Mean-field approach to shape changes in the neutron-rich tungsten region

P. D. Stevenson and M. P. Brine
Department of Physics, University of Surrey, Guildford, GU2 7XH, UK

abstract

We present axially-deformed mean-field calculations of nuclides in the the vicinity of ^{190}W with a constraint on the quadrupolar deformation. While nuclei in this region are known to be gamma soft, the relative energies of the axially-symmetric global minimum, and the saddle point due to the first excited local minimum in the axially-constrained calculations give an indication of the extent to which the nuclides may be considered good rotors, gamma deformation notwithstanding. Calculations with a Skyrme interaction support the experimental observation that N=116 isotones fail to develop a stiff minimum as one decreases the proton number away from the closed shell. The calculations also suggest that heavier isotones will not become rigid rotors, in contrast with the separable interaction predictions, which suggest that heavier isotones will be oblate rotors for decreasing Z.

The region of the nuclear chart around ^{190}W (Z=74, N=116) lies southwest of the doubly-magic nucleus ^{208}Pb. Being a small number of proton and neutron holes away from closed shells means one should expect to find ground state oblate deformation, along with a transition to prolate ground states as one increases the number of holes towards the middle of the shell. This region is becoming accessible to experiment, with Coulex reactions giving data on the low-lying excited states [1].

The ratio of the energies of the first 4+ to the first 2+ state in a nucleus is an indication of its ground state shape. Nuclides spherical in their ground state show a characteristic harmonic vibration spectrum at low energy, with E(4+)/E(2+) close to value of 2.0 expected from a pure harmonic oscillator. Well-deformed nuclides, which can be described to a good approximation as rigid rotors in their low-energy behaviour yield a value of E(4+)/E(2+) close to the expected 3.33. The systematics of the E(4+)/E(2+) ratio in the region of interest are shown in Figure 1.

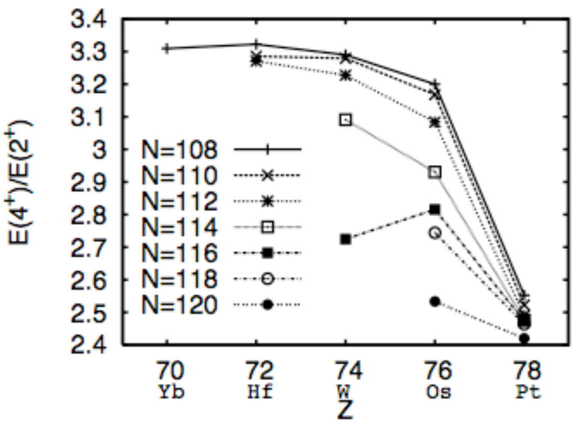

Figure 1: Ratio of observed energies of lowest lying 4+ to 2+ states. Data are from [1] and [2].

One clearly sees the transition from close-to-vibrational behaviour for the weakly-deformed platinum isotopes, 4 proton holes from the closed Z=82 shell, to good rotational behaviour as one decreases Z towards the middle of the shell. The data in this plot become more scarce as one increases neutron number and moves away from stability. The recently-determined data point for ^{190}W shows a deviation from the systematics, with an E(4+)/E(2+) ratio lower than for more proton-rich (and hence closer to a closed-shell) nuclide ^{192}Os. We recently analysed [3] the ground-state potential energy surfaces of the nuclei in this region using the separable monopole interaction [4]. That work confirmed that the failure of either the prolate or oblate configurations to become securely established as the lowest energy configuration, combined with the known softness in the gamma direction in this region led to the description of ^{190}W as a transitional nucleus, with a rather soft and presumably flat potential in the gamma direction. In the present paper, we re-analyse this region using a Skyrme mean-field calculation.

Skyrme forces are well-established as a reliable tool for use with the mean-field approximation and beyond-mean-field approaches across the nuclear chart for ground and excited state properties [5]. In the present work, the Skyrme parameterisation SkI4 [6] is used, which introduced an extended spin-orbit parameterisation to better fit isotope shifts in lead and calcium nuclides. It is therefore a particularly suitable choice for a systematic calculation of nuclear properties in the region under consideration. For a practical calculation of a large number of nuclides, the calculations are restricted to axial deformation, with a constraint on the value of β_2. Nuclei in this region are known, however, to be soft in the gamma degree of freedom [1]. In analysing the results of the axially-constrained calculations it is therefore important to remember that although the global minimum is an authentic minimum, higher-lying intrinsic axial minima are really saddle-points in the β-γ plane. An analysis of the potential energy curve should not therefore be made in terms of such quantities as the deformation energy (difference between spherical and deformed configurations) but instead the difference between what appear as the oblate and prolate minima is the key indicator as it gives the minimum barrier height in the gamma direction. If the axial calculation gives a large (say, several MeV) oblate-prolate energy difference then significant softness in the γ direction is not possible. Figure 2 shows the potential energy curves, with the lowest axial minima linked by the thick black lines.

