FISSION WITHIN THE SPALLATION PROCESS. INFLUENCE OF THE INTRA-NUCLEAR CASCADE AND EVAPORATION MODELIZATIONS ON THE FISSION FRAGMENT PRODUCTION

J.-C. David[1i], A. Boudard[1], B. Fernández-Dominguez[1,2], S. Leray[1] and C. Volant[1]

[1] DSM/DAPNIA/SPhN, CEA/Saclay, F-91191 Gif-sur-Yvette cedex, France
[2] Facultad de Fisica, Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain

Introduction

The spallation process is usually described by two steps. The first one is an intra-nuclear cascade (INC) leading to an excited nucleus and fast particle emission and the second one is a deexcitation phase. The excited nucleus can deexcite by two ways: evaporation of particles (mainly nucleons, but also composites) and possibly fission in the case of heavy residues. Of course, the results depend a lot on the quality of the fission model, but the entrance parameters, i.e. the features of the fissioning nucleus, are obviously important as well. Consequently a precise description of the previous stages, INC and evaporation, is required.

Intra-nuclear cascade and evaporation models

The deexcitation phase has to be described by a consistent competition between two different mechanisms, namely evaporation and fission. For this study the ABLA code from GSI has been used and a full description of the fission model implemented in ABLA can be found in the reference [1].

A main stage is the determination of the fission probability. This probability depends on the fission width which is supposed to be equal to the Bohr-Wheeler width (Γ_{BW}) multiplied by two factors related to the dissipation. We will not discuss here these last factors which are the subject of other studies [2].

$$\Gamma_{BW} = \frac{1}{2\pi\rho(E_i^*)}\int_0^{E_i^*} \rho_{saddle}(E_i^* - B_f - \varepsilon)d\varepsilon \qquad (1)$$

The Bohr-Wheeler width depends principally on the fissioning nucleus state densities ρ. The ingredients needed to describe these level densities are the excitation energy (E^*), the angular momentum (J, via the fission barrier, B_f), and the mass and charge of the nucleus ((A,Z), via the level density parameter, a_f, and via the fissility parameter Z^2/A).

The values of these parameters are determined by the processes occurring before the fission takes place, i.e. the cascade and the evaporation steps.

The codes we have used are INCL4 and ISABEL for the INC and ABLA for the evaporation. They are known to reproduce rather well a large part of available spallation data as neutron emission, mass, charge and isotopic residue distributions. A detailed description of these codes can be found in reference [3] for INCL4, reference [4] for ISABEL, and in reference [5] for the evaporation part of ABLA. We show briefly hereafter the main features of these codes.

The following table gives the differences and similarities between INCL4 and ISABEL.

	INCL4	ISABEL
Nucleus	**A** nucleons **-** Positions shot in a Saxon-Woods density	Homogeneous nuclear density by 16 density steps
Interaction in the nucleus	Minimum distance of approach	Mean free path
Emitted particles	n, p, pions	n, p, pions
Condition for leaving the INC stage	Stopping time	Cutoff energies
Nucleon Potential	V_N = 45 MeV	Nucleon kinetic energy (T_N) dependent potential $V_N=V_i(1-T_N/T_{max})$

The evaporation mechanism in ABLA is based on the Weisskopf-Ewing approach and therefore is a statistical process where the competition to know which particle is emitted is ruled by the emission probabilities. The probabilities depend on the mass, charge and excitation energy of the nuclei (before and after evaporation), and on the mass, charge and binding energy of the candidate emitted particle. The evaporation process stops when all probabilities are equal to zero or, of course, when fission occurs. Fission fragments can also evaporate. In the original version only emissions of n, p and α are considered.

INCL4 and ABLA were implemented in the high energy transport code LAHET3.16 [6] to perform these calculations. Now, all the codes used in this study (INC and deexcitation) are available in the transport code MCNPX [7].

Sensitivity of the fission probability on the INC and evaporation modelizations

State-of-art for two combinations: INCL4/ABLA and ISABEL/ABLA

Since we plan to study how the INC and evaporation models can influence the fission fragment production, it seems obvious to know what the quality of these models is, in order to be able to test its sensitivity to possible improvements.

