Shape polarizations of two-quasiparticle $K^\pi=8^-$ isomeric configurations

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(Received 12 October 1998)

Two-quasiparticle $K^\pi=8^-$ isomeric states in the $A\sim 130$ and 180 regions are studied with configuration-constrained calculations of potential-energy surfaces. Strong shape-polarization effects due to the two quasiparticles are found. In particular, the nuclei ^{188}Pb , ^{186}Hg , and ^{126}Te can be polarized from ground-state spherical or oblate shapes to prolate shapes, indicating a combination of K isomerism and shape isomerism as the Fermi level approaches shell closure. [S0556-2813(99)02902-7]

PACS number(s): 21.60.Cs, 21.10.-k, 27.60.+j, 27.70.+q

Two-quasiparticle $K^\pi=8^-$ isomeric states exist systematically in the even-even $N=74$ and 106 isotones, and $Z=72$ isotopes, with measured half-lives ranging from nanoseconds to hours. These states are associated with the neutron or proton $7/2^+[404]\otimes 9/2^-[514]$ Nilsson configuration, or in the case of the $N=106$ isotones with the neutron $9/2^+[624]\otimes 7/2^-[514]$ configuration. Direct $\Delta K=8$ decays from the 8^- isomers to the $I^\pi=8^+$ members of $K^\pi\approx 0^+$ yrast bands have been widely observed (see [1,2] and references therein) with significantly lower hindrances in many cases than would be expected if K were a good quantum number. The fast decays could originate from configuration mixing [1,2] which is sensitive to the shapes of both the isomeric configurations and the rotating states to which they decay. With rotational bands built on the isomers being observed in many cases, it can be deduced (e.g., from the estimated g -factors of the bands [3]) that the 8^- isomeric states generally have approximately prolate shapes. Although no more direct evidence exists for determining the deformations, recent advances [4] with laser spectroscopic techniques are opening up the possibilities to measure the charge radii and electromagnetic moments for a wide range of isomers with half-lives $\geq 100\ \mu\text{s}$. At the same time, theoretical calculations may be able to elucidate the important shape degrees of freedom, and provide a stimulus for future experimental measurements.

In the $A\sim 130$ and 180 regions, where $K^\pi=8^-$ isomers are observed, nuclear shapes can become very soft when approaching the $Z=50$ and 82 closed shells. For example, shape coexistence is well known in the light Pt, Hg, and Pb nuclei (see, e.g., [5,6]). Significant shape changes could occur in the process of quasiparticle excitations. Even for the well-deformed rare-earth nuclei, it has been shown that one-quasiproton shape polarizations can be strong and important for explaining many systematic behaviors, with calculations limited to axially symmetric deformations [7]. For soft nuclei, however, the inclusion of the axially asymmetric γ -degree of freedom is necessary. Furthermore, γ -distortion can mix different K values, and hence strongly affect the decay properties of the states. The degree to which the ob-

served 8^- isomers can be considered to involve shape isomerism, combined with K isomerism, remains an open question. The present paper addresses these issues through the calculation of intrinsic shapes, using a newly developed configuration-constrained blocking method [8].

In the configuration-constrained calculation of the potential-energy surface (PES) of a given quasiparticle state, the specified single-particle orbitals are kept singly occupied while changing the deformation. For axially symmetric shapes, single-particle orbitals can be specified by their Ω (individual spin-projection) values and it is straightforward to identify orbitals [7]. For axially asymmetric shapes, however, Ω is no longer conserved, and one has to find a different way to identify the specific configurations. We use a method in which we calculate a set of average Nilsson numbers, $\langle N \rangle$, $\langle n_z \rangle$, $\langle \Lambda \rangle$ and $\langle |\Omega| \rangle$ for the configurations that we intend to constrain in deformation space. The orbitals involved for the $K^\pi=8^-$ isomeric states have well-defined and stable average Nilsson numbers in the deformation area considered, and our configuration-constrained calculations can be related unambiguously to the Nilsson configurations.

Calculations have been performed with the nonaxial deformed Woods-Saxon (WS) potential [9] with universal parameters [10]. In order to avoid the sudden collapse of proton pairing around the $Z=50$ and 82 closed shells, the Lipkin-Nogami (LN) description [7,11] is employed with monopole pairing. The pairing interaction strength, G , is first determined by the average gap method [12]. It has been pointed out [8] that the precise G value is particularly important for calculations of configuration excitation energies, but not for determinations of shapes. The usual pairing strength can describe the average behavior of odd-even mass differences, assuming that the quantity $\Delta + \lambda_2$ is identified with the experimental mass difference [7,12] (where Δ is the pairing gap, and λ_2 can be considered as an additional Lagrange multiplier to minimize particle-number fluctuations in the LN description). However, the experimental mass difference contains shape and blocking effects of adjacent odd-mass nuclei, while $\Delta + \lambda_2$ does not. A method [8] to obtain a more realistic pairing strength involves reproducing experimental mass differences using a five-point formula [12] in both experiment and theory. In this method, the shape and blocking effects are included. The PES is computed by the Strutinsky method [7,13] with the standard liquid-drop model and pa-

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FIG. 1. The determined β_2 , γ deformations for the $K^\pi=8^-$ isomers and the ground states (g.s.) in the $N=74$ isotones.

rameters of Ref. [14], in the quadrupole deformation (β_2 , γ) space and with hexadecapole deformation (β_4) variation. Such calculations provide a self-consistent way of treating both pairing and deformation.

