Bulg. J. Phys. **42** (2015) 382–386

High-K Isomers and the Role of β_6 Deformation

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Received *8 October 2015*

Abstract. High-K isomeric states and their decays give access to the excited-state structure of neutron-rich rare-earth nuclides, where a maximum in β_6 deformation has been predicted. Using extensions of the Nilsson-Strutinsky approach, including configuration constraints, we have calculated single-particle energies, and two-quasiparticle excitation energies. Their sensitivity to β_6 deformation is discussed, as well as the possible influence of β_6 deformation on collective rotational energies.

PACS codes: 21.10.-k, 21.60.-n, 23.20.Lv, 27.70.+q

1 Introduction

The structure of nuclei in the doubly mid-shell rare-earth ($A \approx 170$) region is important for understanding the evolution of collectivity where the valence nucleon numbers are maximal [1], and for understanding elemental abundances following r-process nucleosynthesis [2]. A promising avenue for the experimental study of this neutron-rich region is through the occurrence of K-isomeric states, which arise due to the partial conservation of the angular-momentum projection, K, on the nuclear symmetry axis [3, 4]. Such isomers can be used to determine the single-particle energies close to the neutron and proton Fermi surfaces, and, through their decays, they can also reveal the low-lying collective rotational energies.

Recent relativistic projectile fission experiments at RIBF, RIKEN have enabled the discovery of high-K isomers in neutron-rich $Z \approx 64$ nuclei, in particular the $N = 102$ isotones ^{164}Sm and ^{166}Gd [5]. Similar to the $A \approx 250$ region of high-K isomers [6, 7], β_6 deformation could have a significant effect on both the single-particle energies and the rotational energies also in the neutron-rich

$A \approx 170$ region. In both mass regions, the calculations of Möller et al. [8] predict a peak in β_6 deformation of similar magnitude, though over a smaller $N - Z$ range in the lighter mass region, where the β_6 maximum is for ^{164}Sm.

In the present work, we present and discuss the results of configuration-constrained potential-energy-surface (PES) calculations based on the Woods-Saxon-Strutinsky shell-correction method [9], extended to include the β_6 degree of freedom.

2 Methodology and Results

As discussed in previous work, e.g. Refs. [6, 9], the application of configuration constraints with the Woods-Saxon potential and the Strutinsky macroscopic-microscopic method, including Lipkin-Nogami pairing, has been very successful in describing the energies and configurations of multi-quasiparticle isomers in deformed nuclei. The inclusion of β_6 deformation was found [6, 7] to have

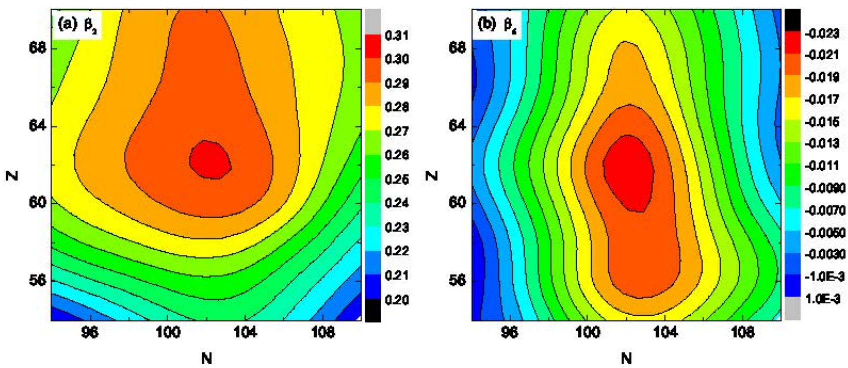

Figure 1. (Color online) Contour plots in the $N - Z$ plane for β_2 (left) and β_6 (right) deformation, in the neutron-rich rare-earth region of nuclei.