We will use afterwards the term *models* for *combinations* of INC and evaporation/fission. We have selected results which can be regarded as representative.

Concerning the charge distributions, we can see on the figure 1 that both models give good results for the fission part, even if the results are better for the reaction with lead compared to those on gold. The third combination, where the deexcitation code is not ABLA but Dresner [8], is plotted here just to validate the choice of ABLA.

The isotopic distributions are well reproduced also in the figure 2 for the reaction p+Pb at 1 GeV/A. The data for these distributions (isotopic and charge) have been obtained at GSI [9][10].

Finally we show a set of excitation functions on the figure 3 for the reaction p+Bi. The data are kindly provided by R. Michel (Hanover University) and will be soon published. We plotted here only INCL4 and not ISABEL, because this observable is very time consuming and because ISABEL is supposed, in LAHET and MCNPX, to be used below 1 GeV and not beyond. On the figure 3 there are two kinds of fission products: the neutron rich (left side) and the neutron poor (right side) fragments. When a nucleus undergoes fission both nuclei produced are neutron rich and afterwards they can deexcite by evaporation and principally neutron emission. The number of emitted neutrons depends on the excitation energy.

The agreement appears reasonable, but looking carefully it seems it could be better if the curves are shifted towards the low energy side. If we come back to the figure 1, we can see the evaporation part of the charge distributions are not so well described by INCL4 and ISABEL, but ISABEL is better. This bad behaviour could be due to a lack of excitation energy, since, on the one hand, as we have just already said, the number of evaporated particles depends on the excitation energy, and, on the other hand, ISABEL let the nucleus with an higher excitation energy than INCL4. And this possible lack of excitation energy in INCL4 could also explains the discrepancies seen on the figure 3. We will come back on this hypothesis later.

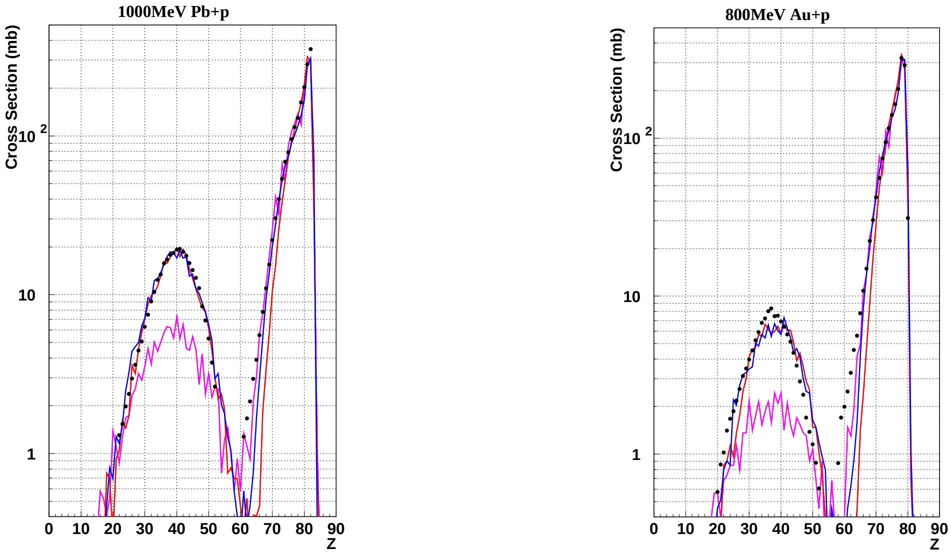

Figure 1: Charge distributions for the reactions p+Pb (left side) and p+Au (right side). The red line stands for INCL4/ABLA, the blue line for ISABEL/ABLA, and the pink line for INCL4/Dresner. Points are data from [9] and [10].

