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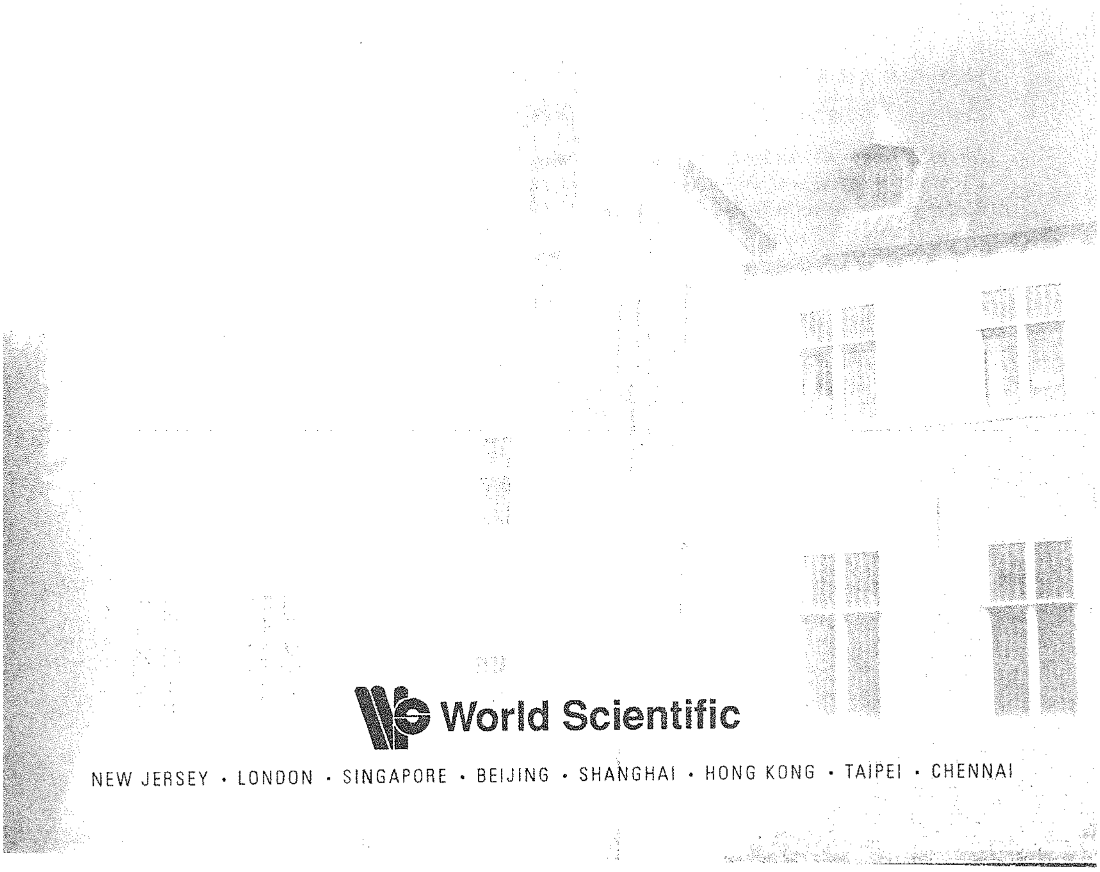

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FISSION IN SPALLATION REACTIONS

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Some properties of fission in spallation reactions in the GeV range are examined. It is shown on theoretical grounds that the charge, mass and excitation energy are strongly fluctuating. The range of accessible excitation energies is determined. The ability of a particular intranuclear plus evaporation model, namely the INCL4+ABLA model to describe the existing data is demonstrated. In view of the numerous parameters used in the fission model, the sensitivity of the results to these parameters is investigated. It is shown that, due to the complexity of the fission modeling, it is hard to get reliable information on the level density parameters at high excitation energy. Finally the influence of the nature of the incident projectile is shortly discussed.

Keywords: Spallation reactions; Fission at high excitation energy; Intranuclear cascade; Evaporation-fisssion model.

1. Introduction

There has been recently a revived interest in spallation reactions triggered in particular by the advent of projects for accelerated driven systems for transmutation of nuclear waste. In such devices, a spallation target is located at the center of a subcritical core and is bombarded by a high energy (typically 1 GeV) proton beam. Rapid neutrons emitted by the spallation source are propagating in the core and transform long-lived radioisotopes in stable or short-lived ones through nuclear reactions. In the last years an important program of theoretical and experimental studies [1] has produced a lot of good quality data concerning spallation reactions, which are expected to be utilized by engineers to design and optimize spallation sources. In particular inverse kinematics experiments conducted by the GSI group has allowed to have comprehensive and precise measurements of the residue production cross-sections [2]. This includes so-called fragmentation (or evaporation) residues, but also fission products. As we discuss below, an investigation of the fission process has so been realized for excitation energy of the order of 100 to a few hundred MeV. Previous data are rather scarce and often limited to fission probability. See Refs. [3–6] for recent reviews.

In this paper, we want to make a short survey of the information which can be learned from this new set of data. We will first try to identify the conditions for fission occuring in spallation reactions induced by protons in the 200 MeV-1 GeV range. We will see that the charge and mass of the fissioning nucleus is not fixed and can fluctuate sizably. This is true for the excitation energy as well and we will identify with model calculations the range of this excitation energy. Despite of these aspects, that complicate the analysis, it turns out that the intranuclear cascade plus evaporation-fission model described in Ref. [7] is able to reproduce successfully the bulk of the experimental results. Finally we will discuss the sensitivity of the calculations to the input of the model, especially for the fission model and try to identify the aspects that should be refined at high excitation energy.

