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Ground-state properties of superheavy elements in macroscopic-microscopic models

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Abstract. Masses, α-decay and spontaneous fission half-lives of superheavy elements are studied in macroscopic-microscopic approaches with two different macroscopic models and the delta-pairing interaction. Model mass deviations obtained with different formulae are 0.5–0.8 MeV.

PACS. 21.10.Dr Binding energies and masses – 21.30.-x Nuclear forces – 25.85.Ca Spontaneous fission – 21.10.Tg Lifetimes

1 Theoretical models

In the presented paper we examine masses, α-decay and spontaneous fission half-lives of superheavy elements studied in macroscopic-microscopic (M-M) models. The macroscopic part of the energy is either the Lublin-Strasbourg Drop (LSD) model introduced in ref. [1], which in addition to the volume, Coulomb and surface terms contains the first-order curvature term, or the *traditional* formula of Myers and Swiatecki but with an estimate for the congruence energy and parametrs fitted to all presently known masses (dubbed as Refitted Liquid Drop-RLD) [1]. The microscopic part, consisting of the sixth-order Strutinsky shell correction and the pairing correction based on the δ-force, is evaluated with single-particle spectra generated in a Woods-Saxon potential with the *universal* set of parameters [2]. The pairing energy is calculated in the BCS or Lipkin-Nogami approaches with a blocking effect in case of odd nuclei.

The pairing interaction is of the form of the zero-range delta force:

$$\hat{V}^{\delta}(\boldsymbol{r}_1, \boldsymbol{r}_2) = -V_{0n|p} \frac{1 - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2}{4} \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2). \qquad (1)$$

The coupling strength parameters (V_{0n}, V_{0p}) are chosen to obtain the best mass formula without any increase of the usual number of parameters of the M-M model. Two fits of the coupling strengths are performed:

1. Constant pairing strengths are found for 258 even-even, odd-even and odd-odd nuclei with $Z \geq 98$, the same values for all combinations of the macroscopic and microscopic parts of the energy. The calculations are performed in a truncated single-particle space containing N levels for neutrons and Z levels for protons. The optimal values, equal for all macroscopic (RLD or LSD)-microscopic (BCS or Lipkin-Nogami) approaches, are

$$V_{0n} = 220\,\mathrm{MeV\,fm}^3, \qquad V_{0p} = 230\,\mathrm{MeV\,fm}^3.$$

2. The δ-pairing strength can be approximated with the following formula [3]:

$$V_0 = \frac{\hbar^2}{m} 2\pi^2 \frac{1}{\pi/2a + k_c}, \quad k_c = \sqrt{2m\epsilon_c/\hbar^2}, \qquad (2)$$

where m is the mass of a nucleon, a is the experimental scattering length of the nucleon-nucleon interaction and ϵ_c is the cutoff energy. In our calculations we have used a renormalized form of V_0 given by eq. (2), namely $V_{0n|p} = wV_0$. The value of w was determined in a fitting procedure to be equal to 0.4 in the case of the WS potential at the cutoff energy $\epsilon_c = e(N, Z) - e(1)$, e being the single-particle energy of the N-th, Z-th or the first level, respectively.

In the calculations of spontaneous fission half-lives the potential energy is determined using the LSD formula as it gives higher accuracy for the fission barriers than other models [1] and results in half-lives being closer to experimental data for heavy nuclei than the RLD model [4]. The fission process of a nucleus is described as a tunnelling through the collective potential barrier in the WKB approximation. In order to minimize the action entering the fission probability we have used the dynamic programming method [5]. The potential energy and all the components of the tensor of inertia (evaluated in the adiabatic cranking model) are calculated on a deformation mesh defined as follows $\beta_2 = 0(0.05)1.2$, $\beta_4 = -0.12(0.04)0.32$, $\beta_6 = -0.12(0.04)0.12$. The other degrees of freedom (*e.g.*,

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Table 1. Standard mass deviations, model mass deviations and model mean errors resulting from M-M calculations. Index "C" means the pairing strengths do not differ from one nucleus to another.