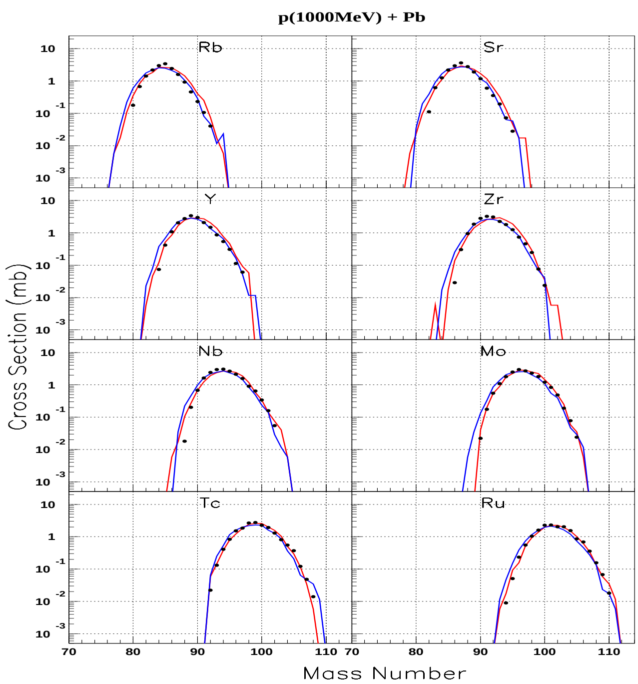

Figure 2: Isotopic distributions for the reaction p+Pb. The red line stands for INCL4/ABLA, and the blue line for ISABEL/ABLA. Points are data from [9] and [10].

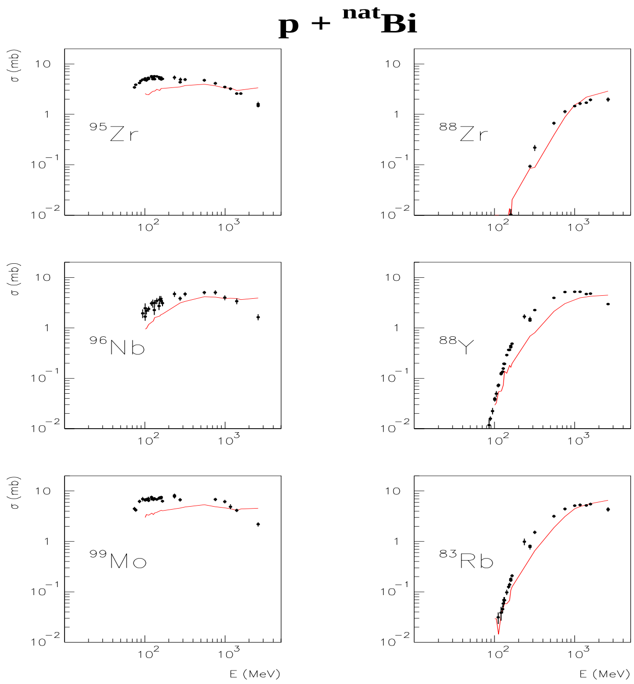

Figure 3: Excitation functions for the reaction p+Bi. The red line stands for INCL4/ABLA.

If the nucleus could evaporate d, t and ^{3}He…

We have seen that both models, INCL4/ABLA and ISABEL/ABLA, give rather good results for the fission part of the spallation process, but we have seen also that some improvements can be done.

The d, t and ^{3}He emission during the deexcitation step is one of these improvements. In fact, it is not directly related to the fission process, but these particles are experimentally detected [11], and we decided to introduce these output channels in ABLA. The way we have used to implement the d, t and ^{3}He emission is exactly the same one already used for n, p and α. Thus we have had to calculate principally the coulomb barriers and the relative emission probabilities. The expression of the relative emission probability is:

$$P_r = \frac{\rho(E^*_{cons})}{\rho(E^*_{ref})} * \frac{(2s_{cons}+1)}{(2s_{ref}+1)} * \frac{M_{cons}}{M_{ref}} * \left(\frac{T_{ref}}{T_{cons}}\right)^2 \quad (2)$$

With:

- "*cons*" stands for the particle considered (or nucleus obtained after emission of the particle considered)
- "*ref*" stands for the particle considered as reference (or nucleus obtained after emission of the particle considered as reference) – (P_r=1)
- $\rho(E^*)$ is the state density of the nucleus after emission
- *s* and *M* are the spin and mass of the particle
- *T* is the temperature of the nucleus

And this probability is set to 0 if the excitation energy is lower than the sum of the separation energy and the coulomb barrier B_c.

$$B_c = \frac{1.44 * Z * z}{b * A^{1/3}} \quad (3)$$

With:

- Z and A the charge and mass of the nucleus after emission
- z the charge of the emitted particle
- b a parameter which takes into account the r_0 radius used for the nucleus radius expression ($R=r_0*A^{1/3}$) and the effect of barrier penetration - b=2.1 for p, and b=2.2 for d, t, ^{3}He and α.