The paper is divided as follows. In Sec. 2 we give a brief general description of spallation reactions. Sec. 3 is devoted to model calculations showing the particular conditions under which fission is occuring in the course of spallation reactions. A short review of the main experimental data concerning fission is given in Sec. 4. After a description of the generic features of intranuclear cascade (INC) and evaporation-fission models, a short description of the specific model used in this paper, namely the Liège INC model, coupled to the ABLA evaporation-fission model, is given in Sec. 5. The next Section shows how the standard version of this combined model can describe the existing experimental data. Sec. 7 is devoted to an analysis of the sensitivity of the model to the input data and to the behaviour at high excitation energy. In Sec. 8, the dependance upon the nature of the projectile is briefly examined. Finally, Sec. 9 contains our conclusion.

2. Spallation reactions

This expression is used to designate both the interaction of a highly energetic particle with a macroscopic target (thick target experiments) and the one with a nucleus (corresponding to thin target experiments). Obviously, the (nuclear) interaction in a macroscopic target starts with the interaction of the high energy particle with a nucleus. Generally fast nucleons with a energy smaller than, but comparable with, the incident particle energy are emitted. These particles can induce further interactions, which in turn produce other (less) fast particles inducing other interactions, and so on. The interation process with a thick target can be viewed as an iteration of microscopic spallation reactions, with a progressive decrease of the energy of the propagating particles. Charged particles are slowed down in the spallation target by Coulomb interactions with the electrons and are largely stopped in the target. Neutral particles, mainly neutrons, but also neutral pions and gamma's, escape from the target. For transmutation applications, the important quantity ξ is the number of escaping neutrons per incident proton divided by the energy of the proton. This quantity is proportional to the ratio of the number of neutrons divided by the "price" to pay for producing them, since the price (in energy) of an incident proton is proportional to the energy E_p at which it is accelerated. It turns out that, for typical spallation targets, the quantity ξ displays, as a function of E_p, a maximum around 1 GeV [8]. That is the reason why the above-mentioned studies of spallation reactions were focused on E_p values in the 100 MeV to 1 GeV incident energy range. We will limit ourselves to the same energy range here.

It is interesting to mention the main features of microscopic spallation reactions. During this process several neutrons are emitted. Their multiplicity increases with the incident energy and with the target nucleus mass number. To give an idea, on the average, about 15 neutrons are emitted in $p+^{208}Pb$ reactions at 1 GeV. Most of these neutrons are evaporation-like. Only a small fraction (~15%) have an energy above 20 MeV, but their spectrum may extend up to the incident energy. Protons, pions and light clusters may also be emitted, but less abundantly. A final residue (two in the case of fission) is ultimately produced. For light targets the residue mass spectrum extends from zero to the original target mass number. For heavy targets, the spectrum, though having strictly the same property, shows two prominent peaks corresponding to fission and evaporation (see below).

In the energy range under interest, the spallation reactions are well described by the INC+evaporation-fission model. The latter views the reaction as a two stage process. The first stage corresponds to a sequence of binary nucleon-nucleon collisions leading to the emission of a few fast particles and to a more or less thermalized nucleus, called the remnant. The second stage consists in the de-excitation of this remnant through the evaporation of slow light particles competing possibly with fission.

3. Conditions of fission in spallation experiments

Conditions of fission in spallation reaction experiments are somehow peculiar. First, the charge and mass of the fissioning nucleus are not fixed, since fission can occur in the course of the second stage. It is thus preceeded and followed by sequences of elementary processes, which can fluctuate from one event to the other. The identification of the fissioning nucleus is practically impossible, except if final products are detedted in coincidence, which is not yet the case (see Sec. 9). One has thus to rely on model calculations to have an idea about the identity of the fissioning nucleus and its other properties. We are going to illustrate this point, using the model of Ref. [7], for three typical cases.

Table 1. Average mass number, charge and excitation energy of the remnant and of the fissioning nucleus.

		Remnant	Remnant/fission	Fissioning nucleus
^{238}U	$< A >$	231	237	225.6
	$< Z >$	91	92	90.2
	$< E^* >$ (in MeV)	143	156	81.4
^{208}Pb	$< A >$	202.7	202	192.5
	$< Z >$	80.5	81	80.1
	$< E^* >$ (in MeV)	136	217	109
^{181}Ta	$< A >$	180.5	175	168
	$< Z >$	72	72	71
	$< E^* >$ (in MeV)	128	241	120

Table 1 gives the average charge, mass number and excitation energy in the cases of reactions of 1 GeV protons with ^{181}Ta, ^{208}Pb and ^{238}U. The third column refers to the remnants for all events, whereas the fourth column refers to fission events only (i.e. the events where fission occurs). The last column refers to the fissioning nucleus and the average is made on fission events only, of course. Several observations are in order. First of all, the average excitation energy of the remnant is much smaller than the available energy (1 GeV). It is increasing with the target mass, but the excitation energy per nucleon is decreasing with the mass number of the remnant. One can also see, as announced before, that only a few nucleons are emitted in the cascade stage and they are predominantly neutrons. More remarkably, fission occurs in events where the mass loss at the end of the cascade is modest and where the excitation energy is substantially larger than for all events. For the latter point, the lighter the target, the larger is the excitation energy. In fission events, the fissioning nucleus is substantially lighter than the remnant, but the charge is not diminished correspondingly. Also, the last column shows that the remnant nucleus has lost considerable excitation energy before fissioning, roughly half of its initial excitation energy, for all cases. On the average, the excitation energy per particle of the fissioning nucleus is rather modest (in view of the available energy): from ~0.4 MeV for *U* to ~0.7 MeV for *Ta*.

