Investigation of the $K^\pi=8^-$ isomer in ^{132}Ce

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The decay of the $K^\pi=8^-$ isomer in ^{132}Ce with an excitation energy of 2340.2 keV has been investigated using the ^{120}Sn(^{16}O,4n)^{132}Ce reaction. A half-life of 9.4±0.3 ms was determined. Two new decay paths have been found in the deexcitation of this isomer. The hindrance factors for the $E1$, $M2$, and $E3$ transitions deexciting the isomer have been determined. The decay properties of the 8^- isomers in the $N=74$ isotones are discussed. A band mixing mechanism involving the ground state and s band seems to be responsible for the behavior of the reduced hindrance factors of the $E1$ transitions deexciting the $K^\pi=8^-$ isomers in these isotones. A K mixing, characteristic of the axially asymmetric nuclei, may account for the reduced hindrance factors of the $E3$ transitions to the 5^+_γ states in ^{130}Ba and ^{132}Ce.

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I. INTRODUCTION

Isomeric states with $I^\pi=8^-$ and $K=8$ have been known in all even–even $N=74$ isotones with atomic number $Z=54$–64 (see Refs. [1–4] and references therein). The respective isomeric half-lives vary by six orders of magnitude, from nanoseconds (Xe) to milliseconds (Ce, Ba). Their modes of decay are also different, but decay branches of $E1$ transitions with a degree of K forbiddenness ν of 7, leading directly to the 8^+ member of the ground state band (g.s.b.) with $K=0$, have been found in ^{130}Ba, ^{134}Nd, ^{136}Sm, and ^{138}Gd. These branches severely violate the K selection rule. The respective $E1$ transition rates differ by four orders of magnitude. The reduced hindrance factor, i.e., hindrance factor per degree of K forbiddenness, f_ν, is about 6 (see Sec. III B) for ^{134}Nd, ^{136}Sm, and ^{138}Gd and increases significantly to a value of 12 for the ^{130}Ba isotope.

The decay modes of K isomers with large changes of the K quantum number are subject to extensive investigations and are not yet adequately understood. Three possible decay mechanisms were suggested for such decays. The first one involves Coriolis mixing of states with different K values [4–6]. The second suggestion takes into account that the orientation of the angular momentum represents a new degree of freedom. For high-K states the angular momentum is aligned along the symmetry axis of the deformed nucleus (deformation alignment) while for the yrast band it is aligned along the rotation axis (rotation alignment). Decay modes involving large K differences represent large changes of the orientation. A hopping concept has been introduced to explain the reorientation of the angular momentum. The intermediate bands are described in the framework of the tilted axis cranking model [7–10].

The third explanation is based on the assumption of a tunneling motion in the γ-deformation degree of freedom [11–14]. The deexcitation of high-K isomers to $K=0$ bands is described as a γ tunneling through a barrier separating the deformation-aligned isomeric states at $\gamma=-120°$ from the rotation-aligned $K\approx0$ states at $\gamma=0°$ (Lund convention). The tunneling occurs through a barrier in the β-γ plane involving the triaxial shape degree of freedom, although the nucleus is axially symmetric (prolate) in the initial and final states. Therefore, this mechanism is important for γ-soft nuclei [15,16].

The investigation of the nucleus ^{132}Ce, which lies just in the region of a significant change of the hindrance factor for the $E1$ transition, has been undertaken with the aim to look for such an $E1$ decay branch and, consequently, to achieve a better understanding of the deexcitation mechanism of the $K^\pi=8^-$ isomers in the $N=74$ isotones. Preliminary results of this study were already presented in Ref. [17]. The second experiment under the same conditions has been carried out to confirm the existence of the weak 788 keV line. Prior to our study only one isomer decay branch from the 8^- isomeric state at 2340.8 keV via the 797.3 keV, $M2(+E3)$ transition to the 6^+ yrast state, has been established and the half-life of the isomer was reported to be 13±2 ms [1]. Recently, new data on excited levels in ^{132}Ce fed in the radioactive decay of ^{132}Pr were published [18] and the 2341.8 keV level has been also observed in this study.

