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Pre-Scission Model Calculation of Fission Fragment Mass and Total Kinetic Energy Distributions for Even-Even Fm, No and Rf Isotopes

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Abstract. The main properties of the fission fragments in spontaneous fission of even-even isotopes of Fm ($Z=100$), No ($Z=102$) and Rf ($Z=104$) are estimated using a pre-scission point model. The underlying potential energy surfaces are calculated with Strutinsky's shell correction procedure. The parametrization of the nuclear shapes is based on Cassini ovals generalized by the inclusion of three additional shape parameters: α_1, α_4 and α_6 . It represents a natural way to describe scission configurations. The corresponding fragment-mass distributions are estimated supposing they are due to thermal fluctuations in the mass asymmetry degree of freedom. A detailed comparison with all existing data for Fm, No and Rf isotopes is presented. For these three series of isotopes the experimentally observed transition from asymmetric to symmetric fission, that happens with increasing mass number A , is well reproduced. In lighter isotopes (e.g. ^{254}Fm and ^{254}Rf) two mass-asymmetric fission modes are predicted to occur with comparable yields: one having relatively compact and the other relatively elongated scission configurations. On the other hand, in heavier isotopes (e.g. ^{264}Fm and ^{264}Rf) the fragment-mass distributions are predicted to be narrow single-peaked around $A/2$ corresponding to essentially one compact fission mode. We call this type of fission "super-symmetric". The corresponding distributions of the total kinetic energy of the fragments are also calculated (in the point-charge approximation) and compared with measurements. Despite the fact that the dynamical effects were neglected, we have obtained a quantitative agreement with the experimental data.

1. Introduction

The scission-point model [1] was recently improved and used to calculate fission-fragment mass and total kinetic energy distributions for Fm, No, Rf and Sg isotopes [2].

The scission process (from the beginning of the neck rupture at finite radius ($r_{neck} \approx 2.0$ fm) till the total absorption of the neck stubs by the fragments) is extremely fast [3]. During this transition the mass distribution is frozen and the distance between the centers of mass of the nascent fragments D_{cm} stays practically unchanged. It is therefore "just-before scission" that the above mentioned fission-fragment properties have to be estimated (and not when the fragments are already separated). This is the first improvement brought to the traditional approach.

The second improvement concerns the description of the corresponding pre-scission shapes in the lemniscate coordinate system (R, x) [4]. It is most convenient since the basic lines $R=\text{const}$ (defined by a parameter ϵ) represent a sequence of shapes (Cassinian ovals) that are surprisingly



close to the sequence of shapes of a fissioning nucleus. Therefore some of these ovals represent two nascent fragments separated by a thin neck. The expansion of such particular ovals in series of Legendre polynomials is used to generate the nuclear shapes along the scission line. Apart from the elongation parameter ϵ , in present work two other relevant shape parameters are included: α_1 (the mass asymmetry) and α_4 (the neck radius). In addition minimization with respect to α_6 is performed.

This improved model was able to describe the observed transition from asymmetric to symmetric fission that occurs, for the above mentioned isotopes, when the mass of the fissioning nucleus increases. A natural continuation of this study would be to make a direct comparison of all existing experimental distributions for the spontaneous fission of Fm, No and Rf isotopes with the model predictions and this is the object of the present work. As a results we will infer how reliable is to apply the model in the unexplored region of even heavier nuclei [5].

2. Computational details

As mentioned above, the variety of the pre-scission shapes involved are expansions of selected Cassini ovals in series of Legendre polynomials $P_n(x)$,

$$R(x) = R_0[1 + \sum_n \alpha_n P_n(x)], \quad (1)$$

where R_0 is the radius of the spherical nucleus and α_n are shape parameters [4].

Instead of elongation ϵ it is convenient to introduce a new parameter α [4] such as a zero neck shape has always $\alpha=1.0$ irrespective of the α_n values. α slightly smaller than 1.0 corresponds to two fragments connected by a thin neck. In [2] and here we choose $\alpha=0.98$ [6].

With this shape parametrization [Eq. (1)] we calculate the potential energy of deformation using the microscopic - macroscopic approach [7]:

$$E_{def} = E_{def}^{LD} + E_{shell} \quad (2)$$

where E_{def}^{LD} is the macroscopic liquid-drop energy and E_{shell} contains the microscopic shell and pairing corrections calculated with a Woods-Saxon type potential and parameters from [8].