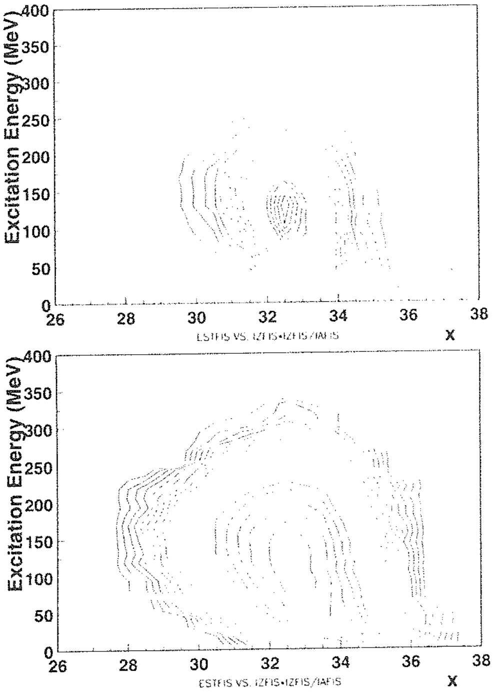

Fig. 1. Contour plots for the joint distribution of the excitation energy and the fissility parameter $x = Z^2/A$. The upper panel refers to the remnant and the lower part refers to the fissioning nucleus in $p(1GeV) + {}^{208}Pb$ reactions.

However, there are considerable fluctuations around the mean values of all the quantities discussed above: charge and mass numbers of the remnant, of the fissioning nucleus and excitation energy. We give an illustration in

Fig.1 for the case of ^{208}Pb. One can see that fission can occur at very low excitation energy and up to very high excitation energy (around 300 MeV), altough the average excitation energy of the fissioning nucleus is 109 MeV. The dispersion of the fissility parameter for the fissioning nucleus indicates that fission can occur at fissility parameters substantially larger than the one of the target nucleus ($x \approx 32$ for this case).

Summarizing this section, analysis of fission in spallation reactions is made somehow difficult because the charge and mass of the fissioning nucleus are subject to large fluctuations. This drawback will be alleviated when experiments detecting both fission products and accompanying light particles are performed. The interesting point is that spallation reactions allows to study fission at high excitation energy, owing to the fluctuations.

4. A short review of the experimental data

Fission cross section data are rather scarce and rather imprecise. One often refer to the Prokofiev systematics [6] which is a rough fit of existing data. This systematics shows a fission probability rising to a plateau around 400 MeV incident energy, where it assumes, for Pb, a value of 77%. There exist three extensive measurements of isotope production cross sections. Two of them are based on radioactive decay mesurements and are thus partial [4,5]. The GSI measurements [9,10] use the inverse kinematics and thus measures production cross sections for individual isotopes, be they radioactive or stable. These complete measurements have been done at very few incident energies, whereas the measurements of Refs. [4,5] offer excitation functions. There are practically no measurement of the neutron multiplicity, except at low incident energy [11,12]. The inverse kinematics experiments allowed also some crude measurements of the velocity of the fragments. We give a little more information below when we compare with models.

5. Theoretical models

5.1. *The general model*

As stated above, the general model for describing spallation reactions is the INC+evaporation model. Of course, for the description of fission events, a competition with fission, and thus a fission model, are required. For the moment, several INC models are used. They are defined by the acronyms of the numerical tools in which they are translated: INCL [7], Isabel [13], CEM2k [14], QMD [15], etc. Evaporation is usually based on the Weißkopf-Ewing model [16] or the GEMINI model [17], which treats emission of $Z > 3$

clusters by the transition-state model [18]. Current fission models are in fact parametrizations of the various fission observables, largely based on systematic studies and sometimes on theoretical arguments. The most popular fission models are named: ABLA [19–21], Atchison [22], Dresner [23] and GEM [24,25]. We give some information below on their common features and differences.

5.2. *The INC model*

In this model, the impinging nucleon initiates a multiple collision process with nucleons in the target. This is realized by simulation. There are two kinds of models. In the first kind, the target is initially taken as a collection of nucleons distributed at random and with momenta taken in a Fermi sphere; then nucleons are set in motion and nucleon-nucleon collisions occur when two nucleons come close enough to each other, i.e. when their minimum relative distance is smaller than the square root of the NN cross section divided by π. In the second kind of INC models, the target is seen as a continuum providing the cascading particles with a path whose mean is the inverse of the product of the NN cross section and the nuclear density. In both kinds of models, collisions can be elastic or inelastic and are subject to Pauli blocking. Nucleons can be emitted if they reach the surface of the nucleus with a sufficient energy and if they pass the test for avoiding reflexion, based on transmission formula for (Schrödinger) waves on a potential step. The simulation process is stopped when the energy of the cascading particles is low enough (the precise criterion may vary from model to model).

