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**On the competition between symmetric
and asymmetric fission.**

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On the competition between symmetric and asymmetric fission

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Abstract

The influence of the asymmetry degree of freedom on the fission process is studied within the framework of the generalized rotating liquid drop model taking into account the proximity and temperature. The Businaro-Gallone point is well reproduced by the model. The study of the dependence on the temperature and angular momentum shows that the rotation as well as the thermal excitation favor symmetric splitting.

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One of the puzzling question remaining about fission is the existence of a transition time. Recent measurements of large pre-fission particle multiplicities [1,2] and the persistence of sizable residue cross sections at high excitation energies [3] have been viewed as proofs of dynamical delay in the fission process. In other words, to reproduce these data, available statistical models had to hinder the fission process causing it to compete less effectively with particle emission.

On the other hand, recently, Moretto et al [4] and Charity [5] have claimed that there is no need for a fission delay time. Moretto et al are able to reproduce energy dependent cross sections for numerous systems without any fission delay time. Charity indicates that a mass dependent delay time cannot give simultaneously the pre-fission neutron number and a realistic fragment mass distribution.

The difference between statistical calculations and certain experimental data may come from an incomplete treatment of dynamical effects such as viscosity and/or of ingredients selected to determine the potential barriers.

This paper focuses on barriers and especially on the temperature and angular momentum dependence of the instability against asymmetric breakup.

Barriers have been determined within the generalized rotating liquid drop model which includes proximity, asymmetry and temperature effects [6–9]. The fission path follows the elliptic lemniscatoid shape sequence which allows continuous evolution from a spherical compound nucleus to two touching spheres.

With the assumption of energy conservation, two parameters, the asymmetry and the ratio of the neck diameter over the elongation of the system, remain. The deformation energy is calculated as the sum of the Coulomb, surface, rotational and proximity energies.

$$B_{def} = \frac{3\pi^2 Z^2}{5R_0} (B_c - 1) + a_s (1 - 2.6I^2) A^{2/3} (B_s - 1) + E_{rot} + E_{prox}.$$

B_c and B_s are shape-dependent functions and A , Z and I are mass, charge and relative neutron excess of the initial system. The proximity energy term takes care of the finite

range effects of the nuclear forces in the gap between the nascent fragments. It is

$$E_{prox} = (a_s/1.5)(1 - 2.6I^2) \int \phi(D/b)h dh,$$

where h is the distance in the transverse plane and D the corresponding distance between the infinitesimal elements of surface. The temperature dependence of the surface coefficient, the effective sharp radius and the surface width are defined as:

$$\begin{aligned} a_s &= 17.9439(1 + 1.5T/17)(1 - T/17)^{\frac{3}{2}} \text{ MeV} \\ R_0 &= (1.28A^{\frac{1}{3}} - 0.76 + 0.8A^{-\frac{1}{3}})(1 + 0.0007T^2) \text{ fm} \\ b &= 0.99(1 + 0.009T^2) \text{ fm} \end{aligned}$$

while the rotational energy is given by

$$E_{rot} = \hbar^2 l(l+1)/2I_{\perp},$$

where $I_{\perp}$ is the rigid perpendicular moment of inertia.

In figure 1, the potential energy surface in the space specified by the asymmetry, $\alpha = \frac{A_1 - A_2}{A_1 + A_2}$ and the distance between the centers of mass of the fragments, r , is displayed for the light ^{86}Kr nucleus and the heavy ^{205}At nucleus at $T=0$ Mev and $L=0$ $\hbar$. The contour levels are equally spaced every 5 MeV.

For the light nucleus, the barrier is maximum for the symmetric fission and decrease monotonically with the asymmetry. For this kind of nucleus, the potential favors decay by light fragment emission.

On the other hand, the heavy nucleus shows the opposite behaviour. The symmetric fission corresponds to a minimum in the potential energy. The potential energy increases with asymmetry reaching a maximum for a very asymmetric configuration. For still greater asymmetry, the barrier decreases again. In this case, decay by light charged particle emission and/or symmetric fission are favored.

