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Properties and decay of actinide and transactinide nuclei

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Abstract

Recent theoretical results on the properties of the heaviest nuclei are presented and discussed. The main attention is paid to half-lives and to effects of the shell structure of these nuclei on the half-lives.

1. Introduction

The objective of the present paper is a discussion of recent theoretical results on the description and predictions of the properties of the heaviest nuclei. Such properties as equilibrium deformation, mass, α decay and spontaneous-fission half-lives are discussed. More discussion of these properties can be found in the other theoretical presentation [1] at this session and in wider recent theoretical reviews (*e.g.* refs. 2 and 3).

The main attention is paid to half-lives and particularly to effects of the shell structure of the nuclei in these half-lives. Even-even nuclei are considered. The theoretical studies described here are closely connected with the experimental research extensively discussed in this session of the conference [4–7].

2. Specific properties of the heaviest nuclei

2.1. Radioactivity

All nuclei of the considered region are unstable, radioactive. Even those lying on the β stability line decay by the α process and by spontaneous fission.

2.2. Deformation

Most nuclei of the considered region are, or are expected to be, deformed. This is because their outer nucleons fill up large nuclear shells. For protons, this is the shell between the last experimentally known magic number $Z=82$ and the theoretically predicted [8, 9] number $Z=114$. Thus, the shell is as large (32 protons) as the largest experimentally observed proton shell between $Z=50$ and 82. For neutrons, this is the shell between the last experimentally known magic number $N=126$ and the theoretically predicted [8, 9] number $N=184$. If the prediction is correct, this shell would be the largest neutron shell (58 neutrons) of all considered up to now. The largest experimentally observed shell is between the magic numbers $N=82$ and 126 (*i.e.* 44 neutrons).

2.3. Essential role of shell effects

Shell effects are important for all nuclei. Their significance for the heaviest nuclei is, however, essential, as many of them would not exist without these effects. This will be illustrated in the next section.

3. Shell effects

Strong shell effects are observed in such properties of the heaviest nuclei as mass, α decay energy, and α decay and spontaneous-fission half-lives. Here, we will illustrate them for the latter quantity.

Figure 1 shows [10] the logarithm of the spontaneous-fission half-lives: experimental and calculated within a macroscopic model without any shell effects. Thus, the difference between the two is the shell effect in the spontaneous-fission lifetime. Instead, however, of showing this difference directly, we show here the half-life itself, to see its values; in particular, to see how fast the half-life T_{sf} decreases with increasing atomic number Z. For example, the value calculated for the nucleus $^{260}106$ with $Z=106$ is by about 40 orders of magnitude smaller than the values obtained for nuclei with $Z=92$ (U).

The macroscopic calculation of T_{sf}, done here, consists in exploiting the widely used Yukawa-plus-exponential model [11], for the calculation of the fission barrier, and a smooth, phenomenological model [12, 13] for the calculation of the mass (inertia) parameter, which describes the inertia of a nucleus with respect to changes in its deformation.

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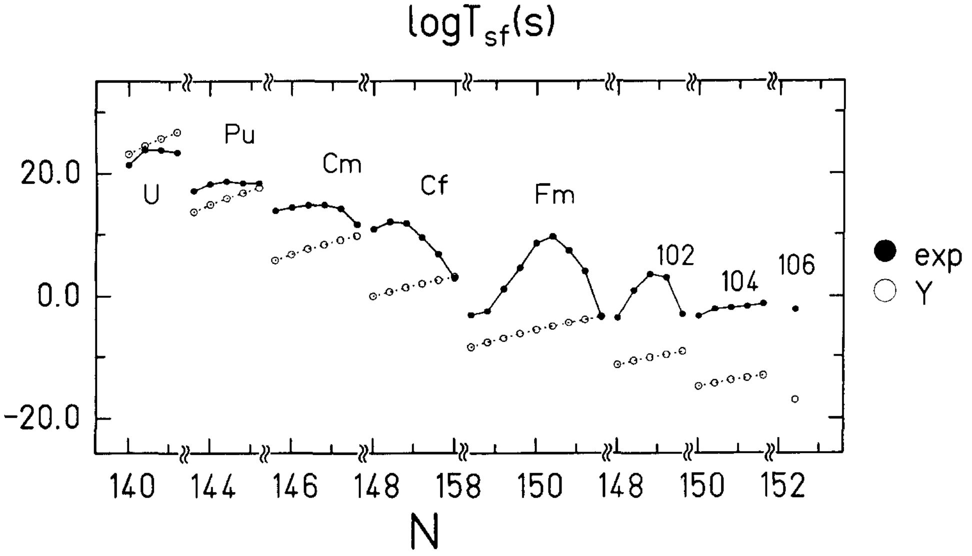

Fig. 1. Logarithm of experimental (●) and macroscopic (○) spontaneous-fission half-lives T_{sf} (s) [10].