Below, we give numerical results for the INC model developped in Liège (usually denominated as INCL4[a]). Therefore we give a little more information on several other features of this model: *(i)* nucleons move in an average potential well, *(ii)* relativistic kinematics is used, *(iii)* isospin symmetry is respected, *(iv)* nucleon-nucleon collisions can be elastic or inelastic (in the last case a Δ-resonance is produced which can further decay into a nucleon and a pion), *(v)* pions can escape or can further interact with a nucleon to form a Δ-resonance, *(vi)* Δ-resonances can scatter elastically on nucleons and on other Δ-resonances, *(vii)* the model can accomodate nucleons and light clusters (up to ^4He) as incident particles. An original feature of the model is that the stopping time, i.e. the time at which the cascade process

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[a] In this paper we stick with the standard version of INCL4, as described in Ref. [7]

is stopped to give place to evaporation, is determined self-consistently, as explained in [7].

Although classical in nature, the model accounts for some quantum aspects: existence of a mean field, Pauli blocking of collisions, quantum transmission through the nuclear surface and stochastic determination of the final states in NN collisions. Finally, we want to stress that the INCL4 model is basically a parameter-free model. It rests on assumptions, of course, but the input are the NN cross sections, which are taken from experiment and the nuclear density, which is taken from electron scattering measurements. The only real parameter is the Fermi momentum, the depth of the potential well being then related to the separation energy.

5.3. *The evaporation-fission model*

The usual evaporation models rest on the Weißkopf-Ewing formula

$$d\Gamma_b = \sigma^{CN}(b + B^\star \to A^\star)\frac{2m}{(2\pi)^3\hbar^2}\frac{\rho(E_B^\star)}{\rho(E_A^\star)}\varepsilon d\varepsilon, \tag{1}$$

for the emission of a light particle b of kinetic energy ε from an excited nucleus $A^\star$, leaving an excited nucleus $B^\star$. However, they differ by the choice of the parameters. The main ones are the inverse cross sections σ^{CN}, the Coulomb barriers (cutting down the cross sections at low energy) and the level density parameter a entering in the level density ρ. The latter is basically written under the form

$$\rho(E^\star) = p\exp(2\sqrt{aE^\star}), \tag{2}$$

where p is some slowly-varying prefactor. Quite sophisticated expressions for a are used, which often include the Gilbert-Cameron parametrization at low energy, correction of the excitation energy for collective (pairing, rotation, etc) effects and the Ignatyuk formulation for the dissapearance of shell effects at increasing excitation energy [26]. More interesting for us here is the behavior at high excitation energy, which is usually assumed as $a \approx A/\xi$, where ξ is a constant, possibly corrected by some surface term. The fission width is usually given by the transition state method

$$d\Gamma_f = \frac{1}{2\pi}\frac{\rho_B(E_B^\star)}{\rho(E_A^\star)}d\varepsilon, \tag{3}$$

where $E_B^\star$ is the excitation energy of the system at the fission barrier and where ε is the kinetic energy (in the collective motion) at the barrier. The crucial parameters are the height of the fission barrier (and its angular momentum dependance) and the level density parameter a_f at the barrier (entering ρ_B). At high excitation energy, the ratio between the fission and the neutron widths, which basically controls the evaporation-fission competition, is given by

$$\frac{\Gamma_f}{\Gamma_n} \sim \frac{1}{E^*} \exp(2(\sqrt{a_f} - \sqrt{a_n})\sqrt{E^*}). \tag{4}$$

Due to the presence of the exponential, this quantity is quite sensitive to the difference of the level density parameters at high excitation energy.

In evaporation-fission codes, the cascade of emission/fission is governed by the relative probabilities

$$P_i = \frac{\Gamma_i}{\sum_i \Gamma_i}, \tag{5}$$

for decays in different channels, which are re-evaluated at each step. This procedure is justified as long as the (average) time separating two successive emissions, of the order of $\tau_i = \hbar/\Gamma_i$, is large compared to the time t_i required for the emission itself. This time is not well known. For neutron emission, it is of the order of R/v, where R is the nuclear radius and v the neutron velocity. For fission, this time is much longer. At low excitation energy, t_i, both for neutron emission and for fission, are smaller than the τ_i's. As excitation increases, τ_n decreases substantially and eventually becomes smaller than t_f. Even if the fission process starts, emission of neutrons may occur before the fission process ends. The independence of successive emissions breaks down and the net effect is an hindrance of fission. Eventually, when the system is sufficiently cooled down, owing to neutron emission, the condition for independant emissions is restored and fission can occur. This phenomena is often related to viscosity effects in the collective motion. It can be taken into account by simply correcting the fission width [27] by the Kramers formula [28]. It is worth to say that this effect can alternatively taken care of by introducing a time delay to fission in the cascade of successive decays [29].

In order to describe the result of the fission process, a partition model should be supplemented. It corresponds to the three following steps:

(1) The neutron number N of one of the fission fragment is generated according to the law

$$Y(E^*, N) = \frac{\int_0^{E^*-V(N)} \rho_B(U)dU}{\sum_{N=0}^{N_0} \int_0^{E^*-V(N)} \rho_B(U)dU}, \tag{6}$$

where $U = E^* - B$, B being the height of the fission barrier, and where $V(N)$ is the so-called conditional potential barrier, i.e. roughly the difference of the potential energy between the configuration of the two touching fragments and the intial one, for the partition under consideration.

(2) The charge Z of the fragment, for a given N, is usually taken from a Gaussian law, with a mean which corresponds to the same N/Z ratio as for the fissioning nucleus and with a variance which is related to the curvature of the potential energy of the touching-sphere configuration for a fixed N and varying Z.