Keeping $\alpha = 0.98$ we calculate the potential energy of deformation as a function of the chosen shape parameters. First we use α_1 (which introduces a left-right (mass) asymmetry in the scission shape) and α_4 which, acting on the quadrupole deformation of each fragment, makes the scission shapes more compact ($\alpha_4 < 0$) or more elongated ($\alpha_4 > 0$). Next we add α_6 and minimize the potential energy surfaces with respect to it.

Each point $(\alpha_1, \alpha_4, \alpha_6)$ on these surfaces has a certain probability to be realized. Supposing statistical equilibrium for the collective degrees of freedom normal to the fission direction [9], the distribution of these probabilities is

$$P(\alpha_1, \alpha_4, \alpha_6) \propto e^{-E_{def}(\alpha_1, \alpha_4, \alpha_6)/T_{coll}}. \quad (3)$$

Projecting on the α_1 axes

$$Y(\alpha_1) = \sum_i P(\alpha_1, \alpha_{4i}, \alpha_{6i}) / \sum_{ij} P(\alpha_{1j}, \alpha_{4i}, \alpha_{6i}), \quad (4)$$

one obtains the fission fragment mass distribution since α_1 determines the mass asymmetry $\eta = (A_F^H - A_F^L)/A$.

T_{coll} is an unknown parameter that controls the overall width of the distribution. It is however E_{def} that determines the main features of the calculated distribution: the most probable masses and the relative intensities of the fission modes. In particular it is the stiffness $\partial^2 E_{def} / \partial \eta^2$ that

controls the stability against variation of the number of nucleons in the fragments, i.e., their relative widths. Smaller or larger T_{coll} values can only reveal or washout the E_{def} structures.

Finally for each shape defined by $(\alpha_1, \alpha_4, \alpha_6)$ one calculates the distance between the centers of mass of the nascent fragments D_{cm} . Then one estimates, in the point-charge approximation, the Coulomb interaction of the fragments supposing uniform charge densities $Z_L/Z_H = A_F^L/A_F^H$.

$$E_{coul}^{int} = e^2 Z_L \times Z_H / D_{cm} = TKE \quad (5)$$

if one neglects TKE_0 , the kinetic energy in the fission direction at $\alpha = 0.98$.

The TKE distribution is obtained using the formula:

$$Y(TKE) = \sum_j \sum_i P(\alpha_{1j}, \alpha_{4i}, \alpha_{6i}) \times \exp[-(TKE_{ij} - TKE)^2 / \Delta E^2] / (\Delta E \sqrt{\pi}) \quad (6)$$

that accounts for the finite energy resolution through the parameter ΔE . The $P(\alpha_{1j}, \alpha_{4i}, \alpha_{6i})$ are the Boltzmann factors given by Eq. (3). The value of ΔE was chosen to be equal to 20 MeV. It corresponds to an experimental energy resolution with a FWHM = 16 MeV.

3. Comparison with existing experimental data

Numerous studies of fission fragment properties in the spontaneous fission of trans-einsteinium isotopes have been performed in the 80's. These nuclei were obtained as evaporation residues in fusion reactions of light ion beams with actinide targets. Refs. [10, 11, 12, 13, 14, 15] are only few examples. The measured mass and total kinetic distributions for Fm, No and Rf isotopes