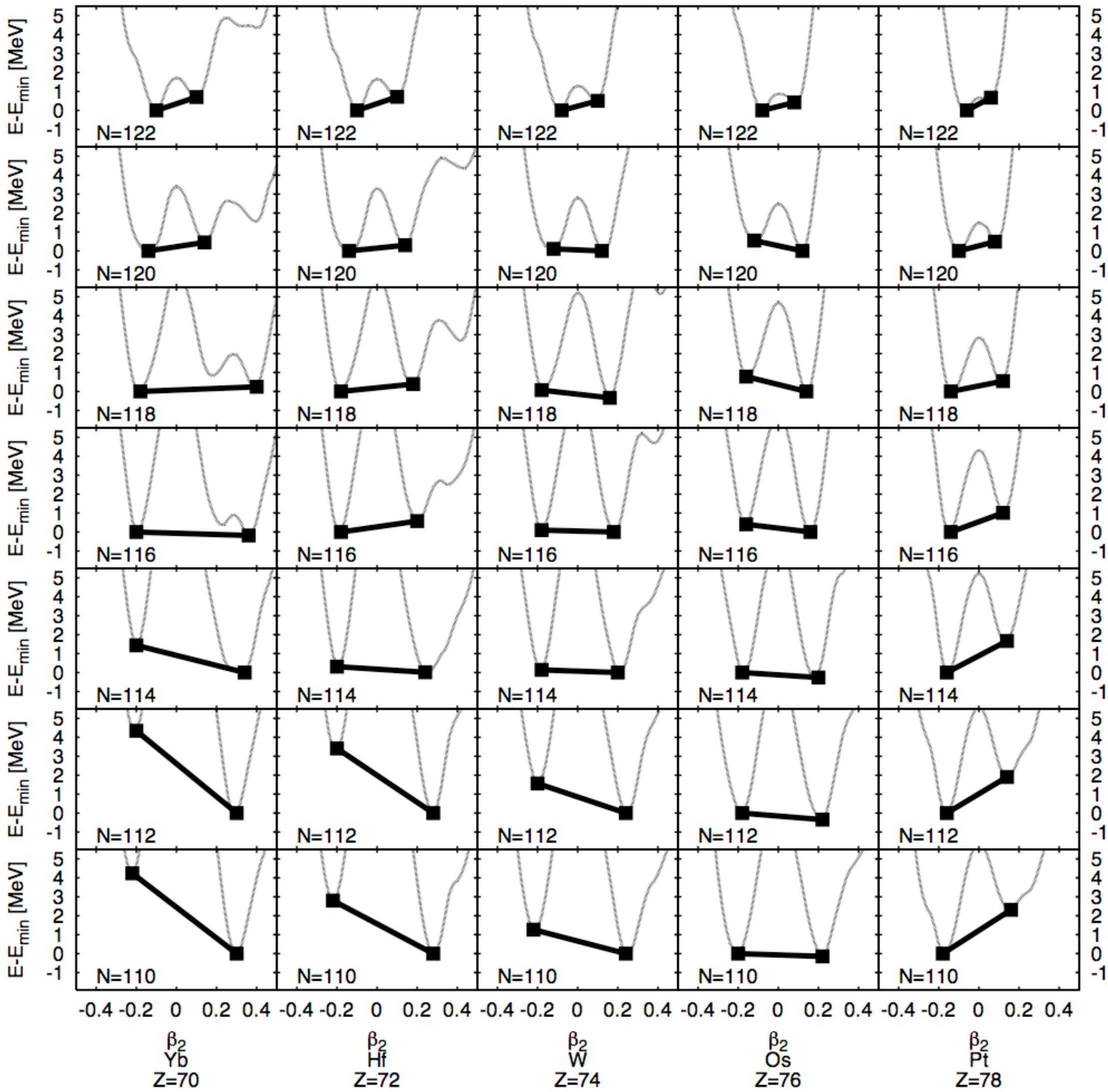

Figure: Potential Energy Surfaces as a function of β_2 as calculated with Skyrme force SkI4. The lowest two axial minima are linked by solid black lines. The lowest minimum is the true global minimum, while other minima are to be interpreted as saddle points in the β-γ plane.

