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## Prediction of high-K isomeric states in transactinide nuclei close to N=162

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**Abstract** Transactinide nuclei around neutron number N=162 display axially deformed equilibrium shapes. In the present study we are particularly interested in the occurrence of high-K isomers in the axially deformed isotopes of Rf (Z=104), Sg (Z=106), Hs (Z=108), and Ds (Z=110), with neutron number N=160-166 and the effect of the N=162 closure on the structure and distribution of two-quasiparticle (2qp) states. The evolution of high-K isomers is analyzed in a self-consistent axially symmetric relativistic Hartree-Bogoliubov calculation using the blocking approximation with time-reversal symmetry breaking.

**Keywords** high-K isomers, transactinides, nuclear density-functionals

### INTRODUCTION

Nuclei beyond the actinides owe their existence to the underlying single-nucleon shell structure. These elements often display axially deformed equilibrium shapes and intruder single-nucleon states with high- $\Omega$  values (projection of the single-particle angular momentum onto the symmetry axis of the nucleus) appear close to the Fermi level. The unpaired quasiparticle excitations form isomeric states with high values of total  $K = \sum_i \Omega_i$  [1]. Because they can only decay by K-forbidden transitions, these states have lifetimes that are significantly longer than most of the neighboring states. The decay of isomeric states provides information on the nuclear wave function, single-nucleon states, pairing gaps and residual interactions [2].

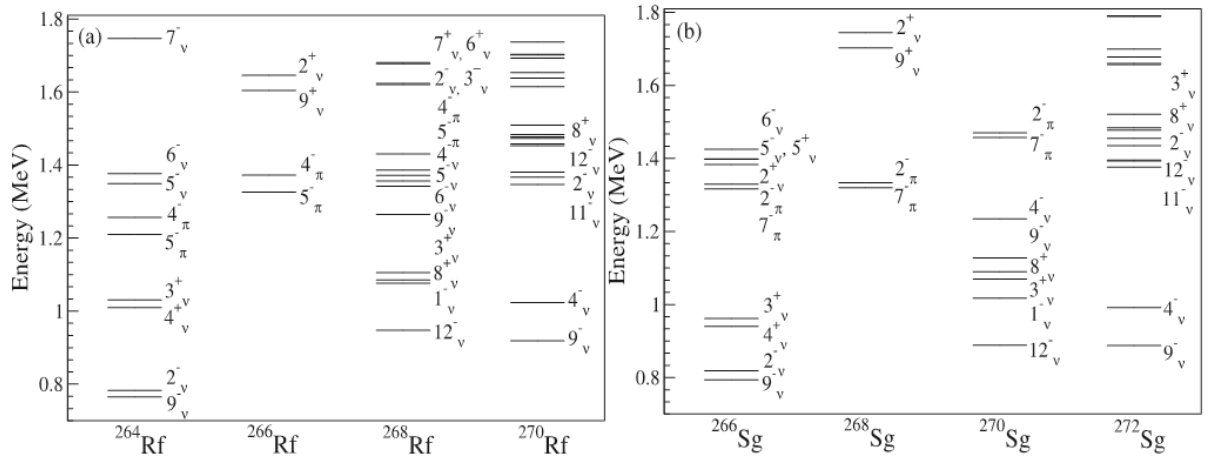
Systematic experimental efforts in the region of very heavy nuclei have produced detailed spectroscopic data in nuclei around  $^{254}\text{No}$  [3- 7]. In addition to the detection of  $\alpha$  and  $\gamma$  decays, recent studies have made use of conversion electrons (CE) to investigate possible K-isomeric states in heavy high-Z nuclei such as, for instance,  $^{256}\text{Rf}$ , in which internal conversion becomes the preferred decay mode [8, 9]. The heaviest nuclei for which characteristic high-K isomeric decays have been investigated are  $^{270}\text{Ds}$  and its  $\alpha$ -decay daughter  $^{266}\text{Hs}$  [10, 11]. Theoretical studies of quasiparticle excitations in the region of transactinide nuclei have been based on the microscopic-macroscopic approach [12-23], self-consistent models with Skyrme functionals [24-29], the Gogny force [30-32], and relativistic energy density functionals [33-38].

