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Prolate-oblate shape transition in heavy neutron-rich nuclei

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Abstract. A large amount of experimental information was obtained on heavy neutron-rich nuclei in the Hf-Hg region during the last decade. In the majority of the cases these nuclei were populated in relativistic energy fragmentation and studied via isomeric and β decays. In addition, deep-inelastic studies gave information to nuclei close to stability. The experimental data were used to establish the sign of quadrupole deformation, prolate or oblate. In the present paper this information is compared with two global theoretical calculations, one which is constrained to axial symmetry and one which considers triaxiality. The prolate-oblate transitional region was reached for (Z=76) Os and Ir (Z=77), as proved by the observation of oblate isomeric states in ^{197,198,199}Os and ^{201}Ir. For Ta (Z=73) and W (Z=74) isotopes no clear evidence of oblate deformation exists so far, with ^{192}W and ^{189}Ta being the most neutron-rich isotopes with spectroscopic information.

1. Introduction

The neutron-rich Hf-W-Os-Pt-Hg region is characterised by the presence of nuclei with different shapes in their ground-states, such as prolate, oblate, triaxial and spherical. Shape transitional nuclei are difficult to treat theoretically, consequently this region is considered to be a crucial testing ground for nuclear models. The lighter isotopes are prolate deformed, and by adding more and more neutrons the shape becomes oblate. As the N=126 closed shell is approached the nuclei become spherical. In the prolate-oblate transition region the nuclei can be described by a potential with similar energy minima corresponding to prolate and oblate shapes. The exact place where the shape transition is predicted depends on the details of the theoretical calculations [1].

The nature of the shape transition depends on the element [2]. For nuclei like Yb (Z=70) and Hf (Z=72) a sudden shape change is expected from well deformed prolate to oblate shape as more and more neutrons are added. In this case triaxiality plays little role. In tungsten, Z=74, isotopes a transitional region with high γ deformation or γ softness (depending of the theoretical calculation) is expected, centred on ^{190}W [1, 3, 4]. Osmium and especially in platinum isotopes the nuclei are more γ soft when compared with tungsten.

2. Recent experimental results

Despite the intense theoretical interest in the shape transitional Hf–W–Pt region, this is the part of the nuclide chart with the least information on neutron-rich nuclei. However, in the recent years a large amount of new experimental information was obtained. This is due to the