(3) Finally, the quantity

$$E_{ex} = E^\star - V(N) + E_{diss}, \tag{7}$$

i.e. the excitation energy of the touching-sphere configuration increased by the energy dissipated from fission barrier to scission, is spread in excitation energy of the fragments proportionally to their masses, and the quantity

$$K = E^\star + Q - E_{ex} \tag{8}$$

is spread in kinetic energy of the fragments, proportionally to their inverse masses.

In the following, we will use the ABLA model, which accomodates n, p and α emission only, but which has a sophisticated fission model, including viscosity effects. Furthermore, many ingredients, especially the quantity $V(N)$, are inspired from microscopic calculations with inclusion of shell effects. The Atchison model does include delay to fission. Its parameters are largely phenomenological and have been essentially fitted on low-energy fission data. Let us also mention that the GEMINI model use the transition state model for any partition except for $Z \leq 3$.

6. Results with the INCL4+ABLA model

We here just want to give a taste of the results of the INCL4+ABLA model of Ref. [7] for fission in spallation reactions. This model predicts a fission cross section of 104 mb for $p(500MeV) +^{208} Pb$, to be compared to the experimental value of 132±10 mb. At 1GeV, the respective numbers are 165 and .

Fig.4 below shows the residue mass spectrum in $p(1GeV) +^{208} Pb$ reactions. The nice agreement obtained for the fission part is of course largely due to the ABLA part of the model, but results also from the predictions of INCL4 for the properties of the remnants. Fig. 2 displays more detail in the

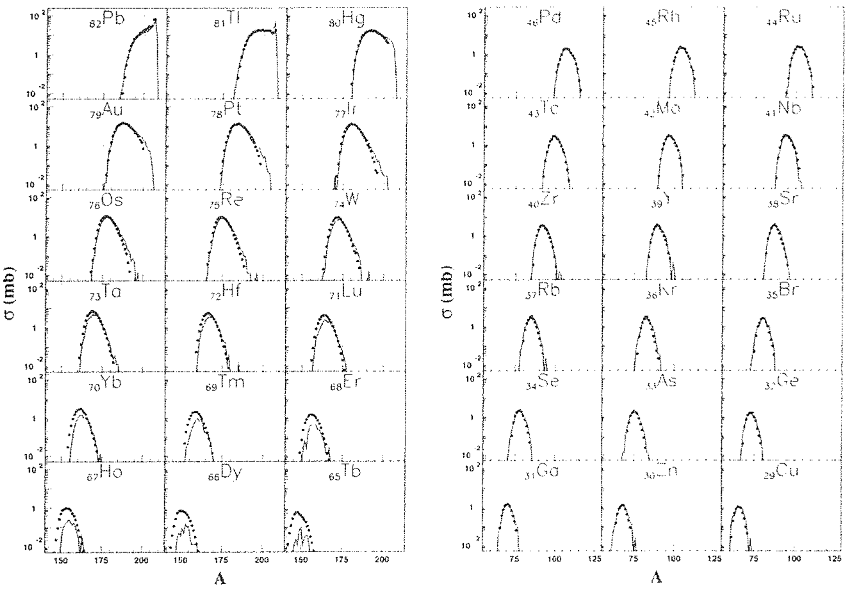

Fig. 2. Isotope production cross sections in $p(1GeV) + {}^{208}Pb$ reactions. Data from Ref. [9] (dots) are compared with the predictions of INCL4+ABLA calculations (curves). The left panel shows spallation residues whereas the right panel refers to fission residues. Adapted from Ref. [7].

form of isotope production cross sections. One can see that a nice agreement prevails in a large mass and charge range, although the calculations underpredict deep spallation products ($Z \approx 65 - 70$). Fig. 3 shows excitation functions for the production of some fission isotopes. The good agreement obtained in these calculations indicates that fission is correctly modelized in ABLA on a large domain of energy, although some shortcomings are observed locally. Good agreement is also obtained for recoil energy of the spallation residues (not shown here), which demonstrates the potentialities of INCL4, evaporation playing a minor role in this respect.

7. Sensitivity to the input data

Although INCL4+ABLA reaches a good agreement with the description of fission in spallation reactions, one may wonder whether the results are sensitive to the input of the model. This is a sound question, since there are alternative models and since part of the input data (for evaporation-fission) are largely based on phenomenology. In this paper, we just want to illustrate a few points, a general sensitivity study being quite involved

