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DISTRIBUTION OF LIGHT PARTICLES EMITTED FROM FISSIONING NUCLEI* **

C. Schmitt, J. Bartel

Institut de Recherches Subatomique, Université Louis Pasteur
4, rue Blaise Pascal, 67070 Strasbourg, CEDEX, France
and
Institut National de Physique Nucléaire et de Physique des Particules, CNRS
23, rue du Loess BP28, 67037 Strasbourg, CEDEX 2, France

A. Surowiec and K. Pomorski

Institut of Physics, University of Maria Curie-Skłodowska
Pl. M. Curie-Skłodowska 1, 20-031 Lublin, Poland

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The formation of an excited rotating deformed nucleus and its subsequent decay through the fission process, or ending up as an evaporation residue, is studied taking into account particle evaporation. Several nuclei ranging from ^{126}Ba to some super-heavy elements are investigated. Until recently, we have only considered average pre-fission multiplicities, as these were the experimental available data. A newly developed analysis of experimental data can now give access to pre-fission multiplicity distributions. A first comparison between theoretical and experimental particle-multiplicity distributions is given.

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The synthesis of super-heavy elements has given a new impetus to the whole field of nuclear structure and nuclear dynamics. To predict the formation and stability of such objects is a challenge for the nuclear physics community.

The model we developed deals with light particle evaporation, such as neutrons, protons and α particles, in conjunction with the fission process. As a first step we have considered symmetric fission. We briefly recall here the main features of our approach which has been detailed in Refs. [1, 2].

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The dynamical evolution from an initial compact shape to very elongated saddle and scission configurations is described, in the case of symmetric fission, by a single collective coordinate q which is assumed to follow classical stochastic equations of motion of Langevin type. To describe nuclear deformation, we use the shape parametrization developed by Trentalange, Koonin and Sierk [3] which is well adapted for describing fissioning shapes [4]. The collective coordinate q we choose is the distance between the centers of mass of the two symmetric nascent fission fragments and denoting p its conjugate momentum, the Langevin equations are :

$$\frac{dq}{dt} = \frac{p}{M(q)} \quad ,$$

$$\frac{dp}{dt} = \frac{1}{2}\left(\frac{p}{M(q)}\right)^2 \frac{dM(q)}{dq} - \frac{dV(q)}{dq} - \frac{\gamma(q)}{M(q)}p + F_{\rm L}(t) \quad .$$

To solve this set of equations, we calculate the collective mass parameter $M(q)$ in the Werner–Wheeler approximation [5] and the friction coefficient $\gamma(q)$ in the wall-and-window friction model [6]. Our collective potential $V(q)$ is defined as the difference of the Helmholtz free energies of the deformed and spherical nucleus determined in the Liquid Drop model [7] whose parameters are temperature dependent [4]. Finally $F_{\rm L}(t)$ is the stochastic Langevin force (see Ref. [1] for details).

At the same time, particle evaporation is taken care of by coupling these Langevin equations to the master equations:

$$\frac{dM_\nu^{\alpha\beta}}{dt} = \Gamma_\nu^{\alpha\beta} \quad .$$

Here particle emission rates $\Gamma_\nu^{\alpha\beta}$ are calculated in the framework of Weisskopf's theory [8] taking into account the excitation, rotation and deformation of the emitting nucleus (which is not the case for most other models).

The competition between fission and evaporation is treated in a Monte Carlo procedure by drawing successive random numbers to decide whether a particle is emitted, and, in that case, which kind of particle and with which energy. Moreover, the loss of excitation energy and angular momentum of the emitting nucleus due to particle evaporation is taken into account, which leads to an increase of the fission barrier, which, in turn, makes fission less probable. Finally, entrance-channel effects related to the impact parameter distribution of the fusion reaction, and consequently to the initial spin distribution of the compound nucleus, are taken care of by convoluting the multiplicity distribution obtained for given angular momentum with the fusion/fission cross section [2].

Within this model, we have well reproduced average experimental neutron pre-fission multiplicities in a wide range of nuclear masses [2]. We will now confront experimental multiplicity distributions with the ones obtained in our model. All measured data presented here were obtained using the DEMON neutron multidetector [9, 10].