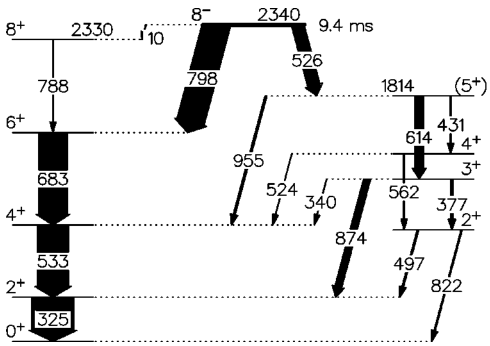

FIG. 1. Decay scheme of the $K^{\pi}=8^-$ isomer in the nucleus ^{132}Ce as established in the present study. The transition energies are given in keV. The widths of the arrows are proportional to the relative intensities of the observed γ transitions.

II. EXPERIMENTAL PROCEDURE

Levels in the ^{132}Ce nuclei have been populated in the ^{120}Sn(^{16}O,4n) reaction at a beam energy of 80 MeV. The ^{16}O beam was provided by the U200P cyclotron at the Heavy Ion Laboratory of the Warsaw University. The beam had a macro- and microtime structure. The macropulses had a length of 1.5 ms with a time separation of 8.5 and 28.5 ms for the coincidence measurements and lifetime measurements, respectively. The microstructure consisted of typical for cyclotron short beam bursts separated by 60 ns. The target was a self-supporting metallic foil (6 mg/cm^2 thick) consisting of isotopically enriched ^{120}Sn. The delayed γ radiation was studied with the OSIRIS multidetector array which consisted of six Compton-suppressed HPGe detectors. The off-beam measurements started 0.2 ms after the end of the macropulse. The γ-γ coincidence events were collected on disc and sorted off-line into a two-dimensional coincidence matrix.

III. RESULTS

A. Level scheme

The decay scheme of the 8^- isomer determined in this experiment is presented in Fig. 1 and the observed γ-transition energies and intensities are given in Table I. An isomer excitation energy of 2340.2$\pm$0.5 keV has been obtained in this study in agreement with the previous value $E=2340.8$ keV [1], confirmed in the later study [19] by the observation of a 1451 keV transition linking the rotational band built on the 8^- isomer with another band decaying to the ground state rotational band. A half-life of 9.4$\pm$0.3 ms which was determined for the 8^- isomer (see Fig. 2) is smaller than the previously published value. Examples of coincidence spectra obtained in this study are shown in Fig. 3.

In addition to the already known isomer decay to the 6^+ level via the 798.0 keV transition, two new isomeric decay paths were established. A weak 788.0$\pm$0.2 keV transition is observed in coincidence with three lowest-lying transitions of the g.s.b. (see Fig. 3). Hence, it was identified with the $8^+\rightarrow 6^+$ g.s.b. transition already known from previous studies [1]. The presence of this transition in the off-beam γ-γ coincidence spectra proves the existence of an unobserved 10.0$\pm$0.5 keV, $E1$ transition connecting the 8^- isomer with the 8^+ g.s.b. level at 2330 keV, and establishes a new decay path of the isomer. A second previously unknown decay proceeds via a 526 keV transition to a new level at 1814 keV, as deduced from coincidence relations. This newly established level deexcites via the 614, 431, and 955 keV transitions to the 3^+_γ and 4^+_γ levels of the γ band [18] and to the 4^+ g.s.b. level, respectively.

