FISSION OF HEAVY NUCLEI AT LOW ENERGY* **

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Considering fission dynamics at low energy, shell and pairing effects can play a crucial role giving rise in particular to multimodal fission. To follow the evolution of the compound nucleus along its path to fission we solve a 2-dimensional Langevin equation taking explicitly particle evaporation into account. The fragment mass distribution and neutron pre-scission multiplicity obtained in a fusion-fission experiment performed in parallel are compared to the predictions leading to an improved theoretical description.

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1. Dynamical description of the fission process

Even if discovered more then 60 years ago, fission remains today, due to the large number of effects entering its description, subject of theoretical and experimental debates related to nuclear structure as well as to dynamics. At high excitation energy the absence of shell effects leads to symmetric fission only and our theoretical 1-dimensional approach has proven rather successful [1]. Nowadays a large variety of available experimental data related to fission at low energy exhibits multimodal fission, *i.e.* the coexistence of symmetric and asymmetric splitting [2].

To describe the evolution of the compound nucleus along its fission path, we use in the present work the Funny-Hills shape parametrisation which only consists of 3 deformation parameters (c, α, h) which have a direct physical

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interpretation [3]. In this space we solve the Langevin equation recalled below in its general multidimensional form:

$$\begin{aligned}
\frac{dq_i}{dt} &= \sum_j [M^{-1}(\vec{q})]_{ij}\, p_j\,, \\
\frac{dp_i}{dt} &= -\frac{1}{2}\sum_{j,k} \frac{d[M^{-1}(\vec{q})]_{jk}}{dq_i}\, p_j\, p_k - \frac{dV(\vec{q})}{dq_i} - \sum_{j,k} \gamma_{ij}(\vec{q})\, [M^{-1}(\vec{q})]_{jk}\, p_k \\
&\quad + \sum_j g_{ij}(\vec{q})\, \Gamma_j(t)\,.
\end{aligned}$$

To account for symmetric as well as asymmetric fission, at least 2 deformation parameters are needed. In a first approach, we restrict ourselves to the 2-dimensional (c, α) space always putting h equal to zero. For the ingredients entering the Langevin equation (inertia, friction, Langevin strength), let us start with the macroscopic concepts successfully used before to describe symmetric fission [1, 4]. One point where we need, however, to go beyond this semi-classical picture at low energy concerns the potential energy which henceforth will include shell and pairing corrections [5].

The Langevin equation is coupled to the Master equations in order to take into account the evaporation which can occur all along the deformation process [4]. In the present work, particle emission is considered through 2 different concepts: the statistical Weisskopf model [6] which proved reasonable at high energy but on the validity of which one might have some doubts at lower excitation and the recently developed more microscopic Thomas–Fermi approach which considers the nuclear system as a Fermi gas of nucleons [7].

2. Experimental investigations

In a fusion–fission campaign performed at the JINR in Dubna, a ^{18}O beam ($E_{\rm lab} = 76$ MeV) was used to bombard a ^{209}Bi target leading to the compound nucleus ^{227}Pa at an excitation energy of 26 MeV. The fission fragments and the neutrons emitted in coincidence were detected by associating the spectrometer CORSET [8] and the liquid scintillators DeMoN [9]. Time-of-flight measurements allowed in particular to extract the fission fragment mass distribution as well as the neutron pre-scission multiplicity.

In Fig. 1 one can observe that this mass distribution displays multimodal fission since it consists of 3 different modes: a symmetric fission mode giving rise to elongated fragments, an asymmetric channel centred at the double magic spherical ^{132}Sn nucleus and a second asymmetric mode corresponding to the slightly elongated ^{140}Ba nucleus [5]. This experiment also showed that the neutron pre-scission multiplicity slightly increases with the asymmetry of the fission channel as can be seen in Fig. 1.