One can see in Fig. 1 that the shell effect delays the fission process in all considered nuclei, except only a few of the lightest (isotopes of uranium). The delay increases from a few orders (Pu isotopes) to about 15 orders of magnitude for the heaviest even–even nucleus with measured T_{sf} (^{260}106). For such a heavy nucleus as ^{260}106 with T_{sf} of the order of a few milliseconds, this elongation makes up practically the whole half-life of these nuclei. In other words, they would not exist without shell effects.

4. Theoretical description and predictions

4.1. Method of the calculations

The main properties of the heaviest nuclei, in the description of which we are interested in the present paper, are mass, and α decay and spontaneous-fission half-lives.

Mass is calculated by the macroscopic–microscopic method with the Yukawa-plus-exponential model [11] taken for the macroscopic part of the mass. The Strutinski shell correction, used for the microscopic part, is based on the Woods–Saxon single-particle potential [14].

The α decay half-life T_α is calculated by the phenomenological formula of Viola and Seaborg [15] with the four adjustable parameters refitted [16] to account for new data.

Finally, the spontaneous-fission half-life T_{sf} is calculated in the dynamical way (*e.g.* ref. 17–19). It consists in the search for a one-dimensional fission trajectory in a multidimensional deformation space which minimizes the action integral corresponding to the penetration of the fission barrier. The inertia tensor appearing in the integral and describing the inertia of the nucleus with respect to its deformation is calculated in the cranking approach (*e.g.* ref. 20).

4.2. Some of the results

Figure 2 shows a map [21] of the shell correction E_{sh} to the potential energy. This correction is the gain in the potential energy of a nucleus due to its shell structure. One can see that the correction is negative in the whole region, *i.e.* it increases the binding of the nuclei. Starting from about 2 MeV (in absolute value), it systematically increases, to about 7 MeV, as one passes from the beginning of the region to about its end. The large value of E_{sh} obtained for nuclei around ^{270}Hs (*i.e.* ^{270}108) is connected with the new deformed shell at the neutron number $N=162$. The experimentally known deformed shell at $N=152$ manifests itself here by a shallow local minimum in the E_{sh} map. Crosses in the figure indicate the heaviest nuclei synthesized

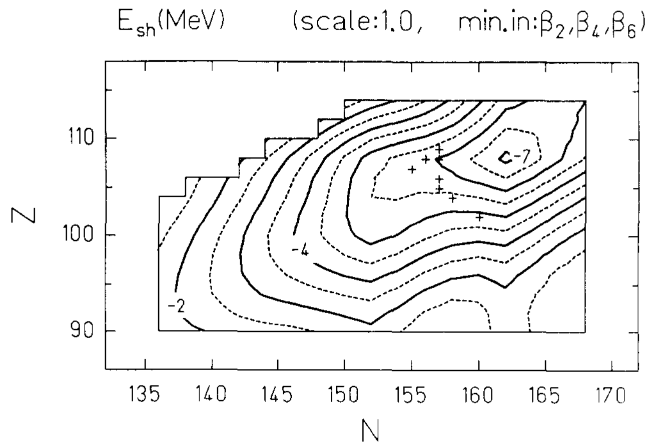

Fig. 2. Shell correction E_{sh} to the potential energy of nuclei [21].

up to now. One can see that these nuclei profit by about 5–6 MeV in their energy from the shell correction. Without this profit they could not exist, as was discussed in section 3. The recently observed nucleus $^{266}106$ [6, 22] is the closest to the nucleus ^{270}Hs with the largest shell correction E_{sh} predicted in Fig. 2. According to the figure, this nucleus should profit from the shell correction by more than 6 MeV in its binding energy.

A large shell correction to the energy of nuclei around the nucleus ^{270}Hs, seen in Fig. 2, indicates a formation of large shells in the single-particle energy spectra of these deformed nuclei. It is interesting then to see explicitly these spectra and also the effect on them of the dimension of the deformation space which is used to obtain them.