No decay from the 1814 keV level to the two low-lying 2^+ levels is observed and, therefore, the only reasonable spin-parity assignment for this level is $I^{\pi}=5^+$ considering the population from the 8^- isomer, the depopulation by three transitions to 3^+ and 4^+ states and the branching ratio indicating that the three deexciting transitions may have only $E1$, $M1$, or $E2$ character. Under this assumption the feeding 526 keV transition from the 8^- isomer would then have an $E3$ character. The strongest 614.5 keV transition deexciting the 1814 keV level proceeds to the 3^+_γ level, and suggests that the parent level is the 5^+ member of the quasirotational γ band. The moment of inertia ($J^{(1)}$) calculated from energy

TABLE I. Energies, intensities, and spin assignments for transitions observed in the decay of the $K^{\pi}=8^-$ isomer in ^{132}Ce.

E_γ(keV)	I_γ [a]	I_{tot} [b]	α_{tot} [b]	Assignment[c]
10.0(0.5)		2.0[d]	24(3)	$8^-\rightarrow 8^+$
325.5	100	104	0.038	$2^+\rightarrow 0^+$
340.0		2.0[e]		$3^+\rightarrow 4^+$
377.2	5.0	5.1	0.024	$3^+\rightarrow 2^+$
431.0	2.0	2.0	$\leqslant$0.02	$(5^+)\rightarrow 4^+$
496.9	5.0	5.1	0.011	$2^+\rightarrow 2^+$
524.5	1.0	1.0	0.010	$4^+\rightarrow 4^+$
526.3	30	31	0.026	$8^-\rightarrow (5^+)$
533.0	76	77	0.01	$4^+\rightarrow 2^+$
561.8	1.0	1.0	0.008	$4^+\rightarrow 2^+$
614.5	22	22	0.006	$(5^+)\rightarrow 3^+$
683.5	70	70	0.005	$6^+\rightarrow 4^+$
788.0	2.0	2.0	0.003	$8^+\rightarrow 6^+$
798.0	68	69	$\leqslant$0.014	$8^-\rightarrow 6^+$
822.4	5.0	5.0	0.003	$2^+\rightarrow 0^+$
874.1	17	17	0.003	$3^+\rightarrow 2^+$
955.0	5.0	5.0	$\leqslant$0.003	$(5^+)\rightarrow 4^+$

[a]Relative intensities were determined from γ-γ coincidences. Their uncertainties range from 10% for strong peaks to 30% for weak ones.
[b]$I_{tot}=I_\gamma(1+\alpha_{tot})$, α_{tot} taken from [21], in a few cases of transitions with mixed multipolarity the upper limit is given.
[c]Uncertain spin-parity assignments are given in parentheses.
[d]Transition not observed directly but implied by off-beam coincidence data. The given total intensity is inferred from the total intensity of the 788.0 keV line.
[e]γ ray not observed directly. Its intensity was calculated from the intensity balance.

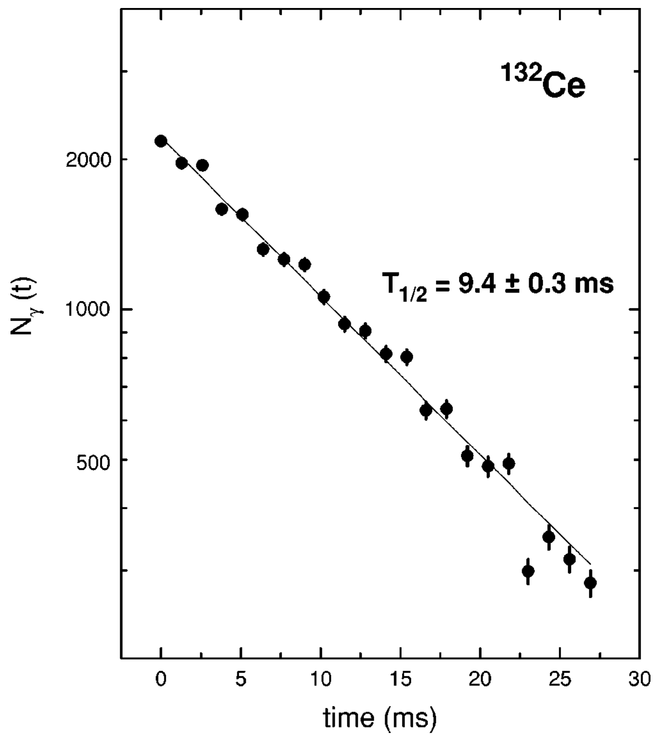

FIG. 2. Decay curve of the 325 keV, $2^{+}\rightarrow 0^{+}$ transition.