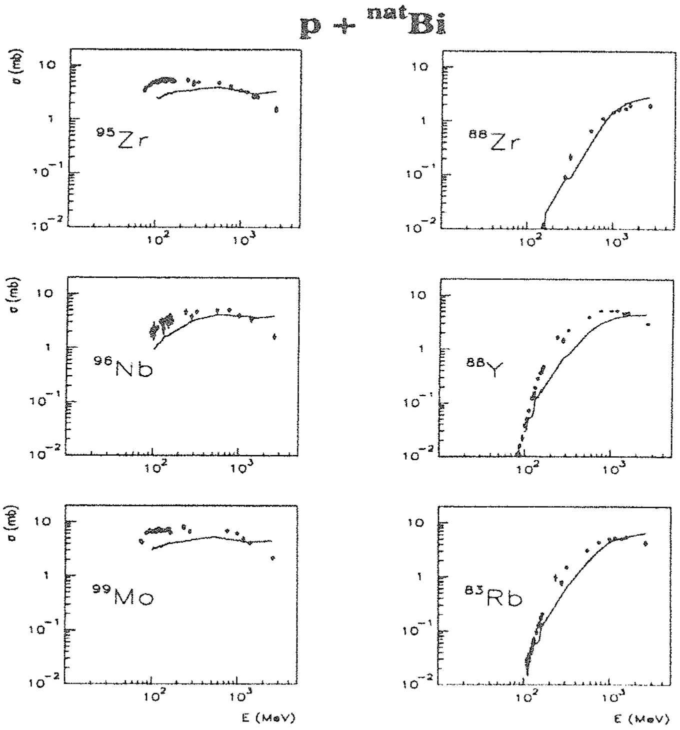

Fig. 3. Excitation functions for the production of a few fission isotopes in $p + {}^{nat}Bi$ reactions. Data from Ref. [30] (dots) are compared with the predictions of INCL4+ABLA calculations (curves). Adapted from Ref. [31].

and outside the scope of this paper. Let us first address the question of the sensitivity to the INC input. As we have said, there is no adjustable parameter in INCL4. However, one may give a partial answer to this question by using another INC model with the same ABLA evaporation-fission. This has actually been done in Ref. [31], where the Isabel model has been used as an alternative to INCL4. As far as fission is concerned, there is practically no difference between the two calculations, whereas there are sometimes noticeable differences for other observables.

The study of the sensitivity on the angular momentum dependence of the fission barriers have been initiated in Ref. [7]. Fig. 4 gives a typical result. One can see that fission cross sections are well reproduced by

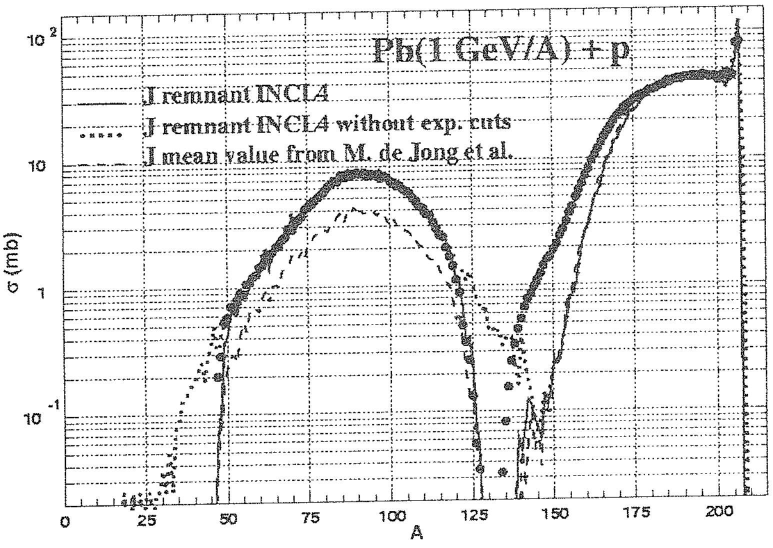

Fig. 4. Residue mass spectrum in $Pb+p$ reactions at 1 GeV/nucleon. Data from Ref. [9] (dots) are compared with theoretical predictions (curves). The dotted line corresponds to the pure INCL4+ABLA predictions, whereas the full curve corresponds to the same predictions after the experimental selection is applied (not all isotopes are measured for some isobar. The dashed curve is further obtained when the INCL4 predictions for the angular momentum of the remnant has been replaced by the de Jong systematics (see text for detail). Adapted from Ref. [7].

INCL4+ABLA (full curve) after the same cuts as in the experiment are applied. When the INCL4 predictions for the angular momentum of the remnants are replaced by the phenomenological distribution proposed by de Jong [32], the dashed curve is obtained. To give an idea of the sensitivity, let us notice that the average angular momentum in INCL4 lies around $18\hbar$ wheras it is roughly $10\hbar$ in the de Jong systematics for this particular case. One can see that the effect is an overall reduction of the fission cross section. This is rather annoying since an overall reduction of the fission probability (by modification of the fission level parameter e.g.) would have basically the same effect.

Let us turn to the sensitivity of the level density parameters and let us assume that we are sufficiently close to the conditions of validity of Eq.4 to simplify the discussion. The calculations above have been done with the standard version of ABLA in which the asymptotic value of a (ordinary states) and a_f (fission barrier states) are given by

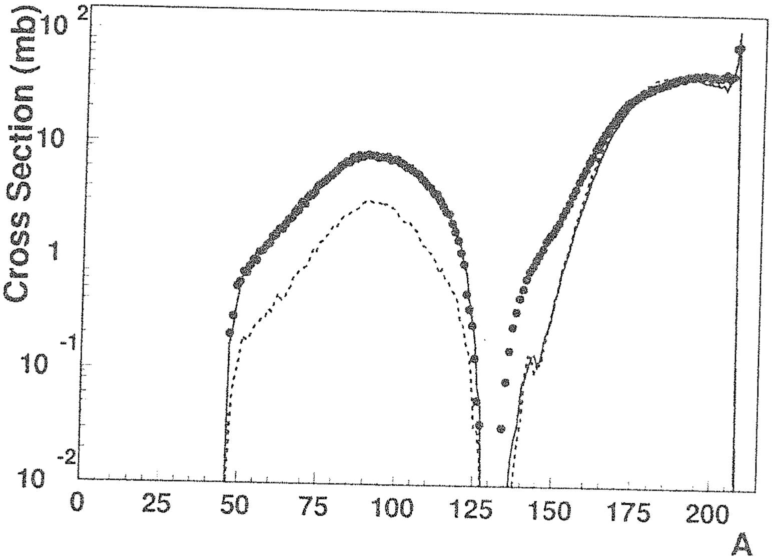

Fig. 5. Residue mass spectrum in $p(1GeV)+{}^{208}Pb$ reactions. Data from Ref. [9] (dots) are compared with theoretical predictions of INCL4+ABLA with the standard values of the asymptotic level density parameters shown in Eqs.9 and 10 (full curve) and with B_S=1 (dotted curve).