Figure 3 shows the dependence of the single-particle spectra of the nucleus ^{270}Hs on the maximal multipolarity λ_{max} of deformations allowed to the nucleus [21]. At each energy level, the projection 2Ω of spin (multiplied by 2) of the nucleus on the symmetry axis as well as parity π are indicated. One can see that a rather small gap at $Z=108$, in the proton spectrum, and a larger gap at $N=162$, in the neutron spectrum, are created by the quadrupole deformation $\lambda=2$. Both gaps are significantly increased, however, by the inclusion of the hexadecapole deformation $\lambda=4$: the gap at $Z=108$ is increased to about 1.2 MeV and that at $N=162$ to about 1.3 MeV. The inclusion of $\lambda=6$ does not practically change the gap at $Z=108$, but it still increases the neutron gap to about 1.4 MeV. The addition of $\lambda=8$ increases the proton gap to about 1.4 MeV, but it does not change the neutron gap. The further inclusion of $\lambda=10$ leaves the spectra practically unchanged.

Thus, large shells in both the proton and neutron spectra, similar to those observed in magic spherical nuclei, are obtained for the well-deformed nucleus ^{270}Hs. To obtain them, however, one needs to give to the nucleus enough freedom in choosing for it the deformation which is really the most confortable. The nucleus ^{270}Hs, not observed yet in experiment, may be expected then to be a double-magic deformed nucleus.

4.3. *Influence of the predicted deformed shell at N=162 on the half-lives*

As has been seen in the previous subsection, the large energy gap obtained in the neutron spectrum at $N=162$ (Fig. 3) has a strong effect on the shell correction E_{sh} to the energy of a nucleus (Fig. 2). It is interesting to see what is the influence of this shell structure of the neutron spectrum on the half-lives of very heavy nuclei. To this aim, the α decay and spontaneous-fission, half-lives, T_α and T_{sf} respectively, have been calculated as functions of the neutron number N for the elements with $Z=104$ and 106.

Figure 4 shows the half-lives for $Z=104$ [23]. One can see the effects of both shells, at $N=152$ and 162, in both the half-lives. The effect of the shell at $N=152$ is smaller. This shell manifests itself more strongly in lighter elements (around Fm). The effect of the shell at $N=162$ is larger. One can also see that, for all isotopes of the element 104, the calculated T_{sf} is smaller than T_α. It is smaller by only less than one order of

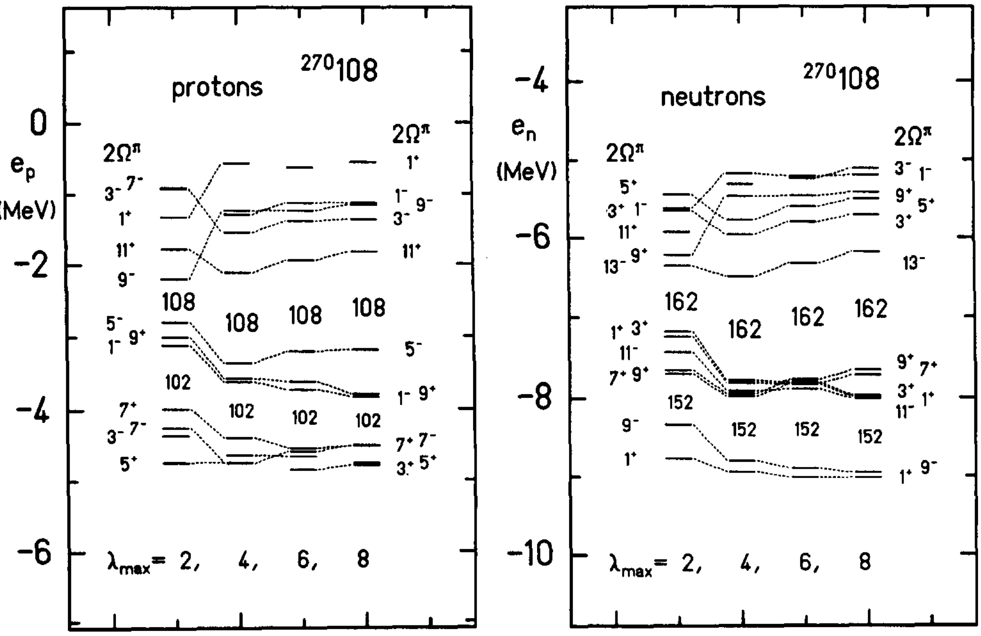

Fig. 3. Proton and neutron spectra of the nucleus ^{270}Hs as functions of the maximal multipolarity λ_{max} of the deformations allowed to it [21].

