the low-spin isomers is probably 1^+, whose EC/β^+ decay populates low-spin states such as 0^+, 1^+, and 2^+. With heavy-ion fusion-evaporation reactions, the population of the high-spin isomers is favored and the low-spin isomers are populated very little. However, in the present experiments, Ce nuclei were produced and mass-separated as a monoxide ion together with the La nuclei with a considerable intensity. Since the spin and parity of the ground state of the even-even Ce nuclei is 0^+, their EC/β^+ decay strongly populated the low-spin isomers of the La nuclei, and following EC/β^+ decay of the low-spin isomers populated excited 0^+ states in the Ba nuclei.

1. ^{130}Ba

For ^{130}Ba, one excited 0^+ state (0_2^+) at 1179.4 keV has been assigned by the present γ-γ angular correlation measurement, which confirmed the previous assignment by Kirch *et al.* [7] from the γ-γ angular correlation measured at 90° and 180°. However, no higher-excited 0^+ state was observed in the present experiment despite an intense production of ^{130}Ce. That is because the ground state spin of ^{130}La is 3^+ and there exists no β-decaying low-spin isomer [17], so that β feedings to the 0^+ states in ^{130}Ba are forbidden. The observation of the 0_2^+ state is due to the population by γ transitions from higher-lying states and not by the direct β feedings.

2. ^{128}Ba

For ^{128}Ba, four excited 0^+ states at 942.6, 1710.1, 2218.9 and 2628.9 keV have been identified, which is due to an intense production of ^{128}Ce and its EC/β^+ decay to the low-spin isomer of ^{128}La. The spin of the 0_2^+ state which was tentatively assigned by Siems *et al.* [10] from the energy systematics was unambiguously assigned in the present measurement. The other three 0^+ states were identified for the first time. Previously, Zolnowski and Sugihara [18] studied the decay of ^{128}La and assigned a number of weak γ transitions. However, they did not report the γ transitions from the 0^+ states strongly observed in the present experiment, except for the 658.5 keV $0_2^+\rightarrow 2_1^+$ γ transition which was observed very weakly and tentatively assigned to the decay of ^{128}La in Ref. [18]. Figure 3 shows a γ-ray singles spectrum observed in the present experiment. In Fig. 3, the 658.5 keV γ line is found with a considerable intensity compared to adjacent 632.7 and 643.7 keV γ lines of the $5^-\rightarrow 6_1^+$ and $6_1^+\rightarrow 4_1^+$ transitions, respectively. The 1934.8 keV γ line of the $0_4^+\rightarrow 2_1^+$ transition is also found more strongly than adjacent 1908.1 and 1919.5 keV γ lines which depopulate high-spin

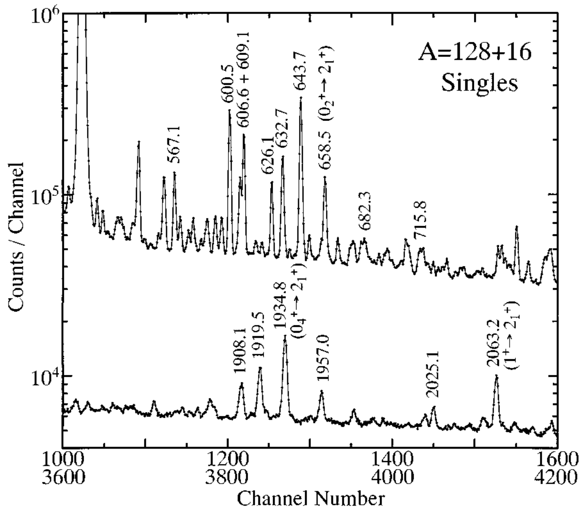

FIG. 3. Parts of a γ-ray singles spectrum obtained at $A=128+16$, in which a number of γ lines originated from the decay of ^{128}La and ^{128}Ce are observed. Strong γ rays from the decay of ^{128}La are indicated with their energies in keV.

states. On the contrary, in the γ-ray spectrum given in Fig. 1 of Ref. [18], these γ lines from the 0^+ states cannot be found. This discrepancy can be explained by the difference in the reaction systems. Zolnowski and Sugihara used the ^{118}Sn(^{14}N,4n) reaction to produce the ^{128}La nuclei, which does never produce the ^{128}Ce nuclei, while the $^{\rm nat}$Mo(^{36}Ar,$xpyn$) reaction was used in the present experiment, which does produce the ^{128}Ce nuclei with a considerable intensity. The fact that the intense γ rays from the 0^+ states were observed in the $^{\rm nat}$Mo(^{36}Ar,$xpyn$) reaction but not in the ^{118}Sn(^{14}N,4n) reaction indicates that the low-spin isomer of ^{128}La was not directly populated by the heavy-ion reactions, but only populated by the decay of ^{128}Ce. The weakly observed 0_2^+ state in Ref. [18] was probably populated by cascade γ transitions from higher-lying high-spin states in ^{128}Ba fed by the decay of the high-spin isomer of ^{128}La.