Figure 2 shows that at as one is furthest from the closed shell at ^{208}Pb, i.e. at the bottom left of the plot, a well-defined prolate deformation is found, which even assuming maximal gamma softness must have a barrier of at least 4 MeV in the gamma direction. Looking in either the direction of fewer proton or neutron holes, or both, the slope of the solid line decreases until the oblate and prolate states compete for being ground state. Moving further to the right (fewer proton holes) or to the top of the plot (fewer neutron holes) oblate ground states dominate. An analysis of the data in this plot is shown in Figure 3. The calculations leading to Figure 3 repeat those of Figure 2 except that no constraint was used and the exact local minimum was sought. Since the constrained calculation had a discrete step in β_2, the details of which minimum lies lowest may be incorrect if they are close in energy. This is not in essence troubling, since a mean field calculation should only be taken as a qualitative guide when such closeness of minima is in evidence.

Figure 3 shows the perhaps surprising result that with SkI4 the ground state seems to be oblate in the N=118 and N=120 isotones for Yb and Hf, yet is prolate for the more proton-rich N=118 and N=120 isotones of W and Os. This is unlike the case of the similar analysis made with the separable monopole interaction [3], shown in the right-hand part of Figure 3, and seems to be due to competition between two different prolate minima in the lighter N=118 and N=120 nuclides (see Figure 2). Nevertheless, the results shown for the Skyrme forces in Figure 3 are in agreement with the experimental data shown in Figure 1. The isotopic chains for N=110-114, which show the development of rotational behaviour as Z decreases are seen to become uniformly prolate in the upper-left panel of Figure 3. The panel below shows that the minima for these three isotonic chains become reliably separated from the second minimum as Z decreases, confirming the onset of rigid rotation shown in Figure 1. The isotones from 116 upwards, on the other hand have global minima which lay never more than 500 keV from the opposite deformation intrinsic state.

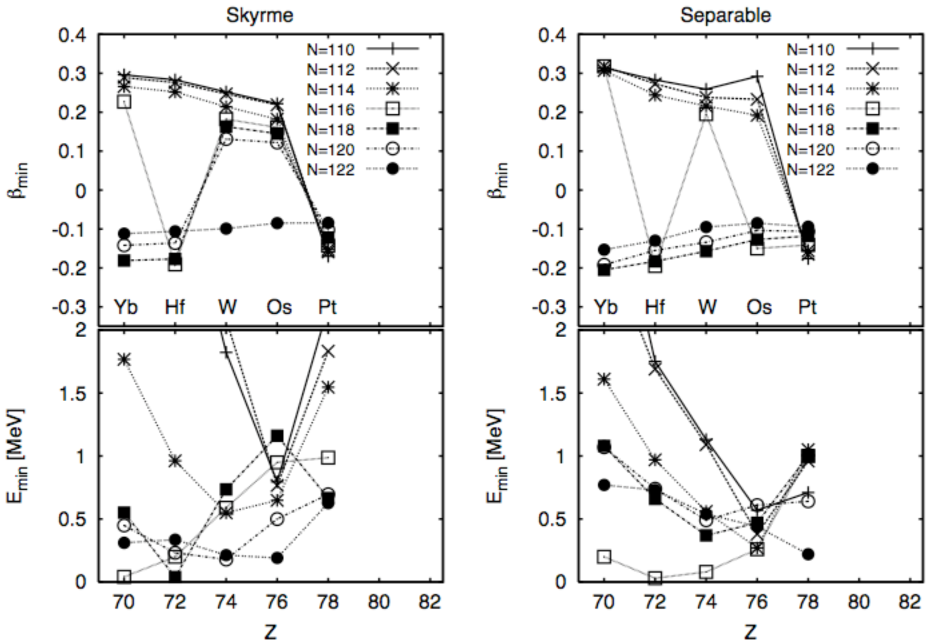

Figure 3: β_2 deformation of global minimum (upper plots) and absolute difference between true minimum and first excited axial minimum (lower plots). New results for the Skyrme force as described in this paper are on the left. Previous results with separable interaction are at the right (from [3]).

The main differences in Figure 3 between the Separable and Skyrme interactions occur for the neutron-rich isotopes of Yb and Hf that have yet to be observed. The separable interaction suggests that for isotones above N=116 a reasonably well-defined oblate ground state occurs. Forthcoming experiments in this region will therefore be valuable for discrimination between these mean-field approaches.

In summary, axially-deformed mean-field calculations have been made for nuclides in the vicinity of ^{190}W using Skyrme forces and the separable monopole interaction. The interpretation of the calculations has been made to account for the gamma-soft nature of these nuclei, and found to be in agreement with the experimental data, that the development of rigid rotation with decreasing proton numbers occurs for isotones about N=116 yet not for N=116. The predictions of the different theoretical models diverge as one moves to the as yet unobserved region.

References

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