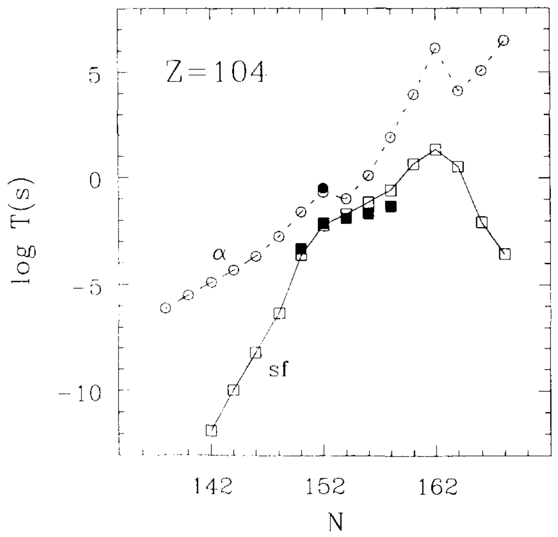

Fig. 4. Dependence of logarithm of the α decay and spontaneous-fission half-lives (given in seconds) on the neutron number N for the element with $Z=104$ [23].

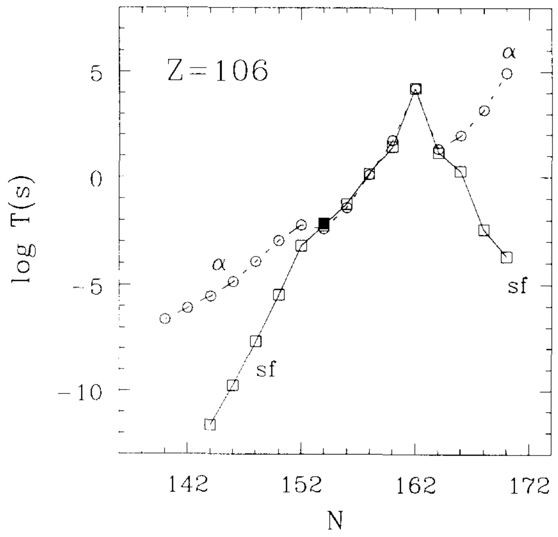

Fig. 5. Same as in Fig. 4, but for the element with $Z=106$ [24].

magnitude for the isotope with $N=154$ but by as much as about seven orders of magnitude for the lightest ($N=142$) and the heaviest ($N=166$) isotopes, for which both half-lives have been calculated. Thus, only spontaneous fission is practically expected to be observed for these light and heavy isotopes.

Figure 5 [24] gives the results for the element 106. Here, the effect of the $N=162$ shell is even stronger than that for $Z=104$, probably because we are closer to the expected double-magic deformed nucleus ^{270}Hs, and the effect of the proton closed shell at $Z=108$ also contributes. The calculated fission half-live T_{sf} (as well as T_α) for the nucleus ^{268}106 is of the order of 10^4 s (around 3 h) and is larger than the half-life T_{sf} of any isotope of the element 104. In particular, it is

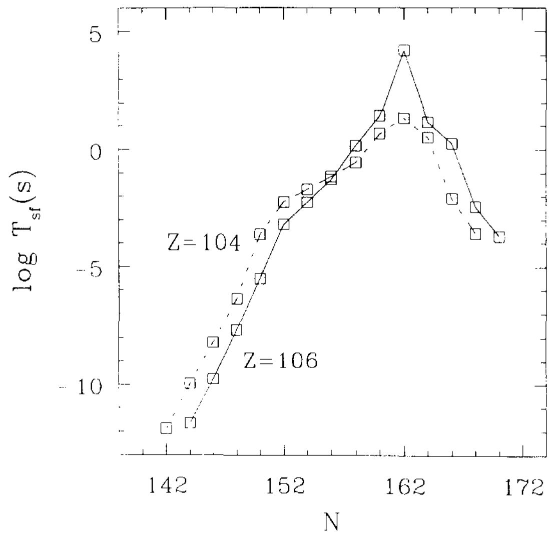

Fig. 6. Comparison between the spontaneous-fission half-lives T_{sf} calculated for nuclei of the elements 104 and 106.

by more than 3 orders of magnitude larger than T_{sf} of the nucleus ^{266}104.

Thus, because of large shell effects in these deformed nuclei, strong deviations are expected from the rule that the fission half-life T_{sf} decreases with increasing atomic number Z. This is directly shown in Fig. 6. One can see that the calculated half-lives T_{sf} for $Z=106$ are lower than those for $Z=104$ only for light isotopes of these elements. For the isotopes with N around 162 and heavier, the relation reverses.

This also illustrates the importance of shell effects in the properties of the heaviest nuclei and also a complexity of the half-life systematics expected for them. These expectations, however, have to be verified by experiment.

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