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In the present study [39] we extend our resent study of shape evolution, collective excitation spectra, and decay properties of transactinide nuclei based on the microscopic framework of relativistic energy density functionals Ref. [33], to two-quasiparticle excitations in the axially deformed isotopes of Rf ( $Z = 104$ ), Sg ( $Z = 106$ ), Hs ( $Z = 108$ ), and Ds ( $Z = 110$ ), with neutron number  $N = 160 - 166$ .

## QUASI-PARTICLE EXCITATIONS

The two-quasiparticle neutron or proton states are obtained in a self-consistent relativistic Hartree-Bogoliubov calculation [39, 40], based on the functional DD-PC1 [41] and with a separable pairing force of finite range [42, 43], using the blocking approximation with time-reversal symmetry breaking. The  $2qp$  states are determined by blocking the lowest neutron or proton quasi-particle orbitals located in the vicinity of the Fermi energy that corresponds to the fully paired equilibrium solution. After performing the iterative minimization, the energy of the two-quasiparticle excitation is obtained as the difference between the energy of the self-consistent blocked RHB solution and the energy of the fully paired equilibrium minimum. The breaking of time-reversal symmetry removes the degeneracy between signature partner states with angular-momentum projection on the symmetry axis  $K_{\min} = |\Omega_i - \Omega_j|$  and  $K_{\max} = \Omega_i + \Omega_j$ , and with parity  $\pi = \pi_i \cdot \pi_j$ .



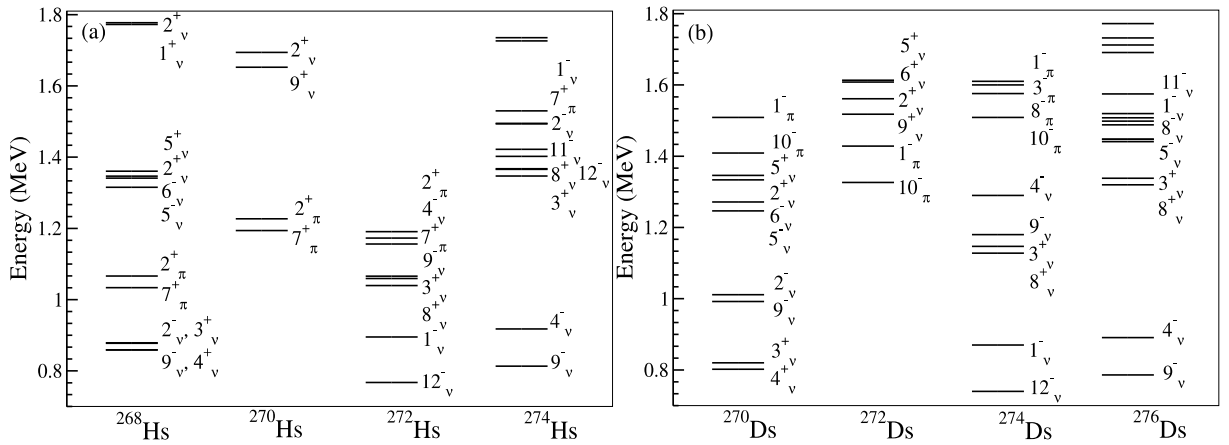
**Fig. 1.** Lowest two-quasiparticle states in Rf (upper panel) and Sg (lower panel) isotopes with neutron number  $N = 160 - 166$ . The  $2qp$  states correspond to axially symmetric solutions obtained with the relativistic functional DD-PC1 and a pairing force separable in momentum space. The calculation includes time-reversal symmetry breaking.

Figures 1 and 2 display the excitation energies of two-quasiparticle  $K_{V(\pi)}$  states for the Rf, Sg, Hs and Ds isotopes with neutron number  $N = 160 - 166$ . In figure 1 the high density of single-particle levels close to the Fermi surface in the isotopes of Rf and Sg with  $N=160$  yields a number of quasiparticle excitations in the energy window below 1.8 MeV. Our calculation predicts the occurrence of the two-neutron isomeric states  $K^\pi = 9^-_v$  and  $2^-_v$