In Fig. 1 we present the pre-fission neutron multiplicity distribution as well as the neutron distribution in coincidence with evaporation residues for the nucleus ^{188}Pt. The experimental pre-fission neutron multiplicity distribution is not yet available for this system, but the agreement between theory and experiment for the mean value (4.53 compared to 4.50) is quite satisfactory.

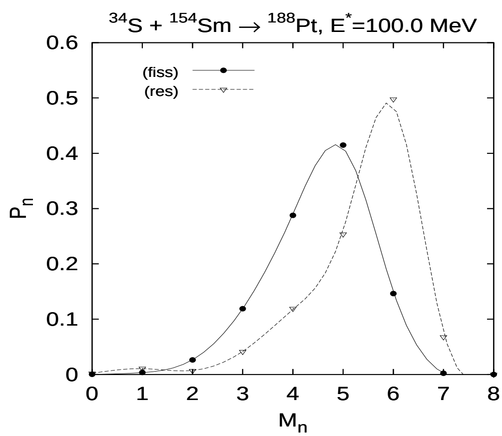


Fig. 1. Neutron pre-fission multiplicity distribution (full line) and neutron multiplicity distribution in coincidence with evaporation residues (dashed line).

In Fig. 2 we consider the element ^{272}110. The distributions for fission (a) and residue events (b) are shown. In both cases, we present results obtained with the full wall-and-window friction coefficient and one reduced by 50%. The friction model we use does not contain any temperature dependence. However, microscopic calculations predict [11, 12] the decrease of friction with decreasing temperature what can play an important role in the case of super-heavy elements. These are generally formed at low temperature and are rather cold when reaching the scission configuration. Hence, we probably overestimate friction for these nuclei, and with it fission time scales, and consequently particle multiplicities. Using a reduced wall and window coefficient allows us to investigate in a crude way to what extent friction can influence our results. Our calculations show a decrease of the neutron pre-fission multiplicity with decreasing friction. They, however, also demonstrate that friction has no influence on residue events. For other super-heavy elements the same behaviour is observed.

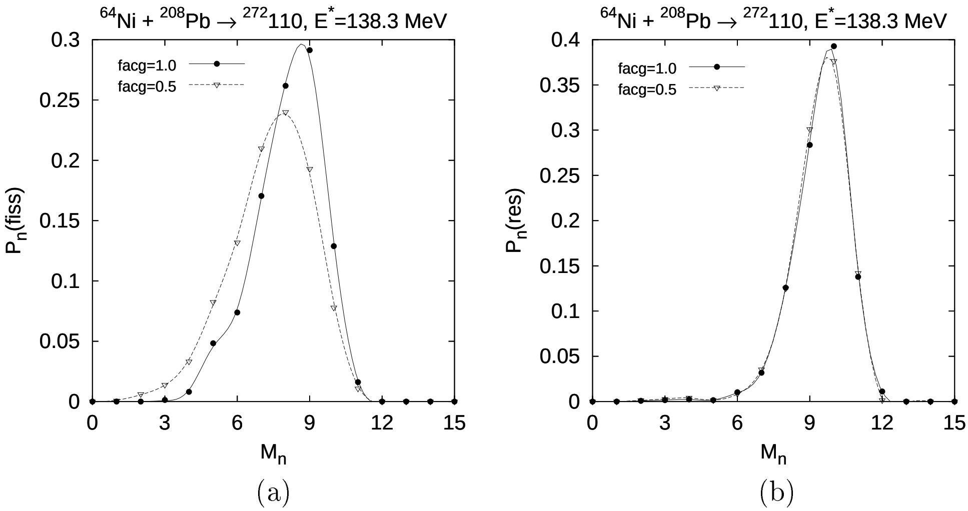


Fig. 2. (a) Neutron pre-fission multiplicity distribution for the full (full line) and reduced (dashed line) friction coefficient. (b) Neutron multiplicity distribution in coincidence with residue events for the full (full line) and reduced (dashed line) friction coefficient.