$$a = A/13.7 + 0.095A^{2/3} \tag{9}$$

and

$$a_f = A/13.7 + 0.095B_S A^{2/3}, \tag{10}$$

respectively. In the last equation, the quantity B_S is a tabulated function decreasing regularly from 1.5 to unity when the fissility parameter x increases from 0 to 50. To give an idea, for fission in reactions on Pb, this yields $a_f/a \approx 1.03$. In Fig.5, we show the results of a calculation where this ratio is put to unity (this is an option of the ABLA code). One finds a considerable change in the fission cross section although the change in the ratio a_f/a is rather small. This result should be confronted with the one of Ref. [31], where a calculation using INCL4 and the Dresner evaporation code which includes the Atchison fission model (altough not the last version) is reported. In this case, the ratio a_f/a is close to 1.08 and a reduction of the fission cross section is also observed. There is probably an explanation to this paradox. The level densities in ABLA and Dresner codes differ at lower energy in a way which is not similar to one indicated for the asymptotic regime. This is consistent with the observation made in Ref. [7] that the Dresner model evaporates sizably more than ABLA, resulting in an enhanced production of deep spallation products. This indicates that the different input data influence in an intricate way the evaporation-fission process.

We also look at the sensitivity of the results to the viscosity in fission. We make two calculations, one for the recommended value of the parameter controling this viscosity ($\beta = 1.5 \times 10^{21} s^{-1}$) and for a modified value ($\beta = 1 \times 10^{21} s^{-1}$). We observed only minor changes. This result is at variance with the results of Ref. [33], in which however a rather crude ablation model is used instead of a cascade model.

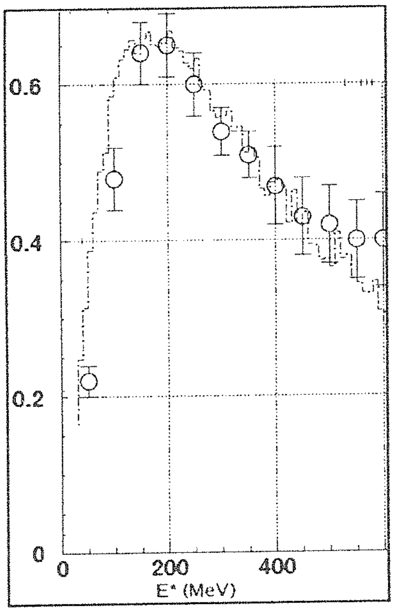

Fig. 6. Fission probability as function of the excitation energy. The circles are the data from Ref. [34] relative to fission occuring after annihilation of 1.2 GeV on ^{238}U nuclei. The dotted histograms refers to the results of INCL4+ABLA for $p(3.08GeV) +^{236} Th$ reactions. See text for detail.

8. Importance of the incident particle

One may wonder whether the fission properties are very dependent upon the nature of the incident particle. We recently made a calculation illustrating this point. In Ref. [34], the fission probability has been measured as a function of the excitation energy in annihilation of 1.2 GeV antiprotons on ^{238}U (the authors claim that a reconstruction of the excitation energy of the remnant is possible from the number of neutrons that they detect). In order to make a meaningful comparison with proton-induced reactions, one has to correct for the annihilation process: for a (A, Z) target, the total system is characterized by $(A-1, Z-1)$ in the case of antiprotons and by $(A+1, Z+1)$ in the case of protons. Therefore, the $\overline{p}+{}^{238}U$ system should be compared with the $p+{}^{236}Th$ system. Furthermore, the annihilation brings roughly 2 GeV extra available energy and transfers less angular momentum than a proton (roughly half, see Ref. [35]). Therefore we compare the results of a INCL4+ABLA calculation for 3.08 GeV protons on ^{236}Th, including a one-half reduction of the remnant angular momentum, with the data of Ref. [34]. This is illustrated by Fig.6. One can see that the agreement is remarkably good, indicating that the nature of the incident particle does not play an important role. What really matters is the available energy, which determines the excitation energy of the remnant, more or less independently of the projectile. This observation was already made in Refs. [35,36].

9. Conclusion

We have tried to deem the interest of fission studies in spallation reactions in order to have more insight into fission at special conditions. Of course fission in spallation present an intrinsic interest since it corresponds to the formation of special isotopes in addition to the usual ones coming from the evaporation of the remnant.

We have tried to exhibit the conditions on which fission occur in this kind of reactions. We have shown that there are large fluctuations of the charge and mass numbers of the fissioning nucleus as well as of its excitation energy. If this complicates the study, it also allows the study of fission at high excitation energy, typically up to a few hundreds of MeV for 1 GeV incident protons. It should be stressed however that future experiments plan to detect event by event fission fragments, light charged particles and slow neutrons [37]. The charge and possibly the mass and the excitation energy of the fissioning nucleus will so be reconstructed, alleviating the drawback just mentioned above.