of this presumably $5_{\gamma}^{+}\rightarrow 3_{\gamma}^{+}$ transition, is equal to $14.7\hbar^{2}\,\mathrm{MeV}^{-1}$. This moment of inertia is in very good agreement with values of 13.8–15.9$\hbar^{2}\,\mathrm{MeV}^{-1}$ deduced from energies of the known $5_{\gamma}^{+}\rightarrow 3_{\gamma}^{+}$ transitions in the neighboring ^{126,128}Xe, ^{128,130}Ba isotopes, and the ^{134}Nd isotone, where these 3^{+} and 5^{+} levels are interpreted as members of the quasirotational γ band.

In contrast, the (5^{+}), 1656 keV level considered up to now as a candidate for the 5_{γ}^{+} state [2,18], gives a moment of inertia ($J^{(1)}$) equals $19.7\hbar^{2}$ MeV^{-1}. Hence, the agreement with the values obtained for the $5_{\gamma}^{+}\rightarrow 3_{\gamma}^{+}$ transitions in the neighboring nuclei is much less favorable.

Our decay scheme of the 8^{-} isomer agrees well with the results of a recent study of ^{132}Ce levels fed in the β decay of ^{132}Pr [18]. The γ-γ correlations measured in that study established spin-parity assignments for the three lowest members of the quasirotational γ band but they are insufficient, however, to give spin assignments to the 1814 and 2340 keV levels. The observation of the $K^{\pi}=8^{-}$ isomer state in the radioactive decay study proves the existence of a β-decay branch from the $I=(7^{-})$ isomeric state in ^{132}Pr.

B. Hindrance factors

Useful information on the decay properties of the 8^{-} isomer can be obtained from hindrance factors deduced for the deexciting transitions. The hindrance factor F of γ transitions is defined as

$$F=T_{1/2}^{p}/T_{1/2}^{W},$$

where $T_{1/2}^{p}$ is the partial half-life of the γ transition and $T_{1/2}^{W}$ is the corresponding Weisskopf single particle estimate. A convenient way to compare the retardation of K-forbidden transitions in a quantitative manner is through reduced hindrance factors (hindrance factor per degree of K forbiddenness), f_{ν}, defined as $f_{\nu}=F^{1/\nu}$, where ν is the degree of K forbiddenness defined as $\nu=\Delta K-\lambda$, where λ is the multipolarity of the radiation. In the case of $E1$ transitions, the Weisskopf estimate is usually multiplied by a factor of 10^4 to take into account the generally stronger $E1$ hindrance with respect to the Weisskopf estimate and thus to facilitate a comparison with transitions of other multipolarities [20].

The resulting values of the reduced hindrance factors are $f_7=9.0(0.5)$ and $f_3=6.7(0.1)$ for the unobserved $E1$ transition of 10.0 keV and the $E3$ transition of 526.3 keV, respectively. The total intensity of the 10.0 keV transition was set equal to that of the 788.0 keV transition. A value of $\alpha_{\mathrm{tot}}=24(3)$ was used for the total internal conversion coefficient