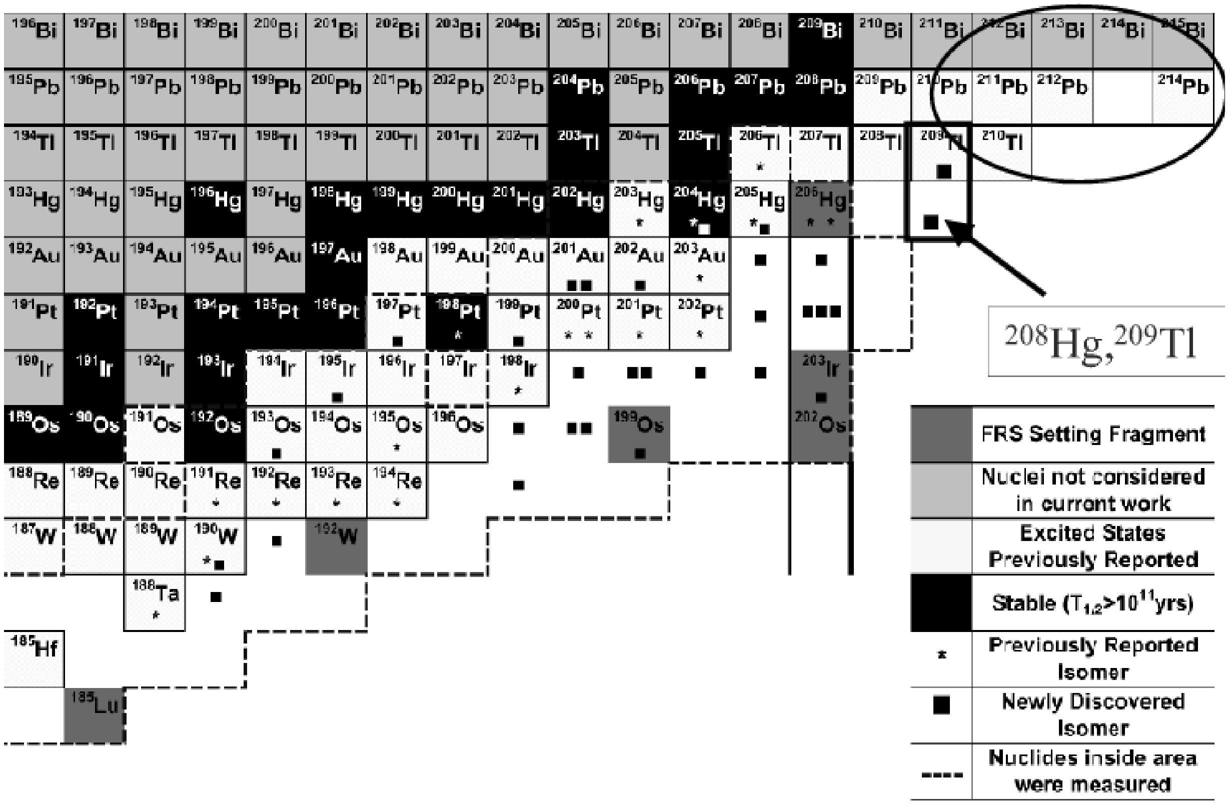

Figure 1. Section of the nuclide chart indicating isomeric states observed in experiments performed at GSI within the RISING [5] campaign. The results on nuclei inside the dashed line (N≤126) were reported in [6, 7]. The results on N=128 ^{208}Hg and ^{209}Tl were published in [8], while the N>126 lead nuclei were studied in [9].

possibilities opened up by the high sensitivity achievable in the isomeric decay experiments and the recent increase in relativistic-energy primary beam intensities.

Several experiments were performed using relativistic energy fragmentation reactions. Presently GSI is the only fragmentation facility where the primary beam energy is high enough, E/A=1 GeV, to obtain unambiguous identification of heavy, A>170, fragmentation products. The highest sensitivity is achieved using decay spectroscopy, both following internal decay and β decay. The majority of the recent results were obtained in isomeric decay experiments, where the technique is sensitive to isomeric decays with lifetimes in the $\sim$ 100 ns–100 μs region. The nuclei for which new results were obtained are shown in figure 1 and were published in references [6, 7, 8, 10, 11, 12, 13, 14]. Similar technique was used to obtain information following the β decay of nuclei [15, 20]. In addition, longer lived isomeric states were observed in storage ring experiments at GSI [16]. This technique is sensitive to isomeric states in excess of the cooling time, usually in the order of seconds. Storage ring experiments can measure the energy and the half-life of isomeric states, but no spectroscopic information can be obtained [17].

Deep-inelastic reactions provided information in the vicinity of the stability line [18, 19]. These studies in general are restricted to a maximum of two neutrons more than the stable isotopes, and often provide information on states at high angular momenta.

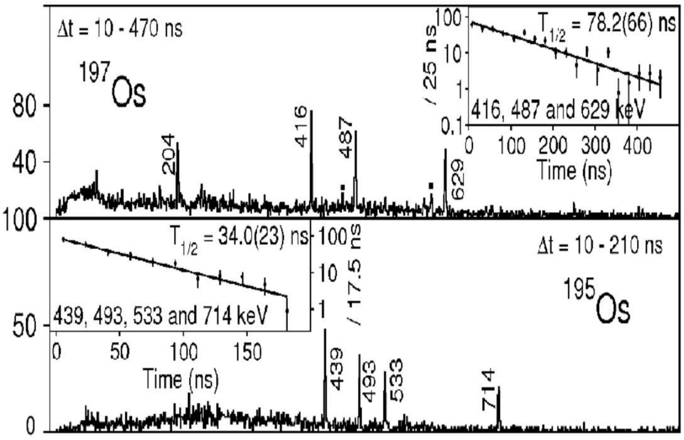

Figure 2. Delayed γ-ray spectra for ^{195}Os and ^{197}Os [7]. While the ^{195}Os spectrum exhibits a rotational band (439-493-533 keV), the ^{197}Os spectrum does not.

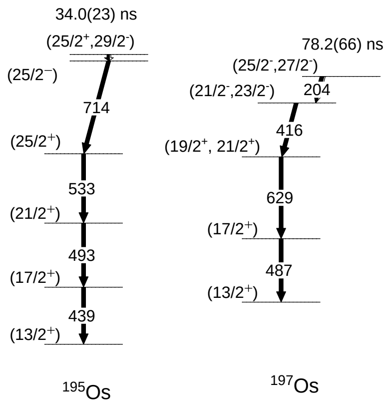

Figure 3. Level schemes of ^{195}Os and ^{197}Os [7]. ^{195}Os is interpreted to be prolate, while ^{197}Os is oblate.

