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The Scission Point Configuration and the Multiplicity of Prompt Neutrons

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Abstract

We defined the optimal shape which fissioning nuclei attain just before the scission and calculated the deformation energy as function of the mass asymmetry and elongation at the scission point. The calculated deformation energy is used in quasi-static approximation for estimation of the mass distribution of fission fragments, total kinetic and excitation energy of fission fragments, and the total number of prompt neutrons. The calculated results reproduce rather well the experimental data on the position of the peaks in the mass distribution of fission fragments, the total kinetic and excitation energy of fission fragments. The calculated value of neutron multiplicitiy is somewhat larger than experimental results.

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1. Introduction

In the theory of nuclear fission the quasistatic quantities like the potential energy surface, the ground state energy and deformation, and the fission barrier height are commonly calculated within the macroscopic-microscopic method Strutinsky (1966); Brack et al. (1972). In this method the total energy of the fissioning nucleus consists of two parts, macroscopic and microscopic. Both parts are calculated at a fixed shape of the nuclear surface. In the past a lot of shape parameterizations were proposed and used. A good choice of the shape parameterization is often a key to the success of the theory. Usually, one relies on physical intuition for the choice of the shape parameterization.

A method to define the shape of the nuclear surface which does not rely on any shape parameterization was proposed by V. Strutinsky in Ref. Strutinsky et al. (1963). In this approach the shape of an axial, left-right symmetric nucleus was defined by looking for the minimum of the liquid-drop energy under the additional restrictions that fix the volume and elongation of the drop.

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Recently the method was further developed by incorporating the axial and left-right asymmetry, and the neck degree of freedom of the nuclear shape, see Ivanyuk (2014) and references therein.

The important result of the Strutinsky procedure Strutinsky et al. (1963) is the possibility to definite in a formal way the scission point as the maximal elongation at which the nucleus splits into two fragments.

Having at one's disposal the shape and the deformation energy at the scission point we evaluated the measurables of the fission experiments: the mass distribution, total kinetic and excitation energy of fission fragments, and the multiplicity of prompt neutrons.

2. Optimal shapes

In Strutinsky et al. (1963) the shape of nucleus is described by rotation of some profile function $\rho(z)$ curve around the z-axis. A formal definition of $\rho(z)$ was obtained looking for the minimum of the liquid-drop energy, $E_{\rm LD} = E_{\rm surf} + E_{\rm Coul}$, under the constraint that the volume V and deformation R_{12} are fixed,

$$\frac{\delta}{\delta\rho}\Big[E_{\rm LD} - \lambda_1 V - \lambda_2 R_{12}\Big] = 0, \quad \text{with} \quad V = \pi\int_{z_1}^{z_2}\rho^2(z)dz\ , \quad R_{12} = \frac{2\pi}{V}\int_{z_1}^{z_2}\rho^2(z)|z|dz\ . \tag{1}$$

The deformation parameter R_{12} was chosen in Strutinsky et al. (1963) as the distance between the centers of mass of the left and right parts of the nucleus, see (1). The λ_1 and λ_2 in (1) are the corresponding Lagrange multipliers.

Since both Coulomb and surface energy are functionals of $\rho(z)$ the variation in (1) results in an equation for $\rho(z)$,

$$\rho\rho'' = 1 + (\rho')^2 - \rho[\lambda_1 + \lambda_2|z| - 10x_{\rm LD}\Phi_S\,]\Big[1 + (\rho')^2\Big]^{\frac{3}{2}}\ . \tag{2}$$

Here Φ_S is the Coulomb potential at the nuclear surface and $x_{\rm LD}$ is the fissility parameter of the liquid drop.

By solving Eq. (2) for given x_{LD} and λ_2 (λ_1 is fixed by the volume conservation condition) one obtains the profile function $\rho(z)$ which we refer to as the *optimal shape*. These shapes correspond to the lowest possible energy of liquid drop with a given volume and elongation R_{12}. Varying the parameter λ_2 one obtains a full variety of shapes ranging from a very oblate shape (disk, even with central depression) up to two touching spheres.

The results of calculations show that the deformation R_{12} of optimal shapes is limited by some maximal value $R_{12}^{(crit)}$. Above this deformation the solutions of (2) for mono-nuclear shapes do not exist. This maximal deformation was interpreted by Strutinsky et al. (1963) as the scission point. Having at one's disposal the shape and the deformation energy at the scission point one can try to evaluate the measurables of the fission experiments like the mass distribution, total kinetic and excitation energy of fission fragments, the multiplicity of prompt neutrons.

3. The potential energy surface and the mass distribution of fission fragments

For the accurate calculation of the deformation energy the account of shell effects is essential. In order to calculate the shell correction the optimal shape was expanded in series in deformed Cassini ovaloids (up to 20 deformation parameters were included). For the shape given in terms of Cassini ovaloids the single-particle energies and the shell correction δE were calculated by the Pashkevich (1971) code with deformed Woods-Saxon potential.

Figs. 1a,b show the total (liquid-prop plus the shell correction including the shell correction to the pairing energy)

$$E_{def} = E_{def}^{LD} + \delta E, \text{ with } \delta E = \sum_{n,p}(\delta E_{shell}^{(n,p)} + \delta E_{pair}^{(n,p)}) \tag{3}$$

deformation energy for ^{180}Hg and ^{236}U. The summation in (3) is carried out over the protons (p) and neutrons(n).

The unexpected mass-asymmetric distribution of fission fragments for beta-delayed fission of ^{180}Hg was reported in Andreyev et al. (2010). In Figs. 1a,b only the liquid-drop part of deformation energy is shown beyond the scission point. In Figs. 1c,d the deformation energy of compact shapes was extrapolated beyond the scission point. In case of ^{180}Hg the lowest energy at the scission point corresponds to the fragment mass number $A_H = 100$ and $A_L = 80$, what coincides with the experimental results Andreyev et al. (2010). One can see also that beyond the scission point the minimum of deformation energy moves towards the symmetric splitting. The knowledge of the scission point is