The question was so: how are the fission product distributions modified?

The figures 4 and 5 show the results for charge and isotopic distributions. It is clear the previous good results are destroyed. Now the fission products are underestimated for both models, and especially for ISABEL.

The introduction of the d, t and ^{3}He evaporation which is a necessary physical improvement seems disturb the predictions for the fission product distributions obtained earlier. We will see later that a good agreement can be obtained for INCL4 with d, t and ^{3}He by increasing the excitation energy, again with physical reasons.

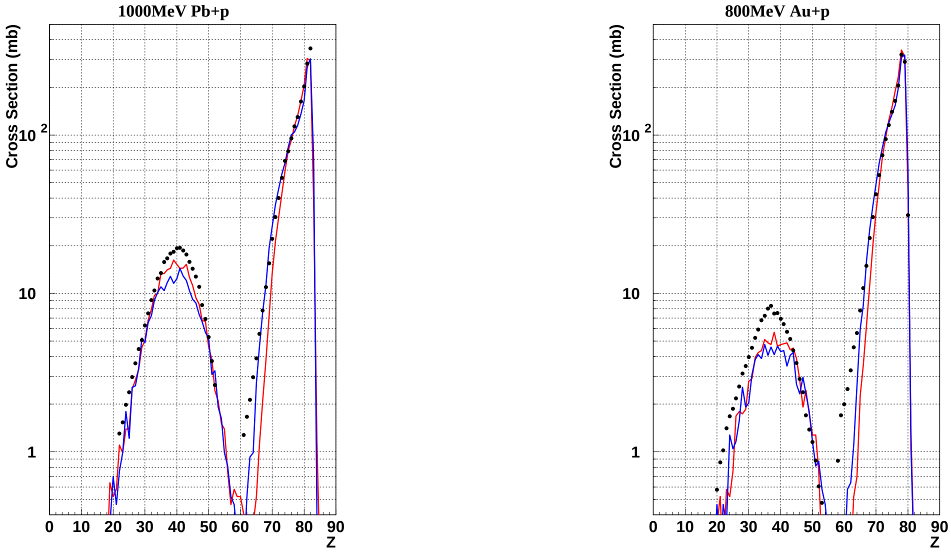

Figure 4: Charge distributions for the reactions p+Pb (left side) and p+Au (right side). The red line stands for INCL4/ABLA(+d,t,^{3}He) and the blue line for ISABEL/ABLA(+d,t,^{3}He). Points are data from [9] and [10].

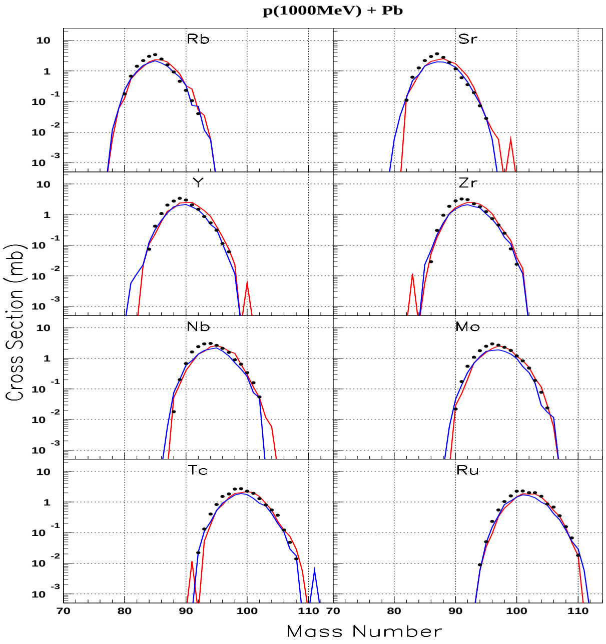

Figure 5: Isotopic distributions for the reaction p+Pb. The red line stands for INCL4/ABLA(+d,t,^{3}He) and the blue line for ISABEL/ABLA(+d,t,^{3}He).