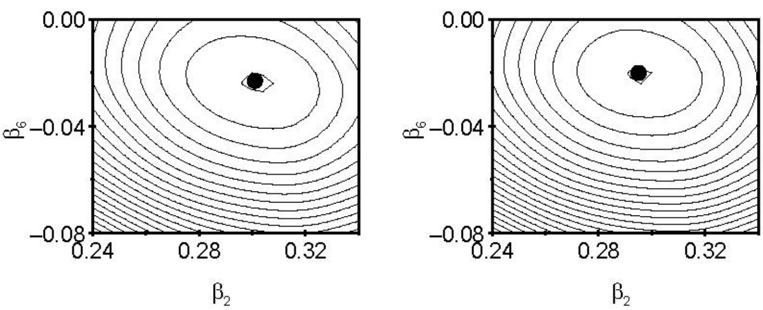

Figure 2. PES plots for the ^{164}Sm ground state (left) and the $K^\pi = 6^-$ isomeric state (right). The energy interval between the contours is 200 keV.

a significant effect in actinide nuclei. The neutron-rich rare-earth region is also calculated to have be a peak in β_6 deformation, as illustrated in Figure 1. This is in overall agreement with the calculations of Möller et al. [8].

Example PES's are given in Figure 2 for the ^{164}Sm ground state and the $K^\pi = 6^-$ isomeric state, which is calculated to have a two-quasineutron $\{\nu\frac{5}{2}^-[512] \otimes \nu\frac{7}{2}^+[633]\}$ configuration. The effect of the calculated β_6 deformation on the neutron and proton single-particle energies is illustrated in Figure 3. It is seen, for example, that an $N = 102$ gap opens up in the presence of β_6 deformation. The effect on the energies of some low-lying two-quasiparticle states in ^{166}Gd and ^{164}Sm is shown in Table 1. It is evident that relative energies can change by more than 250 keV. However, the experimental information on two-quasiparticle excitations in these nuclides is sparse. In ^{166}Gd there is a $K^\pi = 6^-$ isomer, which is observed at 1601 keV, and a possible $K^\pi = 4^+$ state at 1350 keV, while in ^{164}Sm there is a $K^\pi = 6^-$ isomer observed at 1417 keV [5]. Therefore, with the present information, it is not possible to infer the β_6 deformation on the basis the two-quasiparticle energies.

The β_6 deformation could also influence the collective behaviour through its effect on subshell gaps in the neutron and proton single-particle spectra, illustrated in Figure 3. This might be able to account for the variations in the energies of the $I^\pi = 2^+$ states in the ground-state rotational bands. The experimental 2^+ energies are shown in Figure 4. Qualitatively, a subshell gap at $N = 102$ could lead to reduced pairing and hence an increased moment of inertia, thus leading to reduced $I^\pi = 2^+$ energies. However, there is not yet a quantitative explanation. In contrast, Ghorui et al. [10] suggest that there is a subshell gap at $N = 100$, which could account for the $E(2^+)$ variations. It is evident that further theoretical work is needed.

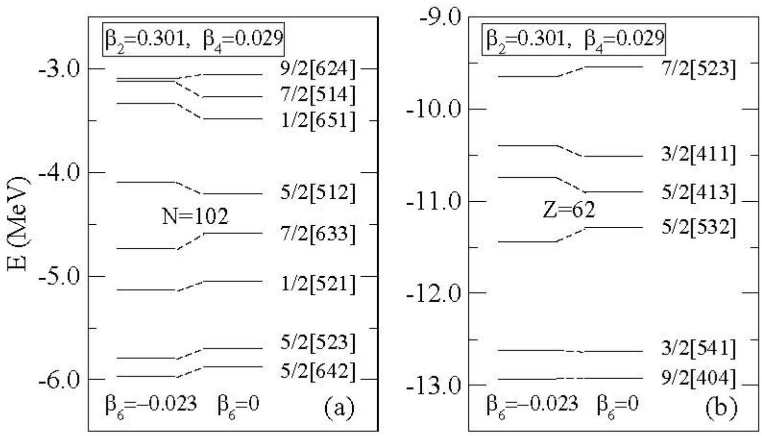

Figure 3. Neutron (left panel) and proton (right panel) single-particle energies with and without β_6 deformation. Within each panel, the $\beta_6 = 0$ levels are on the right.

Table 1. Low-lying two-quasiparticle states in ^{166}Gd and ^{164}Sm, predicted by potential-energy-surface calculations, from Ref. [5]. Configurations marked with * are energetically unfavoured according to the residual spin-spin coupling rules, and therefore 200 keV has been added to their energies. The calculations give $\gamma = 0$ for all predicted states, and minimisation with respect to β_4 deformation was included [5]. Energies were again minimised with respect to β_2 and β_4, for the $\beta_6 = 0$ calculations.