3. Methodology

The experimental observables (γ-ray energies and lifetimes) together with simple theoretical considerations were used to infer the shape of nuclei. For simplicity, we assumed that a nucleus has a well defined shape, either oblate or prolate, which does not change with spin and excitation energy. The only exception is ^{194}Re, where β decays with three different lifetimes were observed and interpreted as originating from both prolate and oblate states [20]. Also, whenever possible we considered axially symmetric shapes only. This generally is a good approximation, however it is a simplification as we know that gamma deformation plays a role in the area, especially around ^{190}W [1, 2].

The projection of the angular momentum on the symmetry axis of the deformed nucleus is characterised by the K quantum number. In the A≈180 mass region the Fermi level is among high K orbitals in the case of prolate deformation and among low K orbitals for oblate shape. Consequently prolate nuclei are characterised by K=I isomeric states which usually decay into rotational bands. In the case of oblate nuclei such states are far from yrast and non isomeric. Here the isomers are rotationally aligned states. We note that in some cases, such as ^{202}Pt, it was possible to perform shell model calculations and understand the wave-function of individual states [7].

To demonstrate how the shape of nuclei was inferred, we consider the case of ^{195}Os and ^{197}Os. The observed delayed γ-ray spectra are shown in figure 2. The ^{195}Os spectrum exhibits three transitions which most likely form a rotational band, at energies of 439, 493 and 533 keV. BCS calculations predict K isomers with energies and spin-parities which explain the experimental spectrum (for details see [7]). Therefore ^{195}Os is prolate deformed, and the level scheme is shown in figure 3. In contrast, ^{197}Os does not exhibit a rotational spectrum, and its level scheme (figure 3) is very similar to those of the oblate platinum nuclei. Therefore ^{195}Os is considered to have oblate deformation [7].

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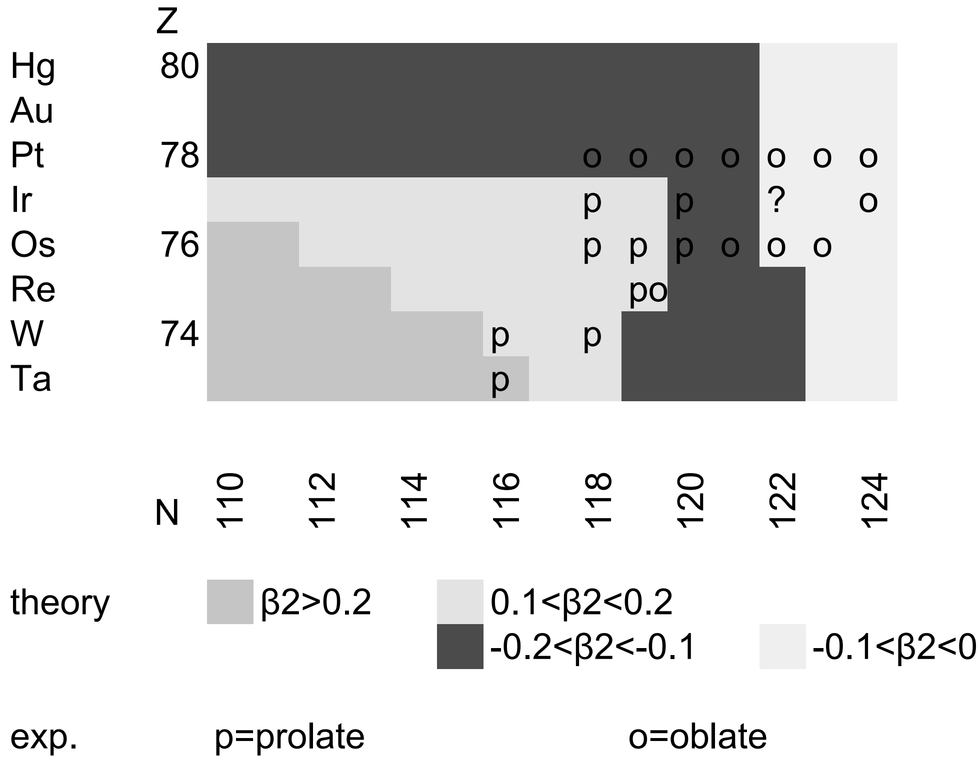

Figure 4. Comparison between experimental and theoretical quadrupole deformation. The theoretical results are from [24] and do not consider γ deformation.