3. ^{126}Ba

For ^{126}Ba, two excited 0^+ states at 983.3 and 2029.7 keV have been identified. The spin of the 0_2^+ state which was assigned by Genevey *et al.* [9] and Siems *et al.* [10] from the energy systematics was unambiguously assigned in the present experiment. The 0^+ state at 2029.7 keV was identified for the first time. Considering systematics of level energies and β-branching intensities, this level was assigned to the 0_4^+ state but not to the 0_3^+ state. The 2029.7 keV is too high compared to the 1710.1 keV 0_3^+ state in ^{128}Ba and the 1357.1 keV in ^{124}Ba. It is rather reasonable that this level is combined with the 2218.9 keV 0_4^+ state in ^{128}Ba. The β-branching intensities for the 0^+ states in the Ba nuclei obtained in the present experiments are given in Table I. The ratio of the β-branching intensity to the 2029.7 keV level over that to the 0_2^+ state was deduced to be 0.72(7), which is much larger than those for the 0_3^+ states in neighboring ^{124,128}Ba and ^{124,126,128}Xe [19–21] nuclei; the β-branching intensities to their 0_3^+ states are one or two orders of magnitude as small as those to their 0_2^+ states. Missing of the 0_3^+ state in ^{126}Ba can also be explained by the small β-branching to the 0_3^+ state. In the case of ^{128}Ba, the weak $0_3^+ \to 2_1^+$ γ transition could be observed due to the high yield of the low-spin isomer of ^{128}La. On the other hand, the yield of the low-spin isomer of ^{126}La is relatively low, so that it is highly probable that the weak $0_3^+ \to 2_1^+$ γ ray was not found owing to less statistics, or hidden by strong γ rays with the same energy.

TABLE I. Experimental β-branching ratios for excited 0^+ states in $^{124-130}$Ba. Beta-branching intensities to the ground state (0_1^+) were not obtained in the present experiments.

Level	^{124}Ba	^{126}Ba	^{128}Ba	^{130}Ba
0_2^+	100	100	100	100
0_3^+	23(5)		12(2)	
0_4^+		72(7)	74(12)	
0_5^+			20(3)	

4. ^{124}Ba

For ^{124}Ba, two excited 0^+ states at 1071.3 and 1357.1 keV have been identified for the first time. Previously, Idrissi *et al.* [11] assigned the 0_2^+ state at 898 keV by observing an $E0$ transition to the 0_1^+ state. They also reported the 668 keV $0_2^+ \to 2_1^+$ γ transition with a relative intensity of 1.5, which is comparable to the 643 keV $2_2^+ \to 2_1^+$ γ-ray intensity of 3.8. However, the 668 keV γ rays were not observed in the present experiment: the upper limit of an intensity ratio of the 668 keV over the 643 keV γ rays was deduced to be <0.006. In addition, the 2_3^+ and (4^+) states which were assigned by Idrissi *et al.* as belonging to the 0_2^+ band were not observed in the present experiment as well. For the 2_3^+ state, the $2_3^+ \to 2_1^+$ and $2_3^+ \to 0_2^+$ γ rays assigned by Idrissi *et al.* were not observed. The 1216 keV γ ray assigned to the $2_3^+ \to 0_1^+$ transition was observed, but this γ ray should be ascribed to the one following the decay of ^{124}Ba. For the (4^+) state, the 1088 keV γ ray assigned to the $(4^+) \to 4_1^+$ transition by Idrissi *et al.* should be incorporated in the different level spacing between the 2263 and 3351 keV level in ^{124}Ba. In the present experiment, reaction products were mass-separated as a monoxide ion, with which only the ^{124}La and ^{124}Ce nuclei were purely obtained. On the other hand, their experimental technique, two kind of which were performed, allowed large contamination from other nuclei; the one was performed using a mass-separation but not free from isobars, especially the ^{124}Ba and ^{124}Cs nuclei, and the other was performed using no mass-separation but only using a helium-jet transport. Therefore, it is concluded that the 0_2^+, 2_3^+, and (4^+) states in Ref. [11] were misassigned. In addition to the newly-assigned 0_2^+ and 0_3^+ states, the 2_3^+ state which is considered to belong to the 0_2^+ band was assigned at 1353.3 keV, whose spin value was assigned due to the observation of depopulating γ transitions to both 0^+ and 4^+ states.

5. ^{130}Ce and ^{128}Ce

For ^{130}Ce, the spin of the 0_2^+ state at 1025.5 keV has been assigned with the present γ-γ angular correlation measure-

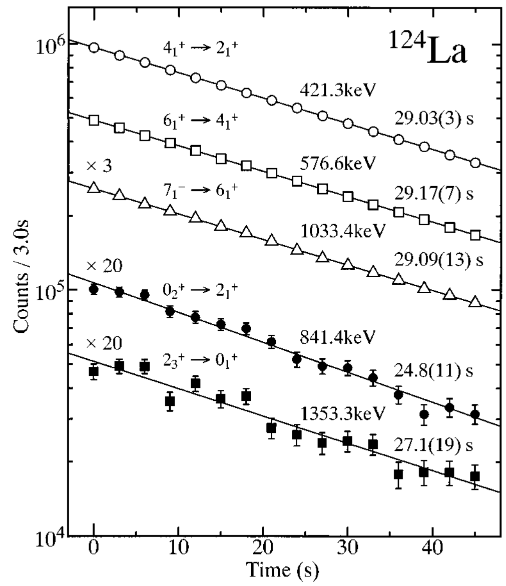

FIG. 4. Decay curves of γ rays associated with the decay of ^{124}La. Fitted lines and half-life values were obtained by the least-squares fitting with a single-component exponential function.