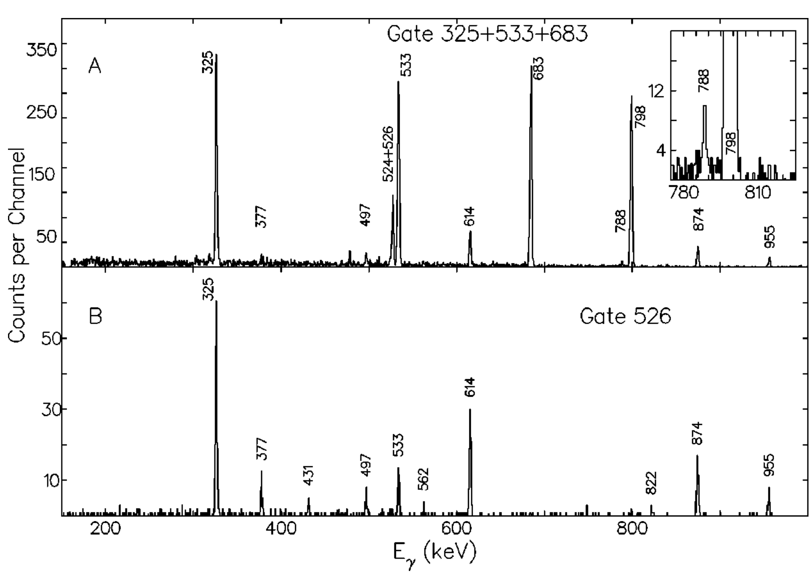

FIG. 3. A: sum of the background-corrected off-beam coincidence spectra with gates on the 325, 533, and 683 keV γ transitions. B: a background-corrected coincidence spectrum gated on the 526 keV γ transition.

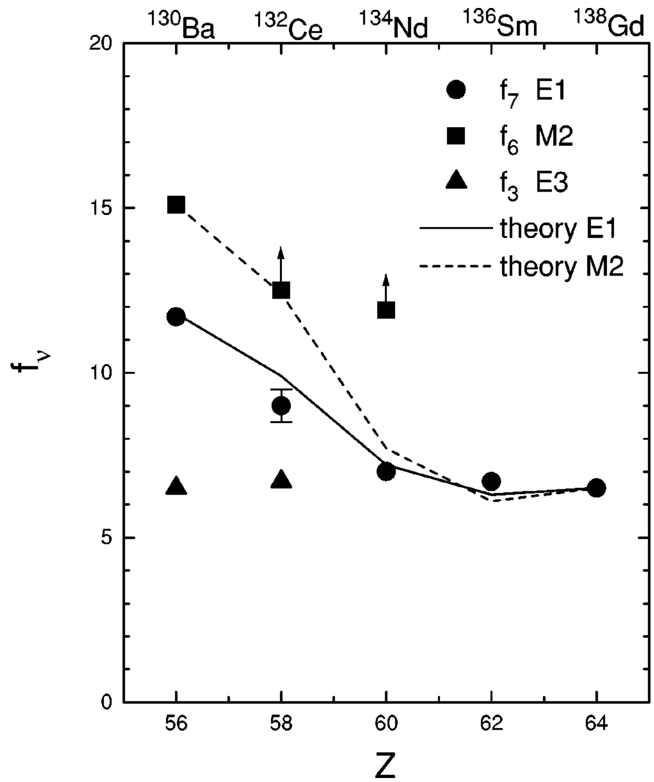

FIG. 4. Systematics of the reduced hindrance factors for the even-even $N=74$ isotones. Calculated values (solid and dashed lines) for f_6 and f_7 (see text) are also shown. In the case of $E1$ transitions the Weisskopf estimates used to calculate f_7 are multiplied by a factor of 10^4 to take into account their generally higher hindrance.