4. Discussion

The heavy neutron-rich nuclei are subject of several region specific advanced theoretical studies. These are mainly based on microscopic-macroscopic Total Routhian Surface [3, 4] and mean-field [1, 2, 21] calculations, but also on interacting boson model where the parameters are determined from mean-field calculations [22] and projected shell model [23]. It is interesting to note the difference between the TRS and mean-filed calculation regarding the role of triaxiality. While mean-field calculations predict a triaxial shape [1] with minimum at $\gamma \sim 30°$ for ^{190}W, the TRS calculations predict two minima, one prolate and one oblate [3, 4]. No clear experimental evidence exists to chose between these two scenarios so far, although delayed X-rays recently observed in ^{190}W can be interpreted as supporting the shape coexistence picture [7].

Here the experimental findings are compared with two theoretical calculations. These representative theories were chosen because they were used to calculate the shapes of nuclei (in their ground-state) for the whole nuclid chart, including the odd- and odd-odd nuclei. The comparison with the calculations of Möller *et al.* [24] are shown in figure 4. These calculations are based on the finite-range droplet macroscopic model and the folded-Yukava single-particle microscopic model and does not consider traixiality [24]. The comparison of experiment with the calculations of Delaroche *et al.* [25] are shown in figure 5. This study used Hartree-Fock-Bogoliubov theory with Gogny D1S interaction. Five degrees of collectivity were considered, including triaxiality.

From figures 4 and 5 it is clear that the two calculations predict the prolate-oblate demarcation

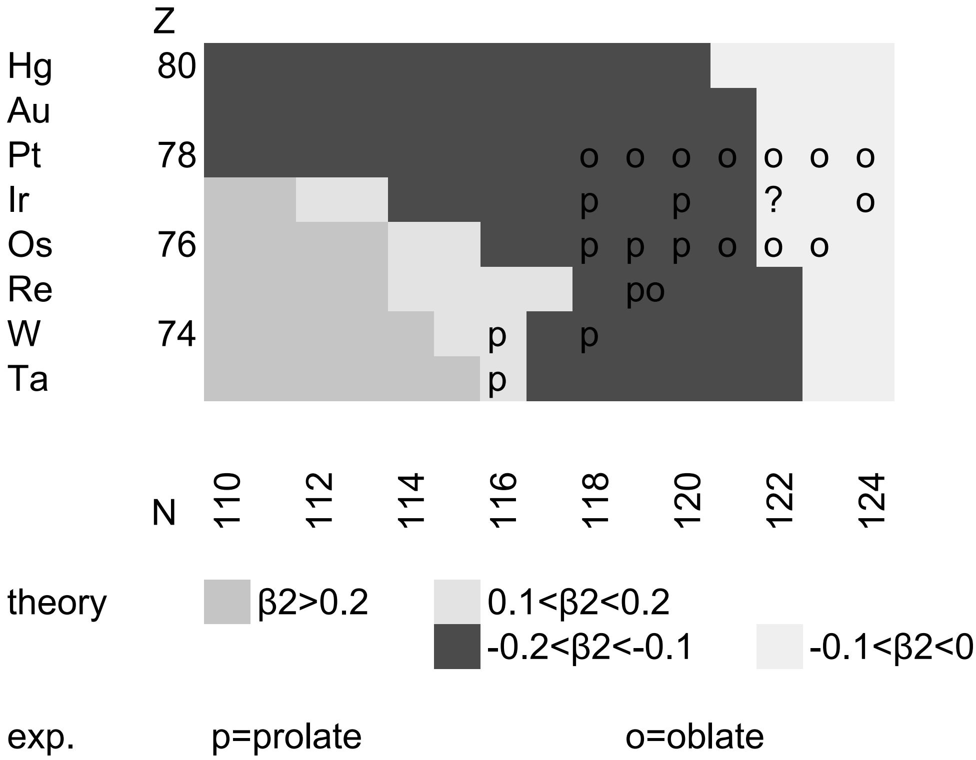

Figure 5. Comparison between experimental and theoretical quadrupole deformation. The theoretical results are from [25] and do consider γ deformation. The nucleus is considered prolate if $\gamma <30°$ and oblate if $60° > \gamma >30°$.

line in different places. The calculations of Delaroche *et al.* [25] predict a much larger number of oblate nuclei than Möller *et al.* [24]. Also, the demarcation line is close to perpendicular (constant N) in Möller *et al.*, while it is more neutron dependent in the other calculation. The experimental (sign of) deformations are more in line with the calculations of Möller *et al.*. However question marks remain. For example, the prolate nature of ^{198}Os is inferred from quite weak evidences (non-observation of an isomeric state) [7]. It is clear that in order to get a clear picture more experimental information is needed pushing the limits towards more neutron-rich nuclei, especially in the Hf-W nuclei where the region of oblate nuclei presently is not reached.

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