ment, which confirmed the previous assignment by Gizon *et al.* [22] with the conversion electron measurement observing a very weak $E0$ transition. However, the 2_3^+ state at 1305 keV assigned by Gizon *et al.* was excluded in the present experiment. The 1356.4 keV level was assigned to the 2_3^+ state instead, owing to the observation of depopulating γ transitions to the 0_2^+, 4_1^+, 2_1^+, and 0_1^+ states. For ^{128}Ce, although γ-γ angular correlations could not be measured, the 0_2^+ and 2_3^+ states at 1052 and 1305 keV were tentatively assigned, which are consistent with the previous assignments by Gizon *et al.* [22].

C. Existence of β-decaying low-spin isomers

The observation of a number of 0^+ states in the present experiments was due to the existence of the β-decaying low-spin isomers and their β feedings to the 0^+ states. This interpretation was experimentally confirmed by the present half-life analysis. All the deexciting γ rays from the 0^+ states observed in the decay of ^{124,126,128}La showed different half-life values from those of the other γ rays from high-spin states, which is direct evidence for the existence of the low-spin isomers.

Figure 4 shows decay curves of γ rays for the decay of ^{124}La. The half-lives obtained by the least-squares fitting with a single-component exponential function are summarized in Fig. 5. The γ rays depopulate the 0^+ and 2^+ states exhibited the shorter half-lives than those of the high-spin states, which indicates the existence of the low-spin isomer having a shorter half-life than that of the high-spin isomer. The half-lives of γ rays with an initial spin of 2^+ took values between 29 s and 24 s, which depend on various contribution from the decay of the low-spin isomer. The γ rays with an initial spin of larger than 3 exhibited the fixed half-life values, which is considered as the half-life of the high-spin isomer. Taking a weighted average of these values, except for that of the $4_1^+ \rightarrow 2_1^+$ γ rays whose decay curve includes

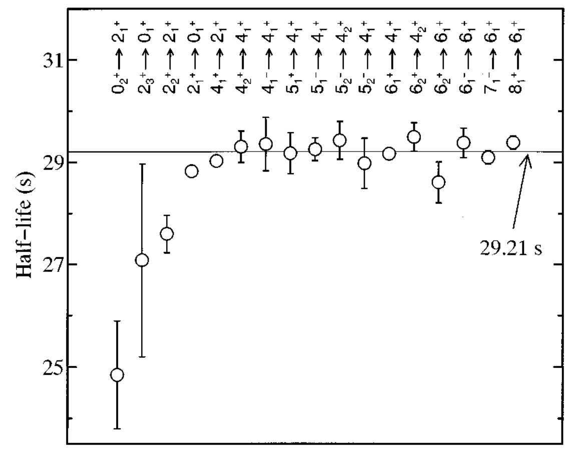

FIG. 5. Half-lives obtained for γ rays associated with the decay of ^{124}La, which depend on their initial spin values owing to the existence of two β-decaying isomers with high spin and low spin in ^{124}La.

small component of the decay of the low-spin isomer, the half-life of the high-spin isomer was determined to be 29.21(17) s. Here, it is assumed that the high-spin isomer is not populated by the decay of ^{124}Ce with the ground state spin of 0^+, which is probably true because the spin of the high-spin isomer is estimated as 7 or 8. The present half-life value for the high-spin isomer is consistent with the previous ones of 29(2) s [23] and 29(1) s [11]. For the half-life of the low-spin isomer, 21(4) s was derived from the decay curve of the $0_2^+ \rightarrow 2_1^+$ γ rays, taking the growth component from the decay of ^{124}Ce with $T_{1/2} = 10.8(15)$ s and cascade γ feedings from the higher-lying high-spin states populated by the decay of the high-spin isomer into account.

For ^{126}La, decay curves of γ rays are shown in Fig. 6. Most of the γ rays decay with $T_{1/2} \approx 64$ s, while two $0^+ \rightarrow 2^+$ γ rays exhibit shorter half-lives of $T_{1/2} \approx 54$ s. Previously, the

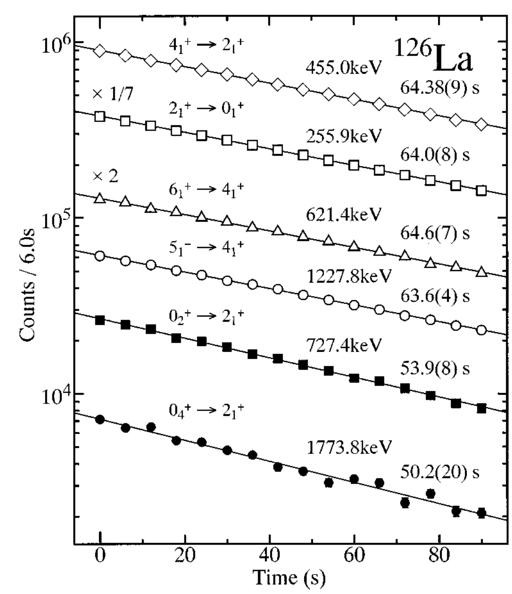

FIG. 6. Decay curves of γ rays associated with the decay of ^{126}La. Fitted lines and half-life values were obtained by the least-squares fitting with a single-component exponential function.