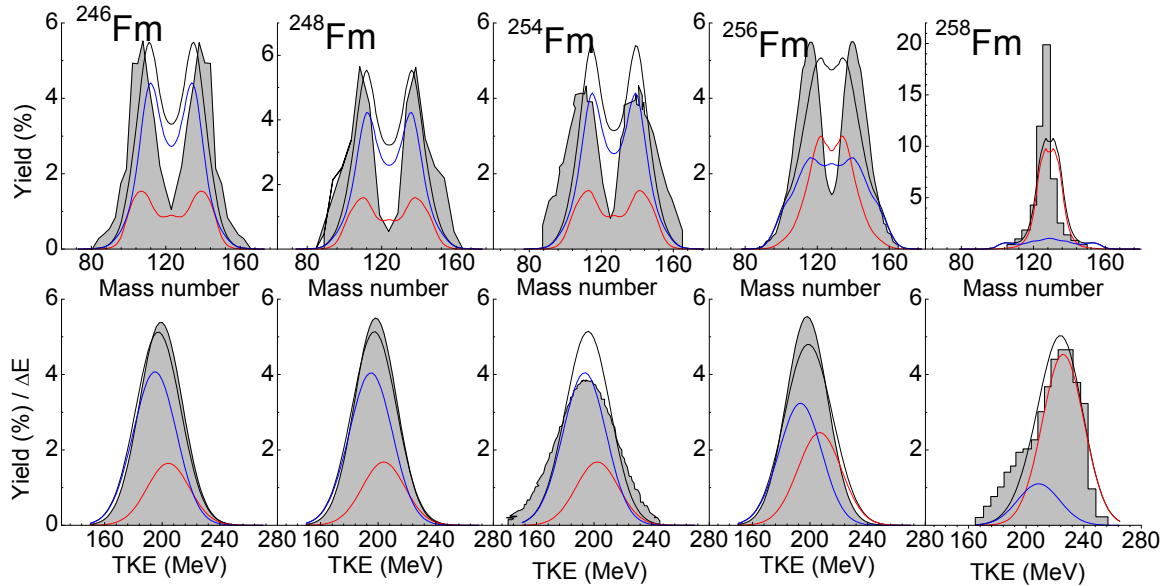


Figure 1. Experimental (histogram) and calculated (black) fragment mass and TKE distributions for even-even Fm isotopes. The red and blue curves represent the compact and the elongated modes respectively. The parameters of the averaging of the energy distributions are: $T_{coll} = 1.0$ MeV, $TKE_0 = 15.0$ MeV and $\Delta E = 20.0$ MeV for ^{258}Fm and $T_{coll} = 2.0$ MeV, $TKE_0 = 0$ and $\Delta E = 20.0$ MeV for the rest of the rest of the isotopes.

are compared with pre-scission model calculations in Figs. 1-3 respectively. It is worth noting that except for the ^{258}Fm the same values of the model parameters ($T_{coll} = 2.0$ MeV, $TKE_0 = 0$ and $\Delta E = 20.0$ MeV) are used for all nuclei. The agreement is surprisingly good taking into

account the simplicity of the theoretical approach. Small differences are however noticeable. For Fm isotopes the transition from asymmetric to symmetric fission is not as sharp as observed. For No and Rf isotopes the TKE's are slightly overestimated.

The compact-symmetric narrow peak observed for ^{258}Fm could not be reproduced using the same model parameters as for the rest of the nuclei. In order to explain the data we need to vary T_{coll} and TKE_0 . The nucleus ^{262}Rf is the heaviest even-even nucleus for which the spontaneous fission properties have been measured [16]. As it is seen in Fig. 3, our calculations agree also with these most recent data. The mass distributions for Fm isotopes are most difficult to explain quantitatively (see Fig. 3). From ^{246}Fm to ^{256}Fm the measured distributions have