Which role for the angular momentum of the fissioning nucleus?

The angular momentum (J) favors the nucleus disruption, because J decreases the fission barrier [12].

J is determined at the end of the INC, since, with the present ABLA code, the decrease of the angular momentum is not taken into account in the evaporation phase. The ways INCL4 and ISABEL calculate J are very different since the nucleus descriptions are different. In INCL4, J is determined out of the nucleus and directly after the cascade by the formula: $\vec{J}^{*} = \vec{J}_{ini} - (\vec{J}_{part} - \vec{J}_{rem})$, where $\vec{J}^{*}$ is here the angular momentum (J) vector, $\vec{J}_{ini}$ the initial angular momentum, $\vec{J}_{part}$ and $\vec{J}_{rem}$ are respectively the momentum taken by the emitted particles and the momentum of the nucleus center-of-mass after the cascade. In ISABEL, the calculation is done in the nucleus and all along the cascade. For each interaction, where a nucleon from the Fermi sea participates or where a nucleon below a threshold comes back to the Fermi sea, the angular momentum is modified.

The values for J are also different. In the table below some examples are drawn from the reference [13].

Reactions	INCL4	ISABEL
p + ^{208}Pb (500 MeV)	20	15
p + ^{208}Pb (1000 MeV)	26	18
d + ^{208}Pb (2000 MeV)	36	24

Figure 6 illustrates the effects of the angular momentum on a charge distribution. Three curves are plotted: ISABEL with its own J, ISABEL with a J calculated with the de Jong method [14], used before in ABLA, and leading to a lower value than ISABEL ($J = J_{isabel} * 0.38$) and INCL4 (with its own $J = J_{isabel} * 1.44$). The role of J is evident if we compare the cases where the only change is the value of J (blue curves). But, when we compare ISABEL to INCL4, where the J values are also very different, we observe the same good agreement with the data. The reason is that J plays an important role on the fission fragment production, but other parameters play an important role as well. And here it is probably the excitation energy, since INCL4 has a high J which favors fission, but ISABEL has a higher excitation energy which compensates its low J value (compared to INCL4).

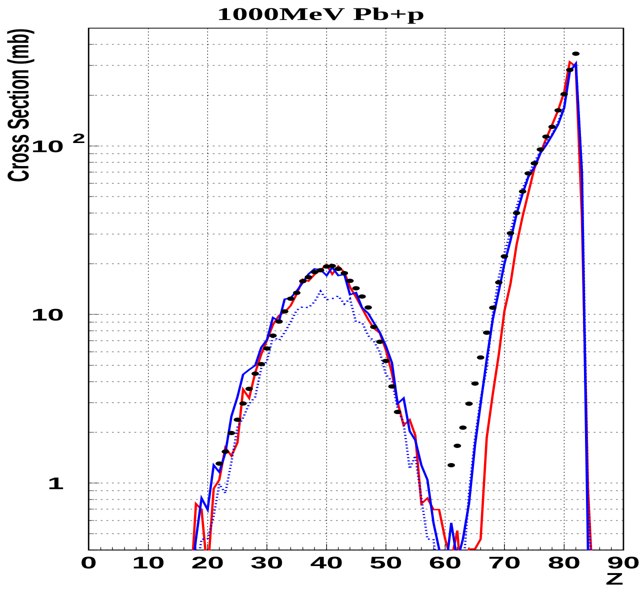

Figure 6: Charge distributions for the reaction p+Pb. The red line stands for INCL4/ABLA, the solid blue line for ISABEL(own J)/ABLA, and the dotted blue line for ISABEL(J=J_{isabel}*0.38)/ABLA. Points are data from [9] and [10].

To sum up, J is an essential parameter, but unfortunately it is difficult to disentangle its role from other ones.

What about the stopping time in INCL4 ?

