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Investigation of the Extra-extra-push by Pre-scission Neutron Measurements with DEMON

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Abstract. The objective of this talk is to present a simple method to calculate pre- and post-scission neutron multiplicities in the frame of the Bass model. This method is of particular interest for very heavy systems for which an extra-extra-push is supposed to hinder fusion. The multiplicities calculated by the model are compared to published data covering a broad range of projectile and target masses, and to more recent ones obtained with the help of the Demon detector and addressing specifically the existence of the extra-extra-push.

INTRODUCTION

The fusion of two nuclei occurs as soon as the bombarding energy exceeds the fusion barrier, which, for light or intermediate mass nuclei, is generally quite close to the interaction barrier. For heavy nuclei, a hindrance to fusion appears. Indeed, it has been shown [1] that the threshold for the production of symmetric fragments can be several tens of MeV higher than the interaction barrier. The two nuclei may come to contact, interact strongly through a deep inelastic reaction, but do not fuse even for head-on collisions.

Deep inelastic collisions are essentially explained by the high angular momentum brought in the system, so that repulsive forces overcome the attractive ones and prevent the system from fusion. The hindrance to fusion in the case of head-on collisions between heavy nuclei can be explained by an increase, with respect to the Bass model, [2] of the Coulomb force, or by a loss of the kinetic energy before the system reaches the entrance saddle point. The first

explanation relies on a dynamical deformation due to the strong mutual electric field [3], the second on the effect of friction for systems where the saddle point configuration is more compact than the contact point [4].

Symmetric fragmentation appears only once the kinetic energy is increased by the so-called "extra-push" which compensates either of the above mentioned effects. This extra-push has of course a direct implication on the minimum excitation energy at which one can expect to fuse heavy nuclei with sizeable cross-section.

But symmetric fragmentation is not a signature for fusion-fission, since other mechanisms such as fast-fission or quasi-fission can produce equal mass fragments without the formation of a compound nucleus. Both mechanisms are explained by the lifetime of the di-nuclear system which can be long enough to equilibrate all degrees of freedom. Dynamical calculations have suggested that an even higher bombarding energy, corresponding to the extra-extra-push, is needed to overcome these mechanisms and reach true fusion.

The extra-extra-push is difficult to measure. A few experiments have tried to distinguish fast-fission from fusion-fission on the basis of fragment angular distributions [5]. The values which were obtained for the extra-extra-push seem too high and contradict the cross-sections which lead to the synthesis of the heaviest elements.

A possible new way to measure the extra-extra-push has been provided by the discovery that, during the fission process, the path from the equilibrated shape to scission lasts long enough to allow many neutrons to be emitted by the compound nucleus before it separates in two fragments [6]. The deconvolution of neutron angular distributions into pre- and post-scission distributions allows to establish a clock [7] on the fusion process. Accordingly, it should allow to distinguish fast-fission from fusion-fission.

THE MODEL

Pre-scission neutron multiplicities ν_{pre} and post-scission ones ν_{post} have generally been analysed in the frame of the statistical model [6]. However, in its original version this model underpredicts strongly ν_{pre} . It has to be modified by introducing a delay during which fission is blocked. This delay allows the compound nucleus to evaporate particles. When the experimental and calculated multiplicities match, one has determined the delay to fission. In the case of the $^{20}\text{Ne} + ^{nat}\text{Re}$ system, for example, a Gemini calculation predicts about $\nu_{pre}=3$ and $\nu_{post}=8$ if the delay is 10^{-20}s (please note that we define ν_{post} as the total number of neutrons emitted by both fragments). For a delay of 10^{-19}s , these numbers become 7 and 4, respectively. The measured values of 5.6 and 4.8 correspond to $4 \cdot 10^{-20}\text{s}$ which is considered as the delay time for fission [8].

Such a model has to be adapted to take into account the effect of an possible extra-extra-push. As a first step, I prefer here to use a more simple model based on the Bass model [2]. Since it has been shown that fission fragments are produced almost cold at the scission point, independent on the bombarding energy, we make the assumption that post-scission evaporation is due to a small excitation energy E_{excff} remaining at the scission point plus the deformation energy stored in the fragments. Moreover, we admit that this deformation energy E_{evapff} is given by the difference between the saddle-point potential energy for two undeformed spheres $E_{spheres}$, and the Viola energy E_{Viola} . Thus

$$E_{evapff} = E_{spheres} - E_{Viola} + E_{excff} \quad (1)$$

$E_{spheres}$ is calculated with the expressions given in ref. [9], which are based on phenomenological radii and a proximity potential.