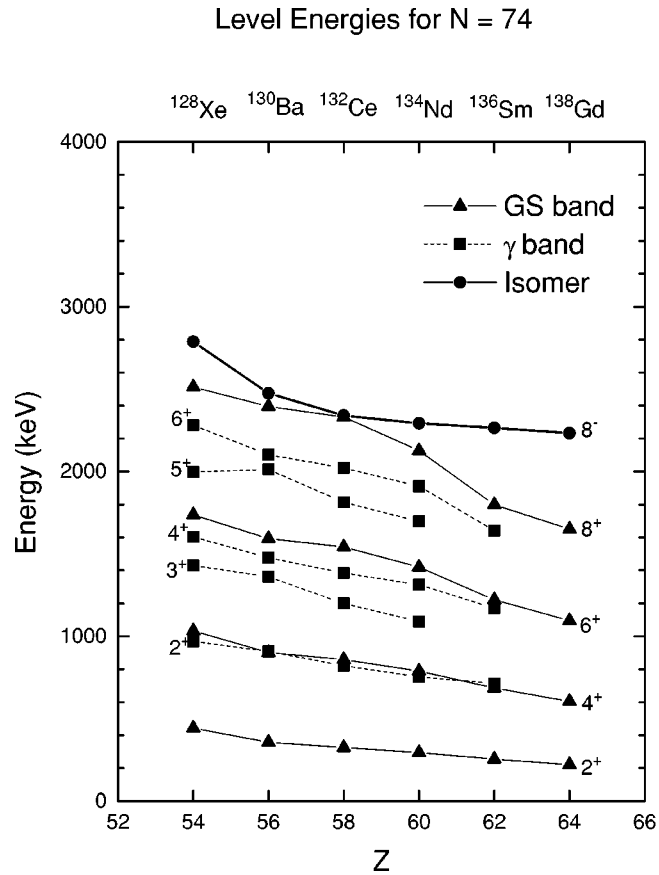

FIG. 5. Systematics of the excited levels with $I\leqslant 8$ relevant for the discussion of the even-even $N=74$ isotones.

of the 10 keV $E1$ transition [21]. For the 798.0 keV transition, lower limits of $f_6\geqslant 12.5$ and $f_5\geqslant 4.8$ can be obtained assuming pure $M2$ and pure $E3$ multipolarities, respectively.

A systematics of reduced hindrance factors for the γ-ray transitions deexciting the $K^\pi=8^-$ isomeric states in the even-even $N=74$ isotones is presented in Fig. 4. Three types of the K-forbidden transitions are included: (i) $E1$ transitions between $(I^\pi,K=8^-,8)\rightarrow(I^\pi,K=8^+,0)$ states; $\nu=7$; (ii) $M2$ transitions between $(I^\pi,K=8^-,8)\rightarrow(I^\pi,K=6^+,0)$ states; $\nu=6$. For ^{132}Ce and ^{134}Nd the $E3/M2$ mixing ratio is not known, therefore the experimental points indicate only lower limits of f_6, calculated under the assumption that the mixing parameter is $\delta(E3/M2)=0$. Any $E3$ admixture can only increase the reduced hindrance factor f_6. For ^{130}Ba, the $E3$ admixture to the $M2$ multipolarity was deduced from its experimental electron conversion coefficient [2,15]; (iii) $E3$ transitions between $(I^\pi,K=8^-,8)\rightarrow(I^\pi,K=5^+_\gamma,2)$ states; $\nu=3$. In this case, we assume that the observed transitions have pure $E3$ character, because a significant admixture of $M4$ multipolarity is rather unlikely.

A significant difference in the behavior of the f_ν factors as function of the atomic number Z for the deexcitation of the isomers into the $K=2$, quasirotational γ band (f_3) and into the g.s.b. (f_6 and f_7) can be noted indicating that the responsible deexcitation mechanisms may not be the same for various degrees of K forbiddenness, ν. In the following section, we shall discuss the deexcitation mechanism of the $K^\pi=8^-$ isomers in the $N=74$ isotones leading to the observed differences.

IV. DISCUSSION

The properties of the $K^\pi=8^-$ isomers in the even-even $N=74$ isotones were recently reviewed in Ref. [4]. Since the $7/2^+[404]$ and $9/2^-[514]$ neutron orbitals lie close to the Fermi levels in these isotones, one would expect a $K^\pi=8^-$ two quasineutron state at an excitation energy close to twice the neutron pairing gap of about 1 MeV for this mass region. Indeed, the $K^\pi=8^-$ isomers in the even-even $N=74$ isotones are found at similar excitation energies changing smoothly from about 2.8 MeV in ^{128}Xe to about 2.2 MeV in ^{138}Gd (see Fig. 5). The assignment of a two quasineutron $7/2^+[404]\otimes 9/2^-[514]$ configuration suggested for these isomers is supported by the electromagnetic properties of the 8^- isomers in ^{128}Xe and ^{136}Sm [22,23].