originating from the single-particle orbitals  $v7/2^+[613] \otimes v11/2^-[725]$ . The neutron orbitals  $v1/2^+[620]$  and  $v7/2^+[613]$  are coupled to form the states  $4^+_v$  and  $3^+_v$  at excitation energy close to 1 MeV. An interesting result, that can also be noticed in the two other isotopic chains considered in this study, is that the lowest two-quasiparticle states in the  $N = 162$  isotones are predicted at considerably higher excitation energies. For the particular choice of the energy density functional and pairing interaction used in this and our previous study [33], the lowest two-quasiparticle states typically occur at  $\approx 0.8$  MeV, whereas in the  $N = 162$  isotones the excitation energies of the lowest  $2qp$  states are predicted at  $E \geq 1.2$  MeV. For  $^{266}\text{Rf}$ , in particular, the doublet of states  $5^-_n$  and  $4^-_n$  states at energy 1.35 MeV originates from the two-proton configuration  $n1/2^-[521] \otimes n9/2^+[624]$ . The lowest two neutron excitations occur at even higher energies: the  $9^+_v$  and  $2^+_v$  states at 1.60 MeV and 1.65 MeV, respectively, based on the high- $j$  configuration  $v7/2^+[613] \otimes v11/2^+[606]$ . In  $^{268}\text{Sg}$ , as a result of the neutron shell-closure at  $N = 162$ , the lowest  $2qp$  excitations are the proton states  $7^-_n$  and  $2^-_n$  at 1.32 and 1.33 MeV, respectively, originating from the Nilsson levels  $n5/2^-[512]$  and  $n9/2^+[624]$ . We note that for this nucleus the only two-neutron  $qp$  states, predicted below 1.8 MeV are the  $9^+_v$  and  $2^+_v$  ( $v11/2^+[606] \otimes v7/2^+[613]$ ) at 1.70 and 1.74 MeV, respectively. The occurrence of  $2qp$  excitations in  $^{268}\text{Rf}$  and  $^{270}\text{Sg}$  already at energies  $\approx 1$  MeV is consistent with the increase of the single-particle level density near the Fermi surface. The lowest-lying two-neutron excitations  $12^-_v$  and  $1^-_v$  originate from the configuration  $v13/2^-[716] \otimes v11/2^+[606]$ . In  $^{270}\text{Rf}$  and  $^{272}\text{Sg}$  the lowest  $2qp$  configurations are:  $v5/2^+[613] \otimes v13/2^-[716]$  ( $9^-_v$  and  $4^-_v$ ),  $v9/2^+[604] \otimes v13/2^-[716]$  ( $11^-_v$  and  $2^-_v$ ),  $v11/2^+[606] \otimes v13/2^-[716]$  ( $12^-_v$  and  $1^-_v$ ), and  $v5/2^+[613] \otimes v11/2^+[606]$  ( $8^+_v$  and  $3^+_v$ ).

In  $^{268}\text{Hs}$  (left panel of figure 2), the lowest-lying  $2qp$  excitations are the signature partner levels  $9^-_v$ ,  $2^-_v$  and  $4^+_v$ ,  $3^+_v$ . The two configurations coincide in energy, with the aligned  $\Omega$ -states at 0.86 MeV and the anti-aligned ones at 0.88 MeV. Adding two more protons (right panel of figure 2), the doublet  $4^+_v$  and  $3^+_v$  ( $v1/2^+[620] \otimes v7/2^+[613]$ ) becomes the lowest  $2qp$  excitation in the nucleus  $^{270}\text{Ds}$ . The partner levels  $9^-_v$  and  $2^-_v$ , which are the lowest  $2qp$  states in the  $N = 160$  Rf, Sg and Hs isotopes, are calculated  $\approx 200$  keV higher in energy. The prediction of a high- $K$  two-neutron quasiparticle configuration at energy  $\approx 1$  MeV is in agreement with the experimental observation of a two-neutron high- $K$  isomeric decay in  $^{270}\text{Ds}$  [11]. In  $^{270}\text{Hs}$ , because of the deformed shell closure, the neutron two-quasiparticle states  $9^+_v$  and  $2^+_v$  are predicted at energies 1.65 and 1.69 MeV, respectively. The lowest-lying  $2qp$  states calculated for  $^{270}\text{Hs}$  are the proton excitations  $7^+_n$  and  $2^+_n$ , with the structure of Nilsson orbitals  $n5/2^-[512] \otimes n9/2^-[505]$ .  $^{270}\text{Hs}$  has been observed in the reaction  $^{248}\text{Cm} (^{26}\text{Mg}, 4n)$ , however,