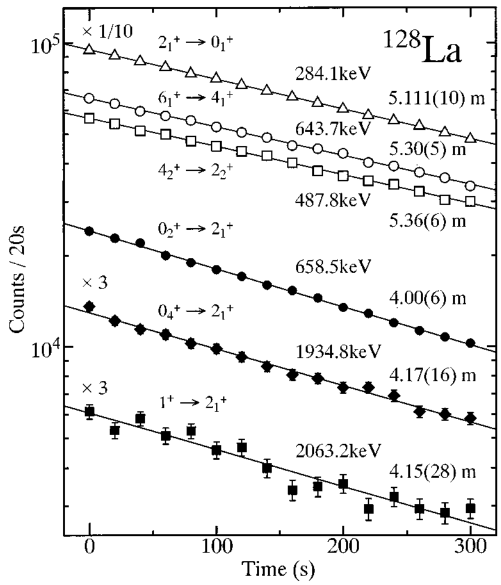

FIG. 7. Decay curves of γ rays associated with the decay of ^{128}La. Fitted lines and half-life values were obtained by the least-squares fitting with a single-component exponential function.

half-life of the high-spin isomer was reported as 54(2) s by Ichikawa *et al.* [23] and 64(3) s by Genevey *et al.* [9]. The inconsistency between the previous values of 54 s and 64 s and the present one of 64 s can be explained by the production of the ^{126}Ce nuclei with $T_{1/2}=50.96(34)$ s and their β feedings to the high-spin isomer via a few medium-spin excited-states in ^{126}La. In the present experiment using the ^{94}Mo(^{36}Ar,$xpyn$) reaction and in the experiment by Genevey *et al.* using the ^{nat}Mo(^{35}Cl,$xpyn$) reaction, the ^{126}Ce nuclei were produced together with the ^{126}La nuclei with a considerable intensity, so that their half-life values were observed to be longer owing to the growth component from the decay of ^{126}Ce. If the contribution to the population of the high-spin isomer through the EC/β^+ decay of ^{126}Ce is 1/5 of that through the direct production and mass-separation of ^{126}La, the decay curves exhibiting the half-life of 64 s are reasonably reproduced by the growth and decay of the high-spin isomer with $T_{1/2}=54$ s. In our additional experiment using the ^{nat}Zr(^{36}Ar,$xpyn$) reaction, in which the ^{126}Ce nuclei were observed with 1/3 intensity of that in the experiment using the ^{94}Mo(^{36}Ar,$xpyn$) reaction, the half-lives for the high- and low-spin states were observed as ≈ 56 s and ≈ 54 s, respectively. The shorter half-life of 56 s than 64 s is reasonably explained in the same manner with the 1/3 intensity of ^{126}Ce. The half-life of the high-spin isomer of ^{126}La should be evaluated as 54(2) s, taking the result of Ichikawa *et al.* in which the ^{nat}Mo(^{32}S,pxn) reaction was used to produce the ^{126}La nuclei, and the ^{126}Ce nuclei were not observed. The half-life of the low-spin isomer could not be determined by the present results, because the half-life of 53.9(8) s for the $0_2^+ \to 2_1^+$ γ rays and 50.2(20) s for the $0_3^+ \to 2_1^+$ γ rays are very close to the 50.96(34) s half-life of ^{126}Ce. It can only be estimated that the half-life of the low-spin isomer is by far shorter than 50 s.

For ^{128}La, decay curves of γ rays are shown in Fig. 7. The difference in half-life values for the decay of ^{128}La was reported by Hayakawa *et al.* [16], in which the half-life of the $2_1^+ \to 0_1^+$ transition was observed to be shorter than those of other transitions from high-spin states. In the present experiment, shorter half-lives were clearly observed for the $0_{2,3,4,5}^+ \to 2_1^+$ transitions and the $1^+ \to 2_1^+$ transition as well as the $2_1^+ \to 0_1^+$ transition. However, the half-life of the low-spin isomer of ^{128}La could not be determined because of the close half-life values between the observed ones and the 3.925(21) m for the decay of ^{128}Ce.

IV. DISCUSSION

Experimental level energies of low-spin states in neutron-deficient Ba nuclei are shown in Fig. 8(a). Since level energies of the 0_2^+ and 2_3^+ states in ^{124}Ba were revised in the