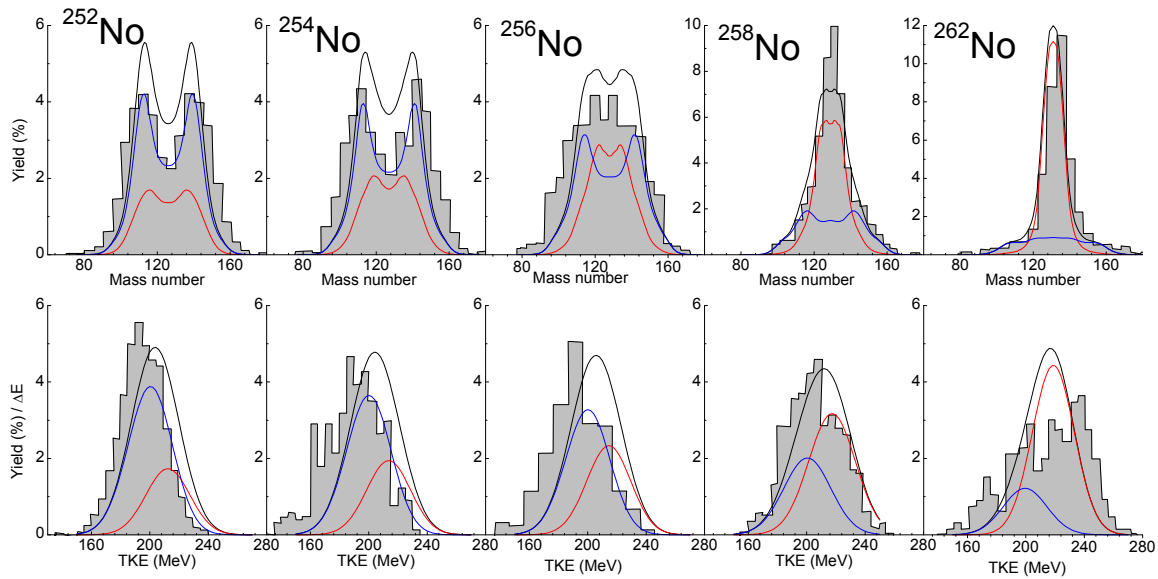


Figure 2. The same as in Fig.1 for No isotopes. The parameters of the averaging of the energy distributions are: $T_{coll} = 2.0$ MeV, $TKE_0 = 0$ and $\Delta E = 20.0$ MeV.

two equally pronounced peaks while the calculations show a transition from two separated to two overlapping peaks.

Few comments on the agreement with data are appropriate. One should not attempt to reproduce every details of the mass distributions since they are sensitive to relative variations of the potential energy E_{def} of the order of 0.2 MeV and no model can achieve such precision. Concerning the sharp transition from ^{256}Fm to ^{258}Fm , it has not been quantitatively explained so far. As it was pointed out from the beginning [13], all fission models (including the Strutinsky's procedure used here) tend to average over the contributions of several Nilsson levels and therefore are incapable to describe abrupt changes from one nucleus to its neighbor.

4. Summary and conclusions

The main properties of the fission fragments in spontaneous fission of even-even isotopes of Fm, No and Rf are estimated using the pre-scission point model. The underlying potential energy surfaces are calculated with Strutinsky's shell correction procedure in a three dimensional deformation space.

The parametrization of the nuclear shapes chosen here is based on generalized Cassini ovals and represents a natural way to describe scission configurations. We think it is this choice that allows us to explain, with only three shape parameters, the observed features.

Despite the fact that the dynamical effects were neglected, we have obtained quantitative agreement with the experimental data. These nuclei are the heaviest spontaneous fissioning

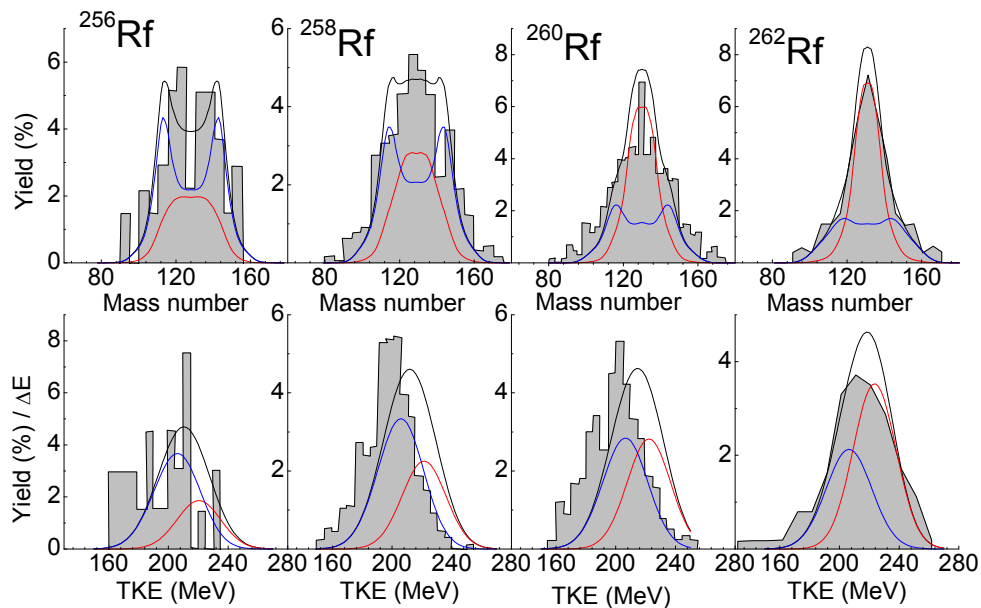


Figure 3. The same as in Fig.1 for Rf isotopes. The parameters of the averaging of the energy distribution are: $T_{coll} = 2.0$ MeV, $TKE_0 = 0$ and $\Delta E = 20.0$ MeV.

nuclei for which fission fragment properties have been measured. It is therefore safe to use the model in the unexplored region of super-heavy nuclei ($Z \geq 110$) [5] and this is our next project.

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