MODEL	$\sigma_{\rm rms}$ (MeV)	$\sigma_{\rm mod}$ (MeV)	$\mu_{\rm mod}$ (MeV)
RLD + BCS$_C$	0.80	0.64	−0.18
RLD + LN$_C$	0.85	0.68	−0.31
LSD + BCS$_C$	0.89	0.75	−0.11
LSD + LN$_C$	0.94	0.79	−0.26
RLD + BCS	0.69	0.52	−0.09
RLD + LN	0.67	0.51	−0.16
LSD + BCS	0.78	0.62	−0.03
LSD + LN	0.75	0.61	−0.13

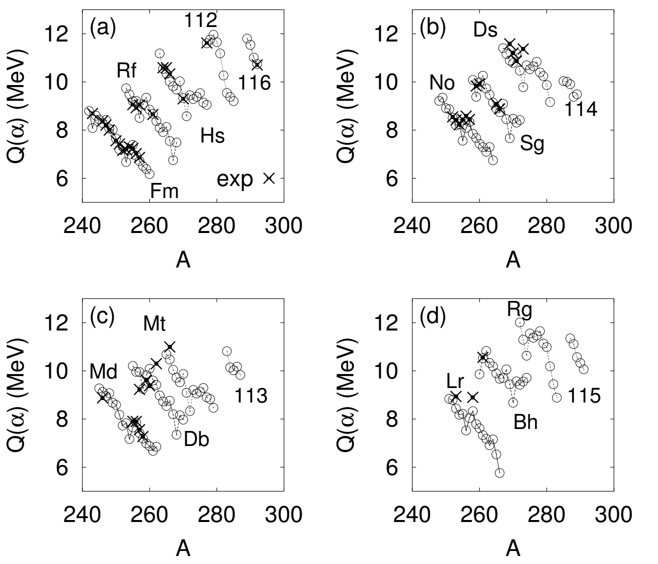

Fig. 1. α-decay energies calculated in the LSD + BCS model (circles) in comparison to experimental data [6] (crosses) for even-Z (panels (a) and (b)) and odd-Z (panels (c) and (d)) superheavy nuclei.

odd-multipolarity deformations) are not taken into account as they are of a minor importance in this type of calculations for superheavy nuclei.

2 Results

In table 1 we list resulting rms deviations for the masses calculated in different M-M models as compared to the experimental measurements and predictions of Audi and Wapstra [6]. Due to the large experimental mass uncertainties (up to 1 MeV for the heaviest nuclei) for a better assessment of the validity of our mass formula we give as well the model standard deviations ($\sigma_{\rm mod}$) and model mean errors ($\mu_{\rm mod}$), defined as in [7]. Taking into account only the nuclei with $Z \geq 98$ for which the experimental mass was measured we obtain a model mass error of 0.45–0.55 MeV, depending on the M-M approach.

In fig. 1 the α-decay energies calculated in the LSD + BCS model are shown in comparison to experimental data [6]. The rms deviation for Q_α is about 0.5 MeV. Figure 2 shows the spontaneous fission as well as the α-decay half-lives (according to the empirical formula from ref. [8]) of $Z = 110$–116 isotopes calculated in the LSD + BCS model as well as the recent experimental data measured in Dubna [9].

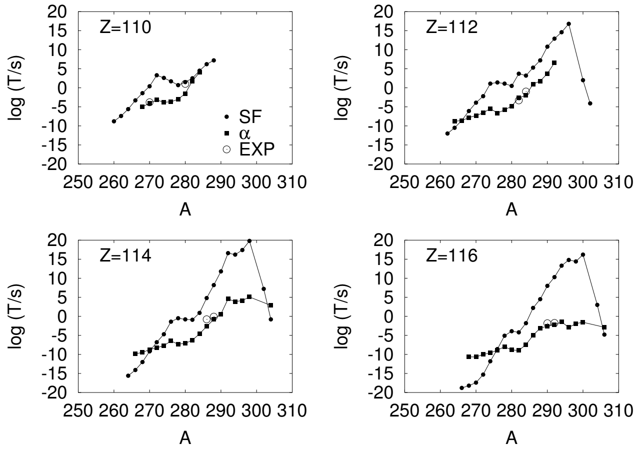

Fig. 2. Spontaneous fission and α-decay half-lives of $Z = 110$–116 elements calculated in LSD + BCS model.

3 Summary

The conclusions of our study are the following:
i) The M-M mass formulae provide an effective method to describe the binding energies of the heaviest elements. Both liquid drop models, RLD and LSD, give similar rms mass deviations so the curvature terms are of no importance in calculations of equilibrium mass.
ii) Using the zero-range pairing force of the δ-type allows to reproduce nuclear masses to a high accuracy by fitting only two coupling strengths for all considered nuclei.
iii) The M-M model based on the LSD macroscopic part and the state-dependent δ-pairing correction is an appropriate approach to study simultaneously masses and α and spontaneous fission decays of heaviest nuclei.

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