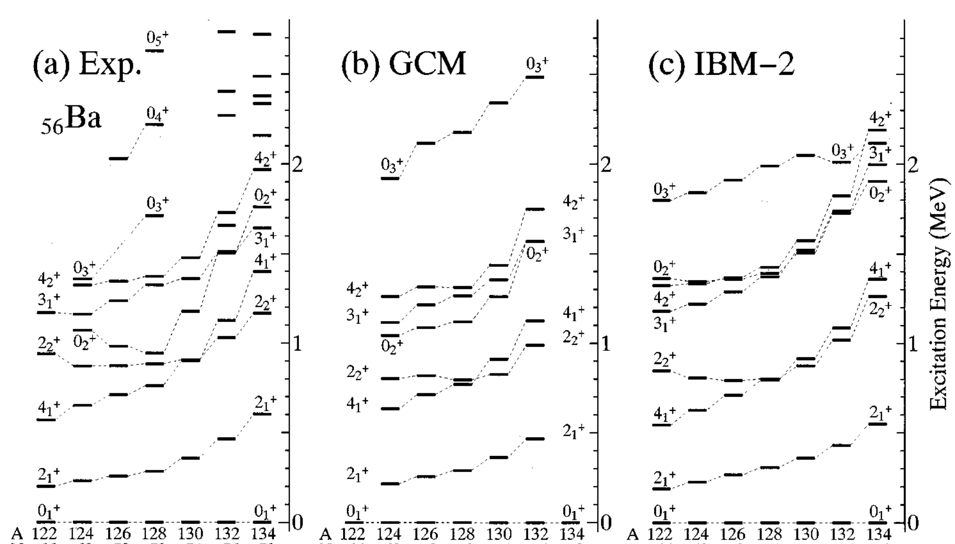

FIG. 8. Energy systematics of low-lying states in neutron-deficient Ba nuclei. (a) The experimental results. Levels whose spin values are not indicated in the figure in ^{132,134}Ba are 0^+ states. (b) The calculations by the GCM [5]. (c) The calculations by the IBM-2.

present experiment, systematic behavior of these states which had previously exhibited an unexpected irregularity around ^{124}Ba turned out to show a smooth change against neutron number. The level energy of the 0_2^+ state in the neutron-deficient Ba nuclei takes a minimum at ^{128}Ba ($N=72$) and then gradually increases toward the neutron midshell ($N=66$). The 2_3^+ state shows a similar behavior, taking a minimum at ^{126}Ba and then rising at ^{124}Ba. In contrast, the level energy of the 0_3^+ state rapidly decreases with decreasing neutron number. Since the level energy of low-lying collective states in this region exhibits a smooth change up to neutron midshell, it is highly expected due to an extrapolation of these experimental data that the energy relation between the 0_2^+ and 0_3^+ state would invert at ^{122}Ba ($N=66$) or at more deformed Ba nuclei. This is a very interesting feature to understand the nature of the 0^+ states in this region as discussed later.

Figures 8(b) and 8(c) show the level energies calculated by the general collective model (GCM) and the proton-neutron interacting boson model (IBM-2). The GCM calculation was performed by Petkov *et al.* [5], to reproduce the experimental level energies and the transition probabilities of the $^{124-132}$Ba nuclei. The IBM-2 calculation was done by the code NPBOS [24] using the parameters taken from Ref. [25], which were derived from the microscopic calculation through the method of the OAI mapping [26]. These theoretical calculations reproduced many properties such as the level energies and the transition probabilities of the ground state band and the quasi-γ band, most of which indicate the typical γ-soft character. However, the level energies of the 0_2^+ and 0_3^+ states as well as their systematic behavior have not been reproduced well like other states. The 0_2^+ states in both the GCM and IBM-2 calculations lie near the 3_1^+ and 4_2^+ states, which is a typical feature of γ-soft nuclei. It is difficult for these calculations to reproduce the lower level energies of the experimental 0_2^+ states around ^{128}Ba which are rather near the two-phonon triplet of spherical vibrational nuclei.

A possible energy depression of 0^+ states due to the admixture of $\pi(g_{9/2})^{-2}$ intruder configuration, which is observed in neighboring even-even Te ($Z=52$) and Xe ($Z=54$) nuclei [27,28], shall be briefly discussed here, although this effect need not be considered for the 0_2^+ states in the Ba nuclei. Around the midshell ($N=66$) Te and Xe nuclei, the particle-hole proton intruder configuration due to the excitation of two $g_{9/2}$ protons across the $Z=50$ shell gap mixes with low-lying collective states, and depresses the level energy of 0^+ states [27]. The excitation energy of the intruder 0^+ state is depressed below the pairing gap energy by the residual proton-neutron interaction, so that the intruder 0^+ state decreases in energy toward neutron midshell and shows a minimum at midshell, corresponding to the number of valence neutrons [29]. This characteristic differs very much from the experimental level energies of the 0_2^+ state in the Ba nuclei, which show a minimum at $N=72$, not at $N=66$, and then increase toward the neutron midshell. The comparison between the excitation energy of the 0^+ states in the even-even Te-Xe-Ba nuclei and the $\pi(g_{9/2})^{-1}$ intruder states in adjacent odd-even Sb-I-Cs nuclei [27] also

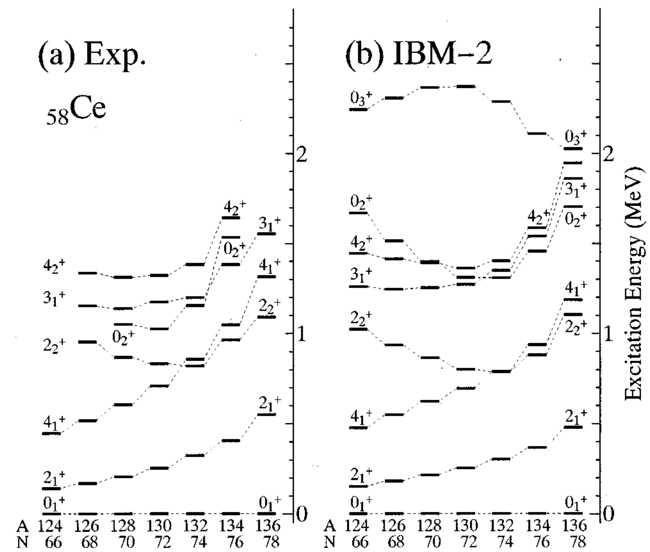

FIG. 9. Energy systematics of low-lying states in neutron-deficient Ce nuclei. (a) The experimental results. (b) The calculations by the IBM-2.

supports no influence of the intruder mixing on the 0_2^+ states in the Ba nuclei.