We make moreover the extreme assumption that no excitation energy is evaporated by the combined system in the case of fast-fission. In the case of fusion-fission, the energy available for pre-scission evaporation is

$$E_{evapcn} = E_{cm} + Q_{gg} - E_{Viola} - E_{evapff} \quad (2)$$

i.e. the total available excitation energy minus E_{evapff} . The multiplicity of evaporated neutrons is given in all cases by

$$\nu = E_{evap} / \Delta E_{evap} \quad (3)$$

where

$$\Delta E_{evap} = e_{bind} + 2t + a_p E_{exc} \quad (4)$$

$$t = (a E_{exc} / A)^{1/2} \quad (5)$$

and E_{exc} is the excitation energy of the given nucleus before it undergoes evaporation. The binding energy e_{bind} for one neutron and the density parameter a have been taken equal to 8 MeV throughout the range of systems studied in this paper. The last term in the expression of ΔE_{evap} is introduced to take the charged particle evaporation into account. A constant value of 0.019 has been taken for a_p .

Measurements of ν_{pre} are generally triggered by the detection of symmetric fragments. Therefore, one may mix events corresponding to fast-fission and fusion-fission. For head-on collisions, the transition between the two mechanisms occurs when the kinetic energy overcomes the extra- extra-push. For a given l -value, one has to take into account the centrifugal energy and therefore the transfer of angular momentum. Thus, ν_{pre} is given by:

$$\nu_{pre} = \frac{\sigma_{fusion}}{\sigma_{fusion} + \sigma_{fast-fission}} \frac{E_{evapcn}}{\Delta E_{evapcn}} \quad (6)$$

where

$$\sigma_{fusion} = (1 - f_{lfusion})^{-2} \frac{\pi r^2}{E_{cm}} [E_{cm} - B_{fus} - E_{push}] \quad (7)$$

$$\sigma_{fast-fission} = (1 - f_{lfast-fission})^{-2} \frac{\pi r^2}{E_{cm}} [E_{epush} - E_{push}] \quad (8)$$

The values of the extra-push E_{push} and of the extra-extra-push E_{epush} have been taken from the systematics of ref. [5]. The only free parameters are therefore:

- E_{excff} which is the total excitation energy of the fission fragments at the scission point. In the same manner as the delay time in the case of the statistical model, E_{excff} can be tuned so that the predicted multiplicities correspond to the measured ones.
- $f_{lfusion}$ and $f_{lfast-fission}$ which give the rate of angular momentum transferred from the relative motion to the intrinsic degrees of freedom. These parameters can vary between 0 and a maximum given by the Bass model [2].

Two different hypothesis have been examined [10]:

- $f_{lfusion}$ and $f_{lfast-fission}$ are equal. This hypothesis corresponds to a picture where the system follows a given path, experiences some energy loss and momentum transfer, and according to the balance between the remaining kinetic energy and the potential energy fuses or re-separates.
- $f_{lfusion}$ is equal to 0 and $f_{lfast-fission}$ is equal to the maximum corresponding to a sticking configuration. It means that two different paths exist, one without friction leading to fusion and the other with friction leading to fast-fission. This hypothesis seems not to agree with the dynamical picture developed in ref [4]. However, it has the merit to lead to a better agreement with the data [10], and has been used in the following sub-section.

COMPARISON WITH DATA

With extra-extra-push

Let us first use the model with the values for the extra-extra-push given in ref. [5] and with E_{excff} equal to 0. Applied to the $^{20}\text{Ne} + ^{187}\text{Re}$ system, the

FIGURE 1. Experimental and calculated neutron multiplicities: ν_{tot} (triangles and dotted curve), ν_{pre} (circles and continuous curve), and ν_{post} (squares and dashed curve). Please note that in this paper $\nu_{tot} = \nu_{pre} + \nu_{post}$.

model predicts $\nu_{pre} = 6.7$ and $\nu_{post} = 4.4$. These values correspond to $9 \cdot 10^{-20}$ s in the Gemini calculation [8] i.e. to a very long time at which the decay process is almost finished. Fig.1 shows a comparison between the data covering a broad range of projectile and target masses [11] and the predictions of the model. Since E_{excf} has been taken equal to 0, the model overestimates ν_{pre} in most cases. However, for the ^{64}Ni induced reactions, it underestimates it strongly. This is due to the extra-extra-push which is not overcome by a system like $^{64}\text{Ni} + ^{208}\text{Pb}$ at 6.2 MeV/u. In opposition to the model, the observed values for ν_{pre} depend little on the target mass, and seem to exceed reasonable expectations for evaporation by the combined system in a fast-fission process. This is a first hint that the concept of the extra-extra-push is not valid.