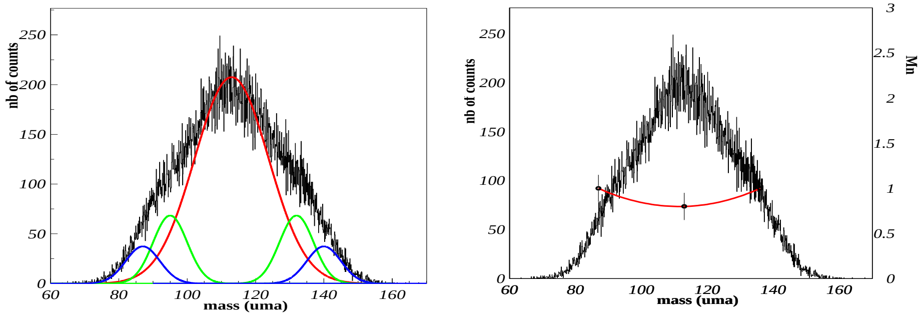

Fig. 1. Fission fragment mass distribution (left) and neutron pre-scission multiplicity as a function of the mass asymmetry (right).

3. Confrontation theory–experiment

To test the validity of the model, the experimental and theoretical mass distributions are compared on the first part of Fig. 2. Let us try to understand what can explain the stricking disagreement. One main reason concerns the wall-and-window friction model [10] used. Indeed, this macroscopic concept is known to be valid in the high-temperature limit. On the other hand recent microscopic calculations [11] showed that friction decreases with decreasing nuclear excitation. We therefore certainly overestimate friction. This seems to be confirmed by Fig. 2 where we can see that reducing friction substantially improves the comparison theory-experiment. In spite of this better reproduction of the experimental data for a reduced dissipation, the theory only gives rise to a single asymmetric mode at $A = 132$, the one at $A = 140$ being absent. It is important to recall here that we are working for the moment in the restricted 2-dimensional (c, α) deformation space putting $h = 0$. We believe that this might be the main reason why we are not able

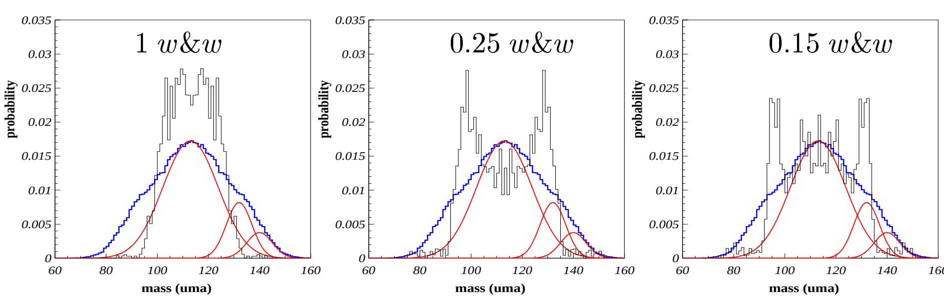

Fig. 2. Experimental (solid line) and theoretical (histograms) mass distributions for the system ^{227}Pa ($E^*_{\rm tot} = 26$ MeV) for different values of friction.

to describe the deformed ^{140}Ba shape and expect that, taking h explicitly into account, the contribution to the mass $A = 132$ will decrease in favour of $A = 140$. In addition, as mentioned before, the Weisskopf evaporation approach is not well-adapted at low energy. As soon as the intricate treatment of the composite $\alpha-$particle emission will be completed we will couple the more microscopic Thomas–Fermi theory to the full dynamical calculation. Bearing in mind all these conclusions, we developed our model and present below the first promising results.

4. Towards a more realistic theoretical description

In order to investigate the influence of increasing the dimension of the deformation space, we compare in Fig. 3 the potential energy along the scission line in the 2-dimensional (c, α) space for $h = 0$ to the one obtained after a minimisation with respect to h. One observes that, whereas a single asymmetric fission valley is present at the mass 132 ($|\alpha| \approx 0.020$) for $h = 0$, another asymmetric channel appears after minimisation around a mass near 140 ($|\alpha| \approx 0.088$). This result seems to attest that extending the dimension of the space could improve the predictions substantially.