In the mass 130 region, the $K^\pi=8^-$ states are based upon the two-quasineutron $\nu\{7/2^+[404] \otimes 9/2^-[514]\}$ configuration. The two orbitals are close to the $N=74$ neutron Fermi level. Experiments have observed 8^- isomers in the even-even $N=74$ isotones from ^{128}Xe to ^{138}Gd (see [1] and references therein). The present calculations show that shape polarization due to the two quasineutrons can be strong, particularly in the isotones with proton numbers close to the $Z=50$ shell gap (see Fig. 1).

It is known that the $A \sim 130$ nuclei have γ soft shapes [15]. The γ deformations have been used to explain the observed features, such as the signature inversions in the rotational bands of odd-odd $A \sim 130$ nuclei [16]. In the present calculations for the $N=74$ isotones, the ground state of $^{128}_{54}\text{Xe}$, for example, has a very γ -soft shape with an energy minimum at $\gamma \approx 30^\circ$, while the 8^- isomeric state has an approximately prolate shape with $\gamma \approx 6^\circ$ and about a 20% increase in β_2 deformation (see Fig. 1). For the nucleus, $^{126}_{52}\text{Te}$, we predict strong shape polarization, though the two-quasiparticle 8^- state has not been observed yet. The two quasineutrons can drive the nucleus from a weakly deformed ($\beta_2 \approx 0.05$) oblate ground state to a prolate ($\beta_2 \approx 0.12$) 8^- state. In contrast to the light Pt, Hg, and Pb nuclei (see below) ^{126}Te has no shape-coexisting 0^+ state in our calculation, but a shape-coexisting 8^- state is predicted. In the case

FIG. 2. The calculated PES's for ^{130}Ba (left) and ^{138}Gd (right). The upper panels are for the ground states, and the lower panels for the 8^- isomers. Note that different deformation scales have been used in the plots (because calculations for the 8^- configurations have to be limited to $|\gamma| < 30^\circ$ due to the requirements of the configuration-constrained procedure). The intrinsic PES's are reflection-symmetric about $\gamma=0^\circ$.

of ^{124}Sn , however, the β_2 deformation of the calculated 8^- state becomes smaller, and the PES minimum is no longer within the deformation space considered.

It can be seen from Fig. 1 that the 8^- isomers have larger β_2 deformations than their corresponding ground states for $Z \leq 60$, but the situation is reversed for $Z \geq 62$. This reversal reflects the crossing between the $\nu 7/2^+[404]$ and $\nu 9/2^-[514]$ orbitals at $\beta_2 \approx 0.25$ ($\beta_4 \approx -0.01$). Based on these two orbitals, the two quasineutrons can drive nuclei either towards larger β_2 deformations when $\beta_2 < 0.25$ (i.e., in the $Z \leq 60$ isotones) or towards smaller β_2 values when $\beta_2 > 0.25$ (for $Z \geq 62$). A similar reversal can also be seen in the γ deformations (Fig. 1). This is because the two quasineutrons have a weak γ -deformation-driving force when $\beta_2 \geq 0.25$ (i.e., for $Z \geq 62$). As representative examples, the calculated PES's for ^{130}Ba and ^{138}Gd are shown in Fig. 2.

The $K^\pi=8^-$ isomeric states in the $A \sim 180$ nuclei are built on the two-quasineutron $\nu\{9/2^+[624] \otimes 7/2^-[514]\}$ or two-quasiproton $\pi\{7/2^+[404] \otimes 9/2^-[514]\}$ configuration. Systematic experimental observations can be found in Ref. [2] (and references therein). The $Z=72$ Hf isotopes have well-deformed prolate shapes in both the ground states and the isomers (shown in Fig. 3, $\gamma \approx 0$ in all cases). In contrast, the $N=106$ isotones show more variable behaviors. It is well known that various shapes can coexist for proton numbers close to $Z=82$ [5,6,17]. In the present calculations, the nucleus ^{186}Hg , for example, has a $\beta_2 \approx 0.13$ oblate ground state and a $\beta_2 \approx 0.20$ prolate coexisting 0^+ state with a calculated excitation energy of $E_x \approx 600$ keV (experimentally $E_x = 523$ keV [17]). The nucleus ^{188}Pb has a spherical ground state, a $\beta_2 \approx 0.17$ oblate coexisting 0^+ state with $E_x \approx 930$ keV (experimentally $E_x = 571$ keV [18]) and a $\beta_2 \approx 0.20$ prolate 0^+ state with $E_x \approx 1200$ keV (empirically E_x