Another study has been performed more recently on the $^{58}\text{Ni} + ^{208}\text{Pb}$ and

$^{64}\text{Ni} + ^{208}\text{Pb}$ systems, for which the excitation functions of ν_{pre} and ν_{post} have been measured by the Demon collaboration [12]. Fig. 2 shows the comparison between the model and the data. A fair agreement is obtained for the ^{58}Ni

FIGURE 2. Same as Fig.1. The dashed-dotted curve indicates the total number of neutrons evaporated in a deep-inelastic reaction.

induced reaction. At the two lowest bombarding energies, the measured ν_{pre} values exceed somehow the calculated ones, but this can be explained by the fact that fast-fission can be accompanied by evaporation from the combined system. More astonishing is the result obtained at the highest energy. An increase of ν_{post} and a decrease of the ν_{pre} is not expected by the model. The phenomenon is more pronounced in the case of the ^{64}Ni induced reaction, where two regimes seem to be observed. The model predicts correctly the higher energy points. But the three lower energy points deviate clearly from the expectations.

Without extra-extra-push

Let us now use the model with different parameters:

- we suppose that the extra-extra-push does not exist, or better said that E_{epush} is equal to E_{push} . Equation 8 shows that the cross-section for fast-fission is then equal to 0, which means that as soon as the system has overcome the extra-push, it fuses to a compound nucleus. Equation 6 is then much simplified, and we need not to make any assumption about the transfer of angular momentum.
- the excitation energy of the fission fragments at the scission point E_{excf} is taken equal to 25 MeV, regardless of the system

Applied to the $^{20}\text{Ne} + ^{187}\text{Re}$ system, the predictions of the model are now 5.2 for ν_{pre} and 6 for ν_{post} . These values are closer to the experimental ones measured for the $^{20}\text{Ne} + ^{nat}\text{Re}$ system and correspond to $3.5 \cdot 10^{-20}\text{s}$ in the Gemini calculation [8].

Fig.3 compares the predictions of the model to the data of ref. [11]. The over-all agreement is greatly improved. The strongest deviations occur for the lightest and the heaviest targets. Light systems are not very far from the Businaro-Gallone point, at which the model may no more be relevant. Especially astonishing is the relatively good agreement for the ^{64}Ni induced reactions, when compared to the preceding calculation (see Fig. 1).

Fig.4 compares the predictions of the model with this parameter set to the Demon data. The model predicts now correctly the three lower energy points of the ^{64}Ni induced reaction. Of course, there is now a definite disagreement for the ^{58}Ni induced reaction, and for the two highest points of the ^{64}Ni induced one.

As shown by Fig. 2, these points seem to correspond better to the hypothesis that the extra- extra-push exists and that E_{excf} is equal to 0. However, it would be difficult to understand why an extra-extra-push could appear only at high bombarding energy in the case of the ^{64}Ni induced reaction. Moreover, we have seen already that the hypothesis we had to make on the angular momentum transfer is not quite founded. Considering the good overall agreement illustrated by Fig. 3, it seems more reasonable to suppose that extra-extra-push does not exist and that in some cases E_{excf} is higher than 25 MeV. Fig.5 shows the result without extra-extra-push and with $E_{excf}=70$ MeV. The agreement is now quite good with nearly all points which are off the model in Fig. 4.

CONCLUSION

It is possible to calculate pre- and post-scission neutron multiplicities through a very simple model based on the Bass model. The predictions have

FIGURE 3. Same as Fig. 1, but here $E_{epush}=E_{push}$ and $E_{excf}=25$ MeV

been compared to data spanning a broad range of projectile and target masses. With one single set of parameters, they agree with most of the data to within less than one unit with the assumptions that:

- $E_{epush}=E_{push}$, which means that no extra-extra-push is needed.
- E_{excf} , which is the total excitation energy of the fragments at the scission point, is equal to 25 MeV.

In the case of the two reactions leading to element 110, only the low energy points for the $^{64}\text{Ni} + ^{208}\text{Pb}$ reaction agree with these parameters. For the higher energies and for the ^{58}Ni induced reaction, a second regime has been evidenced, corresponding to $E_{excf}=70$ MeV. Detailed statistical calculations will be needed to decide if this observation can be interpreted as an indication

FIGURE 4. Same as Fig.3.

that the delay time for fission of some very heavy nuclei at moderately high excitation energy is shorter than suggested by systematics. The difference between the ^{58}Ni and ^{64}Ni induced reactions may mean that not only the mass and the excitation energy play a role in the shortening of the lifetime of the nucleus against fission, but also the A/Z ratio.

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FIGURE 5. Same as Fig.1, but $E_{epush}=E_{push}$ and $E_{excf}=70$ MeV

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