Experimental level energies of low-spin states in another neighboring even-even Ce ($Z=58$) nuclei are given in Fig. 9, together with those of the IBM-2 calculation. The 0_2^+ states and their 2^+ band members (2_3^+) in $^{128-134}$Ce were recently established by Gizon *et al.* [22] and Wiedenhöver *et al.* [30] through the EC/β^+ decay of their Pr parents. The level energy of the 0_2^+ state takes a minimum at ^{130}Ce and then rises at ^{128}Ce like the Ba nuclei. In the IBM-2 calculation, the parameters were also taken from Ref. [25], but the parameter $\chi_\pi=-0.60$ was used instead of -0.42 to improve calculated level energies of the quasi-γ band. From the recent microscopic IBM-2 calculation [31] and the phenomenological fitting by Puddu *et al.* [2], it was indicated that the χ_π value decreases with increasing proton-boson number in this region. Thus the smaller value of -0.60 than -0.52 used for the Ba nuclei is considered to be rather reasonable. The Ce nuclei lie in the same transitional region as the Ba nuclei exhibiting the shape evolution from a γ-soft nucleus to an axially-symmetric deformed nucleus, but are more deformed than the Ba nuclei. Thus the structure of low-lying collective states exhibits more drastic evolution than that of the Ba nuclei. The level energies of the quasi-γ band and the 0_2^+ state in both the experiment and the calculation clearly show a gradual increase toward the neutron midshell, which is interpreted as the manifestation of the shape evolution from a γ-soft nucleus to an axially-symmetric deformed nucleus [2]. Though not very clear, the same trend is noted in the IBM-2 calculation for the Ba nuclei around ^{122}Ba as shown in Fig. 8(c). The specific feature of the 0_2^+ state in the Ba nuclei, taking a minimum at $N=72$ and then increasing in energy toward the neutron midshell, can be also interpreted as the manifestation of this shape evolution. However, it should be noted that the above feature of the 0_2^+ level energy in the Ba nuclei is too drastic compared to those of other levels. It is probably influenced around ^{128}Ba by some low-

TABLE II. Experimental and calculated $B(E2)$ ratios for $0^+_{2,3}$ states to $2^+_{1,2}$ states in $^{124-130}$Ba.

J^π_i	J^π_f	^{124}Ba	^{126}Ba	^{128}Ba	^{130}Ba
Experiments					
0^+_2	2^+_1	1.3	1.0	0.18	3.2(5)
	2^+_2	<100	<100	<100	100
0^+_3	2^+_1	100		100	
	2^+_2	<3000		<70	
IBM-2					
0^+_2	2^+_1	2.9	1.5	0.4	0
	2^+_2	100	100	100	100
0^+_3	2^+_1	100	100	100	100
	2^+_2	140	21	0	6

ering force against the 0^+_2 level energy. Petkov *et al.* [5] suggested that the lower level energy of the 0^+_2 state in the Ba nuclei were associated with the structure of potential in γ direction. The energy staggering index [32] deduced from the level energies of the quasi-γ band indicates the highest degree of γ-instability at ^{128}Ba in this region, which may be associated with the lower 0^+_2 level energy around ^{128}Ba.