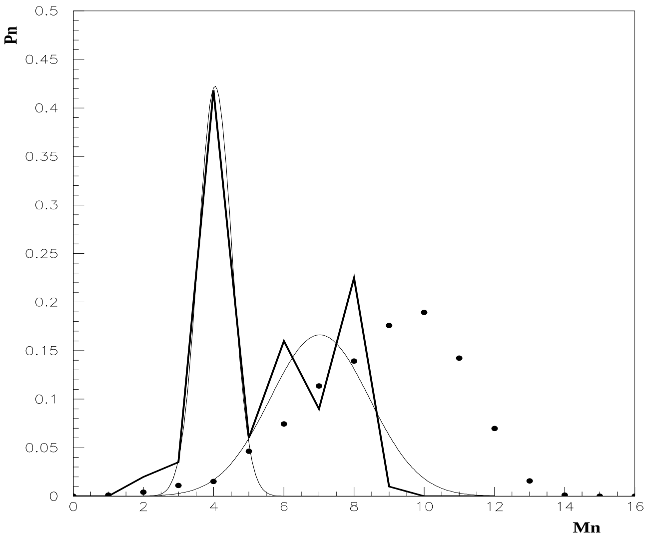
Considering the isotope $^{266}110$ for which the experimental neutron pre-fission multiplicity distribution has been determined using the so-called *Backtracing* method of experimental analysis [13], Fig. 3(a) shows on the same graph the experimental distribution and our predictions (obtained with the reduced friction coefficient). The discussion of the experimental results needs, however, some caution. Indeed, it presents two main features:

(1) some odd/even oscillations probably due to pairing correlations and

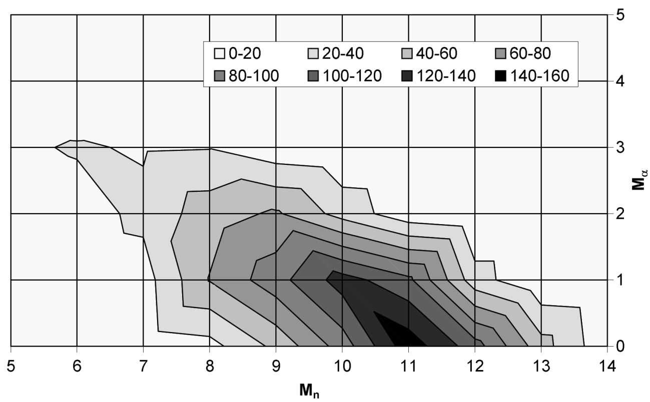
(2) a shape which consists of two components.

Such a structure is the sign of the coexistence of two nuclear processes which differ in fission time scales, and consequently in particle multiplicities. The first component at low multiplicity is connected with fast fission, whereas at higher multiplicity we have to deal with fusion/fission [14]. As our model considers only the fusion/fission channel, we need to compare our predictions with the second component only. We conclude that our theoretical predictions extend to somewhat too high multiplicities. For this system, the correlation, event by event, between the neutron and the α particle multiplicities presented on Fig. 3(b) shows the real coupling of these two evaporation channels.

For lighter nuclei, such as ^{126}Ba, for which the fast fission channel can practically be neglected, a similar analysis is in progress [15, 16]. A quite satisfactory agreement with our theoretical predictions seems to appear. For



(a)



(b)

Fig. 3. System ^{58}Ni+^{208}Pb $\longrightarrow^{266}$110 at $E^* = 185.9$ MeV; (a) neutron pre-fission multiplicity: experimental (full line) and theoretical distributions (dotted line), (b) theoretical correlation between the neutron and α particle multiplicities.

heavy systems for which different nuclear processes can be involved, an accurate experimental discrimination between these different mechanisms is, as just seen, necessary before comparing to our theoretical predictions.

We have demonstrated that within the model presented above we are not only able to reproduce experimental average pre-fission multiplicities but also multiplicity distributions. These comparative studies have, however, also shown that, at least in the case of very heavy systems, our classical description needs to be improved by using more microscopic and temperature dependent transport parameters. Another important development on which we are working, consists in including shell and pairing effects in our theory which can lead, at least at low temperature, to asymmetric fission valleys. The treatment of these additional fission channels requires the resolution of Langevin equations in the multidimensional deformation space. With such a very general approach we expect to explore the countless experimental data dealing, for example, with multimodal fission.

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