K^π	configuration	β_2	β_6	E (MeV)	$E(\beta_6 = 0)$ (MeV)	ΔE (keV)
^{166}Gd						
g.s.		0.30	-0.020			
6^-	$\nu\frac{5}{2}^-[512] \otimes \nu\frac{7}{2}^+[633]^*$	0.29	-0.017	1.288	1.237	-51
4^+	$\pi\frac{3}{2}^+[411] \otimes \pi\frac{5}{2}^+[413]$	0.30	-0.022	1.300	1.369	$+69$
3^+	$\nu\frac{1}{2}^-[521] \otimes \nu\frac{5}{2}^-[512]$	0.29	-0.018	1.400	1.516	$+116$
4^-	$\nu\frac{1}{2}^-[521] \otimes \nu\frac{7}{2}^+[633]$	0.28	-0.013	1.684	1.524	-160
4^-	$\pi\frac{3}{2}^+[411] \otimes \pi\frac{5}{2}^-[532]^*$	0.29	-0.015	1.769	1.652	-117
5^-	$\pi\frac{5}{2}^+[413] \otimes \pi\frac{5}{2}^-[532]$	0.29	-0.017	1.826	1.749	-77
^{164}Sm						
g.s.		0.30	-0.023			
6^-	$\nu\frac{5}{2}^-[512] \otimes \nu\frac{7}{2}^+[633]^*$	0.30	-0.020	1.301	1.241	-60
5^-	$\pi\frac{5}{2}^+[413] \otimes \pi\frac{5}{2}^-[532]$	0.29	-0.020	1.411	1.356	-55
4^-	$\pi\frac{3}{2}^+[411] \otimes \pi\frac{5}{2}^-[532]^*$	0.30	-0.021	1.907	1.872	-35
4^-	$\pi\frac{5}{2}^+[413] \otimes \pi\frac{3}{2}^-[541]$	0.29	-0.020	2.195	2.141	-54
4^+	$\pi\frac{5}{2}^-[532] \otimes \pi\frac{3}{2}^-[541]^*$	0.28	-0.016	2.502	2.356	-146

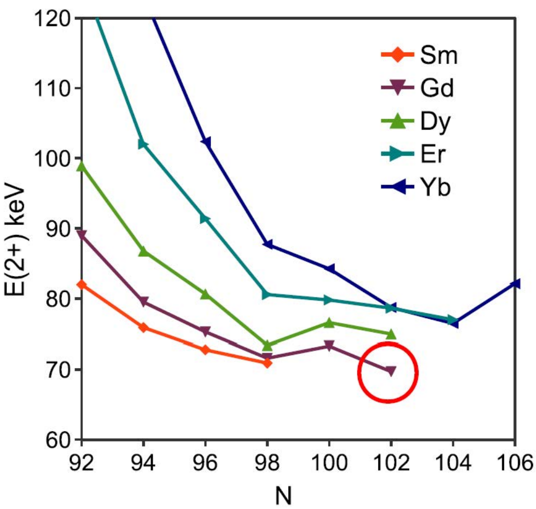

Figure 4. (Color online) Variation with neutron number of $I^\pi = 2^+$ rotational energies for $Z = 62 - 70$ even-even nuclides, from Ref. [5]. The circled value is for ^{166}Gd.

3 Conclusion

Shapes and excited-state energies have been calculated for nuclei in the neutron-rich $A \approx 170$ region, with the inclusion of β_6 deformation, using a configuration-constrained approach. It is found that there is a significant influence from β_6 on the single-particle energies, and also on the two-quasiparticle energies. Specific results are given for ^{166}Gd and ^{164}Sm, where experimental data are now available.

Acknowledgments

This research has been supported by the United Kingdom Science and Technology Facilities Council under grant No. ST/L005743/1, the Bulgarian National Science Fund under contract No. DFNI-E02/6, the National Key Basic Research Program of China under grant No. 2013CB83440, the National Natural Science Foundation of China under grant Nos. 11235001, 11320101004, 11575007, 11205120 and 11575136, and the Open Project Program of State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences under grant No. Y4KF041CJ1.

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