Considering the nature of the 0^+ states in γ-soft nuclei, the inversion of the energy relation between the 0^+_2 and 0^+_3 state observed in the Ba nuclei is also interpreted as the manifestation of the shape evolution from a γ-soft nucleus to an axially-symmetric deformed nucleus. It has been suggested [5] that the nature of the low-lying 0^+ states in the γ-soft nuclei around $A\approx 130$ is more complicated than the one implied by the simple geometrical interpretation in terms of β or (two-phonon) γ vibrations. For the 0^+_2 states in the γ-soft nuclei, the interpretation as the β-vibrational state is excluded because of the large branching ratio $B(E2;0^+_2\rightarrow 2^+_2)/B(E2;0^+_2\rightarrow 2^+_1)$. The $B(E2)$ ratios for the 0^+_2 and 0^+_3 states obtained in the present experiments were summarized in Table II together with the IBM-2 calculations. The experimental $B(E2;0^+_2\rightarrow 2^+_2)/B(E2;0^+_2\rightarrow 2^+_1)$ ratios have been reported for the ^{124,126,128,130}Xe and ^{130,132,134}Ba nuclei, all of which indicate the strong transition to the 2^+_2 quasi-γ bandhead. For the ^{124,126,128}Ba nuclei, although this ratio was not obtained because the energy of the $0^+_2\rightarrow 2^+_2$ transition is too low compared to that of the $0^+_2\rightarrow 2^+_1$ transition to observe this γ ray owing to the E^{-5}_γ multiplication factor, deduced upper limits were consistent with the strong transition to the 2^+_2 state. The GCM and IBM-2 calculations also give the large $B(E2;0^+_2\rightarrow 2^+_2)/B(E2;0^+_2\rightarrow 2^+_1)$ ratios for these nuclei. In the GCM calculation [5], the nature of the 0^+_2 state was described as the one strongly associated with the γ degree of freedom. These characteristics are rather close to those of the two-phonon γ-vibrational state ($0^+_{\gamma\gamma}$) in well-deformed nuclei, although the interpretation as the $0^+_{\gamma\gamma}$ state itself is unlikely because of their lower level energy compared to the expected one from the 2^+_2 level energy and through the description of the multiple Q-phonon scheme in the IBM framework [6]. On the other hand, the 0^+_3 state in both the GCM and IBM-2 calculations preferentially decay to the 2^+_1 state in the ground state band, that is, the nature of the 0^+_3 state resembles those of the β-vibrational state (0^+_β) in well-deformed nuclei. In the present experiments, only the $0^+_3\rightarrow 2^+_1$ γ ray could be observed as the depopulating transition from the 0^+_3 state. The upper limit of the $B(E2;0^+_3\rightarrow 2^+_2)/B(E2;0^+_3\rightarrow 2^+_1)$ ratio for ^{128}Ba was deduced to be <0.70, which also indicate the preferential decay to the 2^+_1 state. In the simple geometrical interpretation, the level energy of the β-vibrational 0^+ state is lower than that of the two-phonon γ-vibrational 0^+ state. Considering the nature of these 0^+ states, the inversion of the energy relation between the 0^+_2 and 0^+_3 state observed in the Ba nuclei is interpreted as the evolution of the 0^+_2 state in γ-soft nuclei toward the $0^+_{\gamma\gamma}$ state in axially-symmetric deformed nuclei, while the 0^+_3 state toward the 0^+_β state. This correspondence was previously suggested by Casten and Warner [33]. The present results support this suggestion.

V. CONCLUSIONS

Excited 0^+ states in $^{124-130}$Ba and ^{130}Ce fed by the EC/β^+ decay of mass-separated La and Pr nuclei were assigned with the γ-γ angular correlation measurement using an efficient five-HPGe detector system. The observation of a number of excited 0^+ states was due to the existence of β-decaying low-spin isomers in ^{124,126,128}La which predominantly decay to low-spin states in the Ba nuclei with a spin of 0^+, 1^+, and 2^+, and their population via the EC/β^+ decay of their Ce parents. All the deexciting γ rays from the 0^+ states observed in the decay of ^{124,126,128}La showed different half-life values from those of the other γ rays from high-spin states, which is direct evidence for the existence of the low-spin isomers.

The present results for the 0^+ states revealed that the level energy of the 0^+_2 state in neutron-deficient Ba nuclei takes a minimum at $N=72$ and then gradually increases toward neutron midshell ($N=66$), while the level energy of the 0^+_3 state rapidly decreases with decreasing neutron number. From an extrapolation of these 0^+ energies, it is highly expected that the energy relation between the 0^+_2 and 0^+_3 state would invert at ^{122}Ba or at more deformed Ba nuclei. Considering the nature of the 0^+_2 and 0^+_3 states in γ-soft nuclei, this energy inversion is interpreted as the evolution of the 0^+_2 state in γ-soft nuclei toward the $0^+_{\gamma\gamma}$ state in axially-symmetric deformed nuclei, while the 0^+_3 state toward the 0^+_β state. The energy systematics of the 0^+_2 and 0^+_3 states in the Ba nuclei exhibit more dynamic behavior than those of theoretical predictions. More precise theoretical investigations as well as the experimental ones, especially to derive absolute transition probabilities, are highly expected to reveal the nature of the low-lying 0^+ states in this transitional region.