The β-deformation parameters of the ground state bands inferred from the respective $B(E2;2^+\rightarrow 0^+)$ values of the ^{130}Ba, ^{132}Ce, ^{134}Nd, and ^{136}Sm nuclei are $\beta_2=0.23$, 0.25, 0.26, and 0.28, respectively. For the rotational bands built on the 8^- isomeric states, which have been observed in ^{132}Ce [19], ^{134}Nd [24], ^{136}Sm [23], and ^{138}Gd [25], the deduced moments of inertia are $J^{(1)}=$ 21.2, 21.4, 22.4, and 23.4 $\hbar$ MeV^{-1}, respectively. An application of the standard

$A^{5/3}$ scaling factor makes all those moments of inertia nearly equal. They are about two times larger than the corresponding values of the deformed low lying states of the g.s.b. These observations show that the nuclei are deformed in the 8^- isomeric states and that the deformation parameters are similar for all the $N=74$ isotones. The presence of a static quadrupole deformation both in the ground and isomeric states allows us to discuss the γ-decay probabilities according to the K-selection rule.

We limit our discussion, of the deexcitation of the $K^{\pi}=8^-$ isomers via the K-forbidden transitions, to the even-even isotones from ^{130}Ba to ^{138}Gd where the $E1$ transitions from the isomeric state to the 8^+ level of the g.s.b. were observed. The dependence of the f_ν values on the atomic number Z as shown in Fig. 4 can be used as a source of information about the mechanism of weakening of K forbiddenness.

One can consider that the isomeric decay properties are attributed to changes in the β- and γ-deformation parameters. In the framework of the Davydov-Filippov model, a simple estimate of the γ-deformation parameter (γ parameter according to Bohr's convention) can be obtained from the ratios of excitation energy of the 2^+ member of the yrast band to the energy of the 2^+_γ level (see Table I in Ref. [26]). These ratios are equal to 0.39, 0.40, 0.39, and 0.39 for the Ba, Ce, Nd, and Sm isotones with $N=74$, respectively. It suggests $\gamma=24°\pm1°$, which corresponds to $E(2^+_1)/E(2^+_\gamma)=0.39\pm0.03$ in Davydov-Filippov model. This implies that the observed significant dependence of the f_7 values for the K-forbidden $E1$ transitions on the atomic number Z cannot be explained by changes of the γ deformation in the respective nuclei. However, the β-deformation parameters of the ground state bands of these isotones change smoothly with atomic number and here some correlation with the behavior of the f_7 values may exist.

Recently, an explanation of the isomer deexcitation mechanism through $8^-\rightarrow8^+$, $E1$ transitions has been suggested in Ref. [4] for the $N=74$ isotones. The proposed mechanism involves the interaction between the g.s.b. and the s band. It is assumed that the g.s.b. has a pure $K=0$ configuration but that the s band and the 8^- isomer have some distribution of K values which is the same for all $N=74$ isotones. The admixture of the s-band wave function to the wave functions of the g.s.b. members depends on the interaction strength between these two bands. An analysis of the alignment as function of rotational frequency shows that this interaction strength changes substantially for different $N=74$ isotones (see Fig. 4 and Table II in Ref. [4]). The admixture of the s-band wave function to that of the 8^+ g.s.b. level has been calculated in the framework of a simple two-band mixing model. The resulting $K=8$ admixture to the 8^+ g.s.b. level allows for $E1$ transitions between the 8^- and 8^+ states with transition probabilities proportional to the percentage of the s-band admixture in the yrast band. Relative values of reduced hindrance factors (f_7) were calculated for ^{130}Ba, ^{132}Ce, ^{134}Nd, ^{136}Sm, and ^{138}Gd [4]. These values normalized to the experimental f_7 value for ^{130}Ba are presented in Fig. 4 as solid line. The experimental f_7 values agree very well with the calculated ones. In the case of ^{132}Ce it suggests that the mixing of g.s.b. with s band is small. According to the calculation (see Table II in Ref. [4]) it corresponds to 2% of the s band admixture in the yrast 8^+ level.