FIG. 3. The determined β_2 deformations and γ softnesses for the $K^\pi=8^-$ isomers and the ground states (g.s.) in the $N=106$ isotones and $Z=72$ isotopes. For all the isomers, $\gamma \sim 0^\circ$. The γ softness is defined [21] as the difference in the γ -value between the PES minimum and 100 keV above the minimum. For each of the $Z=72$ isotopes, the γ softness is about 5° .

estimated to be 720 keV [19]). Their calculated PES's are shown in Fig. 4. For the 8^- isomeric states of ^{186}Hg and ^{188}Pb , the calculations predict sizable prolate deformations ($\beta_2 \sim 0.25$; see Table I) implying striking examples of shape coexistence between the isomers and their respective ground

FIG. 4. Similar to Fig. 2, but for ^{186}Hg (left) and ^{188}Pb (right).

TABLE I. Calculated excitation energies E_{cal} (in keV) and deformations of the two-quasineutron $K^\pi=8^-$ isomers. The experimental energies E_{expt} (in keV) can be found in Refs. [1,2] and references therein.

Nuclei	E_{expt}	E_{cal}	β_2	β_4	$ \gamma $
^{126}Te		2980	0.12	-0.005	0°
^{128}Xe	2787	2490	0.16	-0.008	6°
^{130}Ba	2475	2390	0.18	-0.015	6°
^{132}Ce	2340	2220	0.20	-0.020	5°
^{134}Nd	2294	2140	0.22	-0.023	10°
^{136}Sm	2264	2120	0.24	-0.024	12°
^{138}Gd	2233	2130	0.25	-0.028	13°
^{140}Dy		2150	0.26	-0.039	9°
^{176}Yb	1050	1140	0.28	-0.053	0°
^{178}Hf	1148	1320	0.27	-0.055	0°
^{180}W	1529	1560	0.25	-0.047	0°
^{182}Os	1832	1760	0.22	-0.040	0°
^{184}Pt	1844	1885	0.24	-0.028	1°
^{186}Hg	2217	2230	0.25	-0.022	1°
^{188}Pb		2400	0.26	-0.011	2°

states. Indeed, an 8^- isomer has been observed [17,20] in ^{186}Hg , with a rotational band that is consistent with a prolate, shape-coexisting interpretation. However, there is no corresponding isomer yet observed in ^{188}Pb , where our calculations indicate the greatest difference in β_2 -value between the 8^- state and the ground state.

The calculated excitation energies of the two-quasineutron 8^- isomeric states are listed in Table I, showing good agreement with the experimental values. The predicted energy in ^{126}Te is significantly higher than in the adjacent isotone ^{128}Xe , which can be understood to be due to a large particle-hole excitation energy between the $\nu 9/2^-$ [514] and $\nu 7/2^+$ [404] orbitals at small β_2 deformation. The predicted 8^- isomer in ^{140}Dy is calculated to have similar properties to its isotone ^{138}Gd . It has been pointed out [8] that the detailed excitation energies can be affected by residual interactions between quasiparticles, zero-point rotational energies and possible non-orthogonality, which are not accounted for in the present calculations. However, these effects should not significantly alter the predicted variations with nucleon number, and they should not alter the calculated deformations.

Although quantitative transition-rate calculations are beyond the scope of this work, it is nevertheless useful to discuss briefly the way that the calculated shapes may influence the half-lives of the isomers. The approach towards a closed shell might generally be expected to be accompanied by a breakdown of the K quantum number, hence leading to shorter half-lives, due to decreasing β_2 deformation and increasing γ deformation. However, inspection of Figs. 1 and 3 does not support this view, at least not in a simple way. Rather, the figures illustrate a divergence of the ground-state and isomer deformations (both β_2 and γ) as the $Z=50$ and 82 closed shells are approached. The observed increase in the experimental $E1$ hindrance factors [1,2] may reflect shape differences rather than K -value differences. Further clarification of this effect will be sought.

In conclusion, systematic investigations of the observed two-quasiparticle 8^- isomeric states have been carried out with configuration-constrained PES calculations. Strong shape polarizations have been found, especially in the nuclei approaching the $Z=50$ and 82 closed shells. The calculated shape changes, particularly the γ deformations, can be important for understanding the observed behaviors of the isomers, such as the decay properties. The calculated excitation

energies reproduce well the measured values. Predictions of the 8^- states are made for ^{188}Pb , ^{126}Te and ^{140}Dy . The ^{188}Pb case could provide the most striking example of the effect of shape coexistence.

This work was supported by the U.K. Engineering and Physical Sciences Research Council and the Swedish Natural Research Council.

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