The stopping time in INCL4 has been carefully investigated and fixed from the time behaviour of several observables (excitation energy, momentum-asymmetry, etc.) [2]. Since, from the evaporation part of the charge distributions (fig.1) and the excitation functions (fig.3), it seems we need more excitation energy, a possible way to increase it artificially was to stop the cascade earlier and so to decrease the stopping time. We just multiplied it by a factor 2/3, which is the biggest modification we can do reasonably (according to the stopping time studies in the reference [2]). We have to mention here that with this new stopping time the neutron spectra are not so well reproduced than with the default stopping time, especially in the 20-60 MeV range.

On the figure 7, we see that the previous good results for the charge distributions are destroyed. Now the fission products are overestimated.

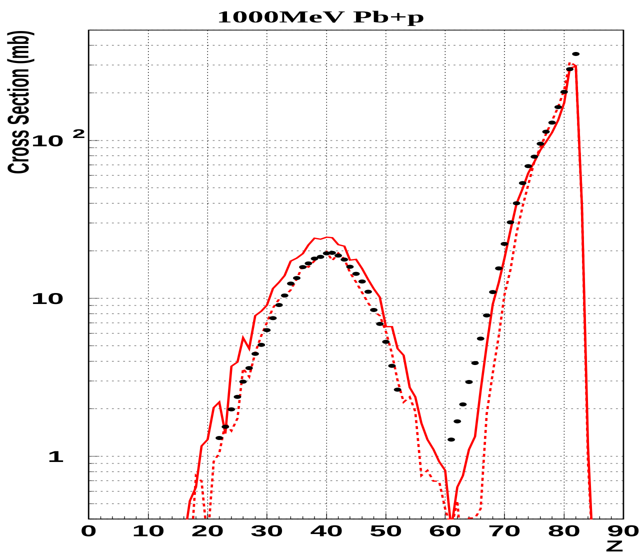

Figure 7: Charge distributions for the reaction p+Pb. The solid red line stands for INCL4(t=t$_{default}$*2/3)/ABLA and the dotted red line stands for INCL4/ABLA. Points are data from [9] and [10].

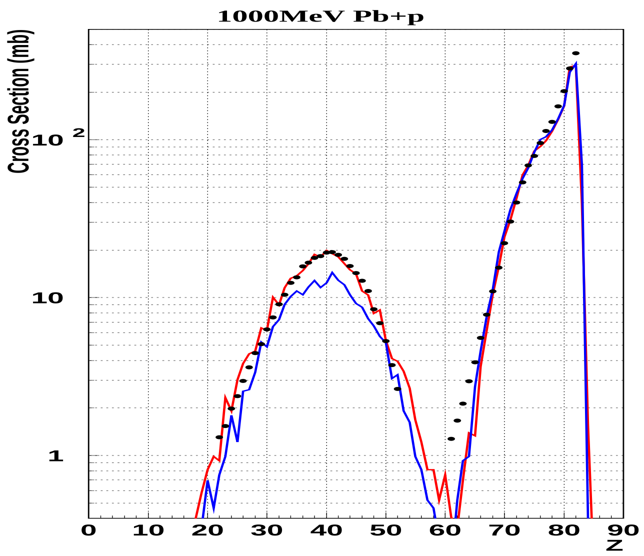

Figure 8: Charge distributions for the reaction p+Pb. The red line stands for INCL4(t=t$_{default}$*2/3)/ABLA(+d,t,^{3}He) and the blue line for ISABEL/ABLA(+d,t,^{3}He). Points are data [9] and [10].

But, by combining the stopping time reduction with the d, t and ^{3}He evaporations, we obtain in the figure 8 the same good results for the charge distribution as before. Further the isotopic distributions, figure 9, are also well reproduced. The main result is for the excitation functions, figure 10. With reduction of the stopping time in INCL4 and opening of the d, t and ^{3}He emissions in ABLA, the shapes are better reproduced than in figure 3.

