Understanding fission fragment mass distribution in the random neck rupture model

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Mass distribution is an important observable of the fission process. Studies on the mass distribution provide valuable information about the potential energy landscape of the fissioning nucleus and the mechanism involved [1,2]. A large amount of experimental data on the mass distribution in nuclear fission has been generated over the years. Early studies on low-energy fission of actinides revealed the importance of the nuclear shell effects in fission. The main interest in the medium-energy heavy-ion–induced fission is to study the effect of entrance channel parameters namely, projectile energy, angular momentum and entrance channel mass asymmetry, on the fission process. An analysis of the data on the variance of the mass distribution over a wide range of the fissility of the compound nucleus was reported in refs. [3,4]. The analysis revealed that the variance of the mass distribution shows fissility dependence when studied as a function of saddle point temperature "T_{cn}" whereas fissility dependence vanishes when studied as a function of fragment temperature "T_f" [4]. Thus, the variance of the mass distribution provides important information about the fission process and can be used to test various models of fission such as the saddle point model [5] and the scission point model [6]. These models, although they qualitatively explain the gross features of the mass distribution, fail to quantitatively explain the mass distribution. Brosa et al. [7] proposed the random neck rupture model (RNRM) for the calculation of post-fission observables such as mass distribution, kinetic energy distribution and neutron multiplicity. According to this model, the pre-scission shape of the fissioning nucleus dictates the post-fission observables. This model has been successful in explaining the width of the mass distribution in low- as well as medium-energy fission [7].

In the present work, experimentally determined variances of the mass distribution have been compared with those calculated using the RNRM of Brosa et al.[7].

According to this model, during the motion of the fissioning nucleus towards scission, a dent is developed in the neck region of the fissioning nucleus, which is deepened by the capillary force, finally leading to fission. The curvature of the fissioning nucleus changes from positive to negative in the motion towards scission. During this transition when the neck becomes flat, there can be a large shift in the dent without sizeable physical mass motion, which finally leads to large mass fluctuations in fission. In the RNRM model [7] the pre-scission shape for the symmetric fissions described by the following set of equations:

$$\rho(\zeta) = \begin{cases} \sqrt{r_1^2-\zeta^2} & r_1 \le \zeta \le \zeta_1 \\ r + a^2 c(\cosh[(\zeta - z)/a]-1) & \zeta_1 \le \zeta \le \zeta_2 \\ \sqrt{r_1^2-(2l-r_2-r_1-\zeta)^2} & \zeta_2 \le \zeta \le 2l - r_1 \end{cases} \quad (1)$$

Equation (1) represents a shape which is made up of two equal spheres which are connected by a neck. Here we assumed symmetric pre-scission shape, made up of two equal spheres. The shape involves six parameters (r_1, ζ_1, r, a, c, l). "r_1, r_2" (r_1=r_2 for symmetric case) are the radii of the spherical heads at both ends of the pre-scission shape, "r" is the minimal neck radius and "ζ_1,ζ_2" (ζ_1=ζ_2 for symmetric case) are the transitional points where the shape changes from head to neck. "c" is the curvature of the neck. The parameter "a" is a measure of the extension of the neck and "*2l*" is the total elongation of the pre-scission shape. By imposing the conditions of continuity of the shape and volume conservation, a set of nonlinear equations are solved to determine "r_1, r, ζ_1, a" and "c". Further the parameter "c" can be correlated to "r_1, r" and *"l"* using the following equation:

$$c = 2c_{rel}\left(\frac{(r_1 - r)}{(l - r_1)^2}\right) \quad (2) \quad .$$

The value of "c_{rel}" is taken so as to "ρ" and "dρ/dζ" become continuous at the transitional points as mentioned in ref. [7] which gives continuous shape as well as continuously differentiable shape. The remaining variable "*l*" is varied to reproduce the experimentally observed average total kinetic energy <TKE>.

For a given value of "*l*", the pre-scission shape is determined and the probability of neck rupture at different positions of the neck (z_r) is calculated using the following equation:

$$W(A) \propto \exp\left(-2\pi\gamma_o\left[\rho^2(z_r) - \rho^2(z)\right]/T_{sc}\right), \quad (3)$$

where "γ_o" is the surface tension coefficient given by

$$\gamma_o = 0.9517\,[1\text{-}1.7828((N_{cn} - Z_{cn})/A_{cn})^2], \quad (4)$$

"N_{cn}" and "Z_{cn}" are the neutron number and atomic number of the fissioning nucleus and "A_{cn}" is mass number of the fissioning nucleus. "T_{sc}" is the temperature of the fissioning nucleus at the scission point. "T_{sc}" is calculated using formula $T_{sc}=E^*_{scission}/a_{cn}$, where $E^*_{scission}$ is the excitation energy of the fissioning nucleus at the scission point and "a_{cn}" ($=A_{cn}/10$) is level density parameter of compound nucleus. The fragment temperature "T_f" corresponding "T_{sc}" is calculated using formula "$T_f=E^*_f/a_f$", where "E^*_f" is the excitation energy of the fission fragment and "a_f"($=A_f/8$) is level density parameter of fission fragment.

The rupture position (z_r) is translated into fragment mass (A_f) using the following relation:

$$A(z_r) = (3A_{cn}/4r_{cn}^3)\int_{-r_1}^{z_r}\rho^2(\zeta)d\zeta \quad . \quad (5)$$

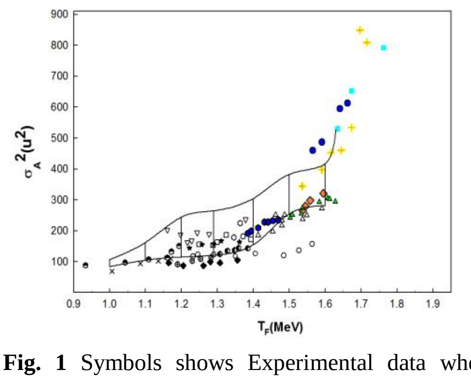

Fig. 1 Symbols shows Experimental data whereas shaded area for Brosa model calculations

Fig.1 shows that the experimentally observed mass variances (ref.4 and cited articles therein) follows single band increasing exponentially with fragment temperature "T_f" and independent of fissility of compound nucleus or any other properties as mentioned in ref.4. This trend is well explained by Brosa Model [7] which has been shown as shaded are in Fig.1.

The variance of the mass distribution is computed using the RNRM. In RNRM calculations, the elongation of the pre-scission shape is varied to reproduce the experimental average total kinetic energy <TKE> for the given compound nucleus system which also determines the shape at scission point. Further this shape ruptures at different points, on the flat neck of scissioning nucleus, depending on the scission point temperature to produce distribution of fragment masses. Eq.(3) indicates that the more is the scission point temperature, more will be the variance of the mass distribution for the given compound nucleus system.

The above result points out, that the scission point configuration, which includes the excitation energy at scission point and the scission point deformation plays important role in deciding width of mass distribution.

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