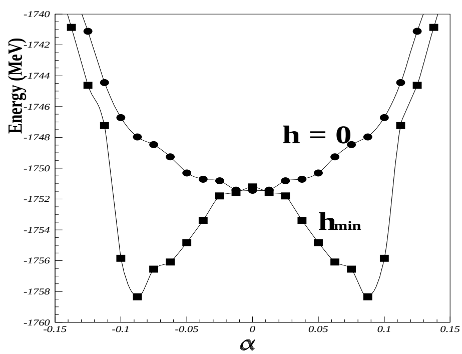

Fig. 3. Potential energy along the scission line for $h = 0$ and after minimisation with respect to h (see the text).

Concerning dissipation, we performed a full dynamical calculation using the temperature dependence of the friction recently proposed by Hofmann and Ivanyuk [11]. Comparing Figs. 2 and 4 one notices the sensitivity of a precise description of this temperature dependence.

Finally we give in Fig. 5 a comparison of the evaporation rates obtained in the Weisskopf and in our recently developed Thomas–Fermi approach [12]. One can see that the latter gives rise to similar but sometimes substantially larger emission rates. Consequently, on average along the path to fission, we expect larger pre-scission multiplicities using this more microscopic picture.

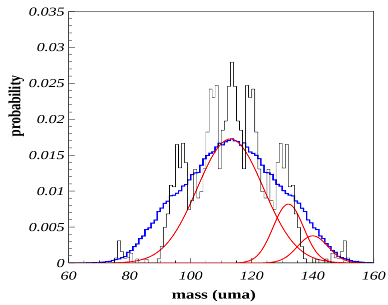

Fig. 4. Same as Fig. 2 for the temperature-dependent friction $\gamma(T)$ of [11].

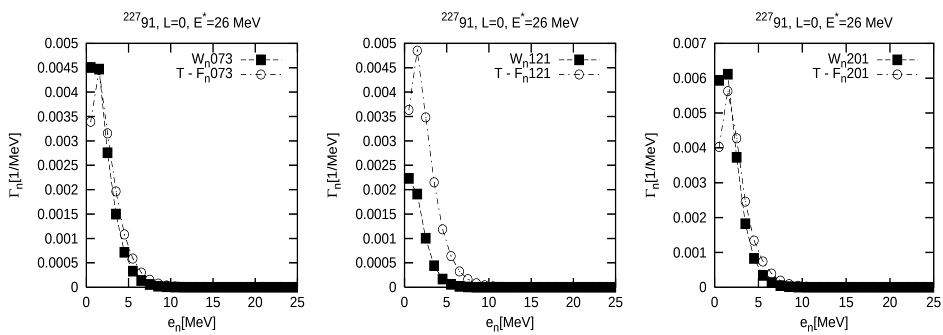

Fig. 5. Neutron emission rates Γ_n in the 2 theories for 3 different deformations: spherical, deformed, close to scission (from left to right).

5. Conclusion and outlook

We extended our quite successful model describing symmetric fission to study systems at low energy by solving the Langevin equation in a 2-dimensional deformation space. The confrontation theory-experiment indicated that we need to increase the dimensionality of the treatment, that the temperature dependence of the transport coefficients has to be taken into account and that the Weisskopf evaporation theory can no longer be used at low energy. The recent results we have obtained following these 3 directions have been shown as quite promising.

We would finally like to mention another interesting result emerging from the present work. The pre-scission multiplicity was often considered as the pertinent variable to study in order to investigate fission processes, [1]. At low energy, however, the number of emitted particles is rather small.

We have seen here that for multimodal fission where one has to deal with the competition of at least 2 channels, the fragment distribution seems to be a relevant variable to investigate dynamics, in particular nuclear dissipation.

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