because of the low production cross section and consequently low number observed events (3), no detailed spectroscopic data are available except for  $\alpha$  decay energies and decay times [44]. The calculation for  $^{272}\text{Ds}$  predicts the proton two-quasiparticle states  $10^-_\pi$  and  $1^-_\pi$  based on the configuration  $n9/2^-[505] \otimes n11/2^+[615]$ . Because of the  $N = 162$  deformed shell gap the two-neutron doublets  $9^+_\nu$ ,  $2^+_\nu$  and  $5^+_\nu$ ,  $6^+_\nu$ , appears only at higher excitation energies (1.5 MeV).  $^{272}\text{Ds}$  is the  $\alpha$ -decay daughter of  $^{276}\text{Cn}$ , which could be produced in a similar way as  $^{270}\text{Ds}$  [11] via the reaction  $^{207}\text{Pb}(^{70}\text{Sn}, 1n)^{276}\text{Cn}$ . An order of magnitude lower production cross section could be compensated by higher beam intensities at future linear accelerator facilities, e.g. the LINAG project presently under construction for SPIRAL2 [45], or the project for a high-intensity continuous wave machine at GSI [45]. Consistent with the results obtained for Rf and Sg isotopes,  $^{272}\text{Hs}$ ,  $^{274}\text{Hs}$ ,  $^{274}\text{Ds}$  and  $^{276}\text{Ds}$  exhibit an increased density of two-quasiparticle states at low excitation energies. The lowest Nilsson levels that form the  $2qp$  configurations in the energy window below 1.8 MeV are the  $13/2^-[716]$ ,  $11/2^+[606]$ ,  $5/2^+[613]$  and  $3/2^+[611]$  for neutrons, and the orbitals  $11/2^+[615]$ ,  $9/2^-[505]$  and  $5/2^-[512]$  for protons.



**Fig. 2.** Same as described in the caption to Fig. 1 but for the isotopes of Hs (upper panel) and Ds (lower panel).

## CONCLUSIONS


In summary, we have employed the self-consistent mean-field framework based on relativistic energy density functionals to study the structure of two-quasiparticle excitations in axially deformed Rf, Sg, Hs, and Ds isotopes, with neutron number  $N = 160 - 166$ . The calculation of excitation energies of  $2qp$  states is based on the blocking approximation with time-reversal symmetry breaking. Our microscopic self-consistent calculation has provided a detailed prediction for the evolution of  $2qp$  states close to the  $N = 162$  deformed-shell



gap. The excitation energies of  $2qp$  configurations depend on the specific choice of the energy density functional, and the strength of the pairing interaction. In the particle-hole channel we have used the relativistic functional DD-PC1 that was adjusted to the experimental masses of a set of 64 axially deformed nuclei in the mass regions  $A \approx 150 - 180$  and  $A \approx 230 - 250$ . The strength of the separable pairing force of finite range was fine-tuned to reproduce the odd-even mass differences in the region  $A \approx 230 - 250$ . A stronger (weaker) pairing would automatically increase (decrease) the energies of the  $2qp$  states (shown in Figs. 1 and 2) with respect to the corresponding ground states. The calculation predicts the occurrence of a series of low-energy high-K isomers, most notably the  $9^-_{\nu}$  in the  $N = 160$  and  $N = 166$  isotopes, and the  $12^-_{\nu}$  in the  $N = 164$  nuclei. A very interesting result is the low density of  $2qp$  states in the  $N = 162$  isotones, with no two-neutron states predicted below 1.6 MeV excitation energy. The two-proton states in these nuclei are calculated almost 0.5 MeV higher in energy than the lowest  $2qp$  states in neighboring isotopes. This is a consequence of the deformed-shell closure at  $N = 162$  and presents an interesting observable that can be used, together with the separation energies and  $Q_{\alpha}$ -values, to characterize the evolution of deformed shell gaps in this mass region, and possibly verified experimentally in the near future for  $^{270}\text{Hs}$  and  $^{272}\text{Ds}$ .

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