We have shortly described the experimental situation and made a review of the theoretical tools. We have shown that the combination of the INCL4 cascade model and the ABLA model for evaporation-fission stage gives accurate description of representative experimental data. We have indicated that the results for fission are not very sensitive to the choice of the INC model, but in view of the partially phenomenological input of the ABLA model, we initiated a short investigation of the sensitivity of the theoretical results on the input data. We have found that the results are very sensitive to the asymptotic values (at high excitation energy) of the level density parameters, more precisely of the ratio between the fission and neutron level density parameters. The hope to determine this ratio is however mitigated by the observation that results are also sensitive to angular dependence of the fission barriers, which is badly known. On the other hand, we did not find a large dependence upon the viscsosity parameter as used in ABLA. Finally we have given indications showing that the fission properties do not depend really on the nature of the incident particle, for the same excitation energy.

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References

1. J.-P. Meulders et al, *HINDAS Detailed Final Report*, EU Report, 2005.
2. A. Kelić et al, in *Proceedings of the Workshop on Nuclear Data for the Transmutation of Nuclear Waste*, ed. by A. Kelic and K.-H. Schmidt, GSI publications, ISBN 3-00-012276-1,2004.
3. *Proceedings of the International Conference on Nuclear Data for Science and Technology, Nice, April 2007*, ed. by R. Jacqmin et al., to be published.
4. M. Gloris et al, *Nucl. Instrum. Meth. Phys. Res. A* **643** 593 (2001).
5. Yu. Titarenko et al, *Nucl. Instrum. Meth. Phys. Res. A* **414** 73 (1998).
6. A. V. Prokofiev et al, *Nucl. Instrum. Meth. Phys. Res. B* **463** 577 (2001).
7. A. Boudard, J. Cugnon, S. Leray and C. Volant, *Phys. Rev. C* **66**, 044615 (2002).
8. R. G. Vassil'kov and V. Yurevich, in *Proc. of ICANS-11*, KEK Report 90-25, Tsukuba, Japan, p.340 (1991).
9. T. Enqvist et al, *Nucl. Phys. A* **686**, 481 (2001).
10. P. Armbruster et al, *Phys. Rev. Lett.* **93**, 212701 (2004).
11. T. Ethvignot et al, *Phys. Lett. B* **575**, 221 (2003).
12. T. Ethvignot et al, *Phys. Rev. Lett.* **94**, 052701 (2005).

13. Y. Yariv and Z. Fraenkel, *Phys. Rev. C* **20**, 2227 (1979).
14. S. Mashnik, *AIP Conf. Proceedings* **768**, 1188 (2005).
15. J. Aichelin, *Phys. Rep.* **202**, 233 (1991).
16. V. F. Weißkopf and D. H. Ewing, *Phys. Rev.* **57**, 472 (1940).
17. R. J. Charity et al, *Nucl. Phys. A* **483**, 371 (1988).
18. N. Bohr and J. A. Wheeler *Phys. Rev.* **56** 426 (1939).
19. J.-J. Gaimard and K.-H. Schmidt, *Nucl. Phys. A* **531**, 709 (1991).
20. A. R. Junghans et al, *Nucl. Phys. A* **629**, 635 (1998).
21. J. Benlliure, A. Grewe, M. de Jong, K.-H. Schmidt and S. Zhdanov , *Nucl. Phys. A* **628**, 458 (1998).
22. T. Atchison, in *Proceedings of the Meeting on Targets for Neutron Beam Spallation Sources*, KFA-Jülich, Jülich Conf. 1980, p.17 (1980).
23. L. Dresner, *Oak Ridge Report*, ORNL-TM-196, 1962.
24. S. Furihata, *Nucl. Instrum. Meth. Phys. Res. B* **171**, 251 (2000).
25. S. Furihata and T. Nakamura, *J. Nucl. Sci. Technol. Suppl.* **2**, 758 (2002).
26. A. V. Ignatyuk et al, *Sov. J. Nucl. Phys.* **21**, 255 (1975).
27. B. Jurado , K.-H. Schmidt and J. Benlliure, *Phys.Lett.B* **553**, 186 (2003).
28. H. A. Kramers, *Physica* **VII 4**, 284 (1940).
29. B. Jurado, C. Schmitt, K.-H. Schmidt, J. Benlliure, T. Enqvist, A. R. Junghans, A. Kelić and F. Rejmund, *Phys. Rev. Lett.* **93**, 072501 (2004).
30. R. Michel et al, cited in Ref. [31], to be published.
31. J.-C. David, A. Boudard, B. Fernández-Dominguez, S. Leray and C. Volant, in *Proceedings of the Conference on Nuclear Fission*, Obninsk, (2003).
32. M. de Jong, A. V. Ignatyuk and K.-H. Schmidt, *Nucl. Phys. A* **613**, 435 (1997).
33. J. Benlliure et al., *Nucl. Phys. A* **700**, 469 (2002).
34. S. Schmid et al, *Z. Physik A* **359**, 27 (1997).
35. J. Cugnon, *Phys. Atomic Nuclei* **57**, 1705 (1994).
36. J. Galin and U. Jahnke, *J. Phys. G* **20**, 1105 (1994).
37. A. Boudard and J. Benlliure (spokesmen), *Proposal S293 at SPALLADIN, GSI: Proton-induced fission in the GeV domain*, 2007.