To include these trends in statistical models, Moretto defined for a fixed mass asymmetry the "conditional" saddle point(CSP) [10]. It corresponds to the barrier for that mass asymmetry. If we plot all these CSP, we obtain the ridge line which summarizes the whole

set of information in a single curve. These curves are represented in figure 2 for several β – *stable* nuclei. The fissility coefficient x gives the interplay between the Coulomb and the surface energies. It is defined as:

$$x = \frac{E_{coul}}{2E_{surf}}.$$

Because different macroscopic models do not use the same surface coefficients, the fissility parameter can lead to some confusion. To avoid these problems, the chosen nucleus is always specified in addition to the fissility. In the figure 2, different ridge lines have been normalized to the compound nucleus surface energy to separate them more clearly.

For light nuclei the curve is monotonic and reaches its minimum value for very asymmetric splitting. As the nucleus becomes bigger, the symmetric configuration barriers decrease. For a fissility value between 0.4 and 0.5, the curve is a plateau. All the exit channels have very similar CSP values. For still heavier nuclei, the symmetric splitting turns out to have the lowest CSP. The ridge curve in this case reaches a maximum at very asymmetric configurations and then drops again for the most asymmetric cases.

The fissility for which the ridge curve is a plateau is often defined as the Businaro-Gallone point [11]. This point tells us that the nucleus becomes unstable to breakup of all asymmetries. In our calculation for $T=0$ MeV and no angular momentum this Businaro-Gallone point falls in the interval $[0.4 - 0.5]$. To be more precise, it is included between $A=81$ and $A=145$. These values are in good agreement with the experimental estimations which locate the BG point between $A=85$ and $A=145$ [12]. The small difference between our value and the usually accepted LDM value [13,14] reflects different model assumptions. Besides, over a wide range of fissility values there is a plateau which makes a very precise determination of the BG point difficult experimentally.

The competition of the symmetric and asymmetric fission can then be studied generalizing the BG point to include other effects such as angular momentum and temperature.

In our model, we assume a rigid body. In figure 3, the generalized BG point has been determined for different angular momentum values at $T=0$ MeV. As the angular momen-

tum increases, the fissility at which the BG occurs decreases, which means that symmetric fission may compete more effectively for lighter nuclei. It is well known that an increase of the angular momentum results in lowering of the barrier height. The maximum angular momentum that a nucleus can sustain without disintegrating is also reported on figure 3 as a solid line. Around $60\hbar$, the BG point intersects the L_{max} line. Above this limit, symmetric splitting is always the most likely decay channel.

Another effect which is potentially important is that of the temperature. Figure 4 is the same as figure 2 but for $T=5$ MeV. At this high temperature, all barrier heights go down but the decrease is more important for the symmetric splitting than for asymmetric ones. This results in a shift of the plateau to lower fissility values. We have summarized the generalized BG point values for different temperatures in figure 5. As in the case of increasing angular momentum, there is a shift of the BG point toward lower fissility values as the temperature increases. That means that increasing temperature increasingly favors symmetric fission.

In conclusion, we have shown that the generalized rotating liquid drop model which takes into account the proximity and temperature effects is able to reproduce the Businaro-Gallone point in the deformation valley through compact and creviced shapes. As for angular momentum increases, temperature increases favor symmetric fission over asymmetric fission. As we know, the temperature dependence is still missing in statistical calculations. The inclusion of such temperature dependence in a statistical model is actually in progress. Its effect will be especially emphasized if no transition time is taken into account. The inclusion of the temperature degree of freedom does not rule out dynamical aspects such as the fission delay time which we believe to be important features of the fission process.

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FIGURES

FIG. 1: Potential energy surface in the two dimensional space tends by the asymmetry and r at $L=0 \hbar$ and $T=0$ MeV. The upper panel corresponds to a typical light nucleus and the lower one to a typical heavy nucleus.

FIG. 2: Ridge lines for different nuclei at $L=0 \hbar$ and $T=0$ MeV. The conditional saddle point energy is normalised to the surface energy of the corresponding compound nucleus.

FIG. 3: Angular momentum dependence of the generalized BG point at $T=0$ MeV. The full line corresponds to maximum angular momentum against symmetric fission.

FIG. 4: Same as figure 2 but for $T=5$ MeV.

FIG. 5: Temperature dependence of the generalized BG point at $L=0 \hbar$

FIGURE 1

FIGURE 2

FIGURE 4

FIGURE 3

FIGURE 5