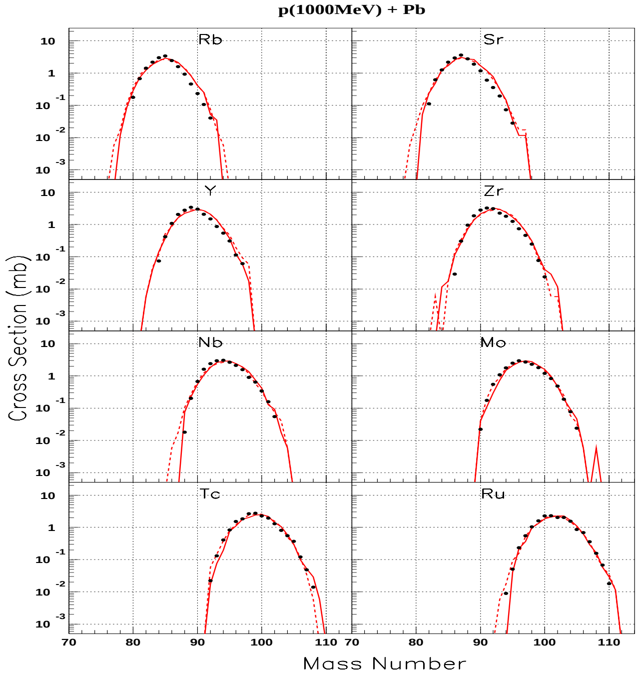

Figure 9: Isotopic distributions for the reaction p+Pb. The red line stands for INCL4(t=$t_{default}$*2/3)/ABLA(+d,t,^{3}He) and the dotted red line stands for INCL4/ABLA. Points are data [9] and [10].

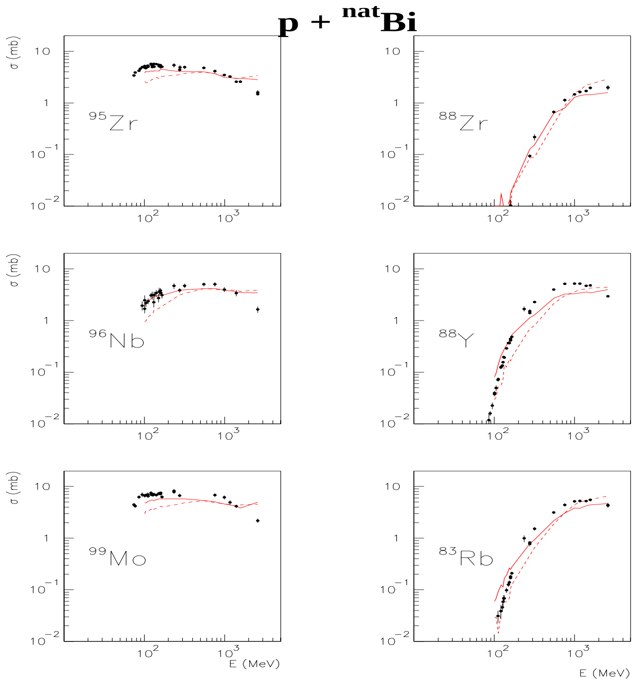

Figure 10: Excitation functions for the reaction p+Bi. The red line stands for INCL4(t=$t_{default}$*2/3)/ABLA(+d,t,^{3}He) and the dotted red line stands for INCL4/ABLA.

Conclusion

We have shown that the modelizations of the intra-nuclear cascade and the evaporation phase influence strongly the fission fragment production, since the features of the fissioning nucleus are determined by these two previous processes.

The fission cross section is sensitive to the angular momentum (and to dissipation and fissility, not studied here), but the role played by the angular momentum can be compensated by the excitation energy. In fact, for example, we cannot decide which is the best INC code since INCL4 and ISABEL give the same good results with two different angular momenta. More constraining experimental data on this observable would be very interesting.

If we try to build models which are as close as possible to the reality, and if we try to understand what the defaults of the models are, we can hope to improve them on the right way. That is what we have understood by the d, t and ^{3}He evaporation and by the stopping time reduction, after analyzing excitation functions. If the necessary d, t and ^{3}He emission during the deexcitation step damaged the previous good charge distribution results and the stopping time reduction as well, both combined led to better results than before.

Other parameters have to be taken into account, and the results presented here will be perhaps affected, but we know it will be on the right direction. For example, during the INC some composites can be emitted (d, t, ^{3}He and α), and the very next work will be to test the influence of these new channels on the fission, since they have been introduced recently in INCL4 [15].

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[i] jcdavid@cea.fr