TABLE II. Band mixing calculations for the yrast 6^+ state.

Nucleus	(amplitude)^2 for 6^+ state % ground state band	 % s band	f_6 calc.[a]	f_6 exp.
^{130}Ba	99.9	0.15	15.1	15.1(11)
^{132}Ce	99.5	0.5	12.4	$\geqslant$12.5
^{134}Nd	91.2	8.8	7.7	$\geqslant$11.9
^{136}Sm	65.5	34.5	6.1	
^{138}Gd	77.1	22.9	6.5	

[a]Normalized to experimental f_6 value for ^{130}Ba.

The same mechanism can be used to explain the values of the reduced hindrance factors f_6, for $M2$ transition from the 8^- isomers to the 6^+ members of the yrast band. Admixtures of the s band into the 6^+ yrast state wave functions have been calculated [4,27]. The resulting f_6 values normalized to the experimental f_6 value for ^{130}Ba, are given in Table II and shown in Fig. 4. Only the experimental lower limits of the f_6 values are known in ^{132}Ce and ^{134}Nd. The value for ^{134}Nd differs significantly from the calculated one. This may indicate that band-mixing model is not sufficient to explain the data for the $M2$ ($8^-\rightarrow6^+$) transitions.

The f_3 data for the $E3$ transitions from the isomeric 8^- state to the 5^+_γ ($K=2$) state are very scarce (see Fig. 4) and, therefore, the forbidden $E3$ γ transitions cannot be discussed in details. However, one may argue that a nonaxial deformation may be responsible for the weakening of the K forbiddenness in the case of the isomeric decay to the quasirotational γ-band members. For the deduced value of the deformation parameter $\gamma\approx24°$ the wave function of the 5^+_γ state calculated in the framework of the Davydov-Filippov model [28] contains about 4% of $K=4$ admixture to the $K=2$ wave function in the nuclei of interest. This may facilitate the $8^-\rightarrow5^+$, $E3$ transition observed in ^{130}Ba and ^{132}Ce through $K=7$ and $K=4$ admixture to the wave function of the initial and final states, respectively. Such $K=7$ admixture coming from the $7/2^+[404]\otimes7/2^-[523]$ two-neutron configuration in the 8^- isomer was found in ^{134}Nd [24]. Similar values for the amplitude of $K=4$ admixture have been deduced for both nuclei (since the γ deformations are similar) explaining the nearly equal f_3 values for these transitions.

V. CONCLUSIONS

The decay properties of the isomeric $K^{\pi}=8^-$ state in the nucleus ^{132}Ce have been studied. The isomer decays via highly K-forbidden γ transitions to the members of the ground state band and quasirotational γ band. The values deduced for the reduced hindrance factors $f_7=9.0(0.5)$, $f_3=6.7(0.1)$, and the lower limit $f_6\geqslant12.5$ fit nicely into the systematics of the hindrance factors for the even-even

$N=74$ isotones. A simple two-band mixing model involving an interaction of the g.s.b. and the s band, as suggested in Ref. [4], allows for an explanation of the observed Z dependence of the reduced hindrance factors f_7 for $E1$ transitions. However this model fails to reproduce the f_6 values in a consistent fashion. In the case of the $E3$ transitions (reduced hindrance factors f_3) it is shown that the nonaxial deformation should be taken into account. The similar values of f_3 for ^{130}Ba and ^{132}Ce may be related to a nearly constant γ deformation deduced for these nuclei. A more detailed study of the $K^{\pi}=8^{-}$ isomeric decay in the heavier ^{134}Nd, ^{136}Sm, and ^{138}Gd nuclei would be very helpful for a better understanding of the mechanism leading to forbidden γ transitions.

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