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[1] R. F. Casten and P. von Brentano, Phys. Lett. **152B**, 22 (1985).
[2] G. Puddu, O. Scholten, and T. Otsuka, Nucl. Phys. **A348**, 109 (1980).
[3] R. F. Casten, Phys. Rev. Lett. **54**, 1991 (1985).
[4] J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. van Duppen, Phys. Rep. **215**, 101 (1992).
[5] P. Petkov, A. Dewald, and W. Andrejtscheff, Phys. Rev. C **51**, 2511 (1995).
[6] R. Kühn, K. Kirch, I. Wiedenhöver, O. Vogel, M. Wilhelm, U. Neuneyer, M. Luig, A. Gelberg, and P. von Brentano, Nucl. Phys. **A597**, 85 (1996).
[7] K. Kirch, G. Siems, M. Eschenauer, A. Gelberg, R. Kühn, A. Mertens, U. Neuneyer, O. Vogel, I. Wiedenhöver, P. von Brentano, and T. Otsuka, Nucl. Phys. **A587**, 211 (1995).
[8] Gh. Cata-Danil, D. Bucurescu, L. Trache, A. M. Oros, M. Jaskola, A. Gollwitzer, D. Hofer, S. Deylitz, B. D. Valnion, and G. Graw, Phys. Rev. C **54**, 2059 (1996).
[9] J. Genevey, A. Gizon, N. Idrissi, B. Weiss, R. Béraud, A. Charvet, R. Duffait, A. Emsallem, M. Meyer, T. Ollivier, and N. Redon, in *Proceedings of the 5th International Conference on Nuclei Far From Stability, Rosseau Lake, 1987*, edited by Ian S. Towner, AIP Conf. Proc. No. 164 (AIP, New York, 1988), p. 419.
[10] G. Siems, T. Fricke, U. Neuneyer, K. Schiffer, D. Lieberz, M. Eschenauer, I. Wiedenhöver, and P. von Brentano, *Proceedings of the 6th International Conference on Nuclei Far From Stability and 9th International Conference on Atomic Masses and Fundamental Constants, Bernkastel-Kues, 1992* (IOP Publishing, Bristol, 1993), p. 675.
[11] N. Idrissi, A. Gizon, J. Genevey, P. Paris, V. Barci, R. Barnéoud, J. Blachot, D. Bucurescu, R. Duffait, J. Gizon, C. F. Liang, and B. Weiss, Z. Phys. A **341**, 427 (1992).
[12] M. Asai, K. Kawade, H. Yamamoto, A. Osa, M. Koizumi, and T. Sekine, Nucl. Instrum. Methods Phys. Res. (to be published).
[13] T. Sekine, A. Osa, M. Koizumi, S. Ichikawa, M. Asai, H. Yamamoto, and K. Kawade, Z. Phys. A **349**, 143 (1994).
[14] S. Ichikawa, T. Sekine, H. Iimura, M. Oshima, and N. Takahashi, Nucl. Instrum. Methods Phys. Res. A **274**, 259 (1989).
[15] C. W. Reich and J. H. Douglas, Nucl. Instrum. Methods **35**, 67 (1965).
[16] T. Hayakawa, T. Komatsubara, J. Lu, J. Mukai, and K. Furuno, Z. Phys. A **358**, 15 (1997).
[17] S.-W. Xu, T.-M. Zhang, Y.-X. Xie, R.-C. Ma, Y.-X. Ge, Y.-X. Guo, C.-F. Wang, Z.-K. Li, B. Guo, J.-P. Xing, T.-R. Guo, S.-F. Zhu, W. Xu, and J.-Z. Du, Z. Phys. A **356**, 35 (1996).
[18] D. R. Zolnowski and T. T. Sugihara, Phys. Rev. C **16**, 408 (1977).
[19] B. Weiss, C. F. Liang, P. Paris, A. Peghaire, and A. Gizon, Z. Phys. A **313**, 173 (1983).
[20] P. F. Mantica, Jr., B. E. Zimmerman, W. B. Walters, J. Rikovska, and N. J. Stone, Phys. Rev. C **45**, 1586 (1992).
[21] E. W. Schneider, M. D. Glascock, W. B. Walters, and R. A. Meyer, Phys. Rev. C **19**, 1025 (1979).
[22] A. Gizon, J. Inchaouh, D. Barnéoud, J. Genevey, C. F. Liang, P. Paris, A. Plochocki, and I. Penev, *Proceedings of the International Conference on Nuclear Shapes and Nuclear Structure at Low Excitation Energies, Antibes, 1994* (Editions Frontières, Gif-sur-Yvette, 1994), p. 315.
[23] S. Ichikawa, T. Sekine, M. Oshima, H. Iimura, and Y. Nakahara, Nucl. Instrum. Methods Phys. Res. B **70**, 93 (1992).
[24] T. Otsuka and N. Yoshida, JAERI-M 85-094 (Japan Atomic Energy Research Institute, 1985).
[25] T. Otsuka, X.-W. Pan, and A. Arima, Phys. Lett. B **247**, 191 (1990).
[26] T. Otsuka, A. Arima, and F. Iachello, Nucl. Phys. **A309**, 1 (1978).
[27] J. Rikovska, N. J. Stone, P. M. Walker, and W. B. Walters, Nucl. Phys. **A505**, 145 (1989).
[28] P. F. Mantica and W. B. Walters, Phys. Rev. C **53**, R2586 (1996).
[29] K. Heyde, J. Jolie, J. Moreau, J. Ryckebusch, M. Waroquier, P. van Duppen, M. Huyse, and J. L. Wood, Nucl. Phys. **A466**, 189 (1987).
[30] I. Wiedenhöver, T. Diefenbach, M. Luig, M. Wilhelm, H. Meise, A. Gelberg, P. von Brentano, K. H. Kim, T. Mizusaki, and T. Otsuka, ANL/PHY-96/1 (Argonne National Laboratory, 1996), p. 134.
[31] T. Otsuka and T. Mizusaki, in Frontiers of Nuclear Structure Physics, edited by M. Ishihara, T. Otsuka, T. Mizusaki, and K. Yazaki (World Scientific, Singapore, 1996), p. 69.
[32] W. Lieberz, A. Dewald, W. Frank, A. Gerberg, W. Krips, D. Lieberz, R. Wirowski, and P. von Brentano, Phys. Lett. B **240**, 38 (1990).
[33] R. F. Casten and D. D. Warner, Rev. Mod. Phys. **60**, 389 (1988).