The low-energy limit of the intranuclear cascade model*

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Abstract

The intranuclear cascade model is generally considered to be valid when the incident particle has a sufficiently small de Broglie wavelength to interact with individual nucleons. On this basis, a lower limit of 250 MeV is usually quoted for the incident energy in nucleon-nucleus reactions. Here we investigate to what extent this condition can be relaxed, just by comparing the predictions of the Liège intranuclear cascade model with available data at lower incident energy, down to 40 MeV. It is found that this model gives surprisingly good results at energies well below the above-mentioned limit. Results are also compared with the predictions of other models commonly used in this energy range. A tentative interpretation of these results is proposed.

1 Introduction

The intranuclear cascade (INC) model has been proven to be very successful in the description of the main features of proton-nucleus reactions in the GeV range [1, 2]. In fact, this model provides a good description of the first stage of the reaction process, characterized by hard nucleon-nucleon scatterings, and predicts satisfactorily the high-energy part of particle spectra. When supplemented by an evaporation (after-burner) model for the later stage of the reaction, when softer processes take place, the INC model also well describes the low-energy (evaporation-like) part of particle spectra.

The basic assumption of the INC model views the reaction process as a succession of binary collisions, well separated in time and space. This picture is generally justified by the mere comparison of the de Broglie wavelength $\lambda\!\!\!{}^{-}_B$ with the average distance d between nucleons, an argument first proposed by Serber [3]. This was the starting point of the INC model, which is basically a classical multiple scattering model. Later on, other aspects, like a constant nuclear mean field, the Pauli blocking and the stochastic determination of the final state in binary collisions were introduced.

Nucleon motion should be described a priori quantum mechanically and one may wonder under which conditions the quantum description reduces to the classical multiple scattering picture. For this to happen the scattering wave for the relative motion of two colliding nucleons should become asymptotic before another collision involving one of these nucleons takes place. In other words, a collision should be over before the next one begins. Separation of collisions thus requires

$$vt_{coll} \ << \ d \ , \ \lambda\!\!\!{}^{-}_B \ << \ d, \tag{1}$$

where v is the average relative velocity and t_{coll} is the time span during which the relative motion wave packet is not asymptotic (in other words the collision time). Furthermore, the INC model relies on classical linear trajectories with sudden changes of direction induced by collisions. This picture is valid if $\lambda\!\!\!{}^{-}_B$ is much smaller than the range of interaction r_0. The quantity t_{coll} is at least equal to r_0/v, the time of passage. Altogether, the presumed condition of validity of the INC model can be written as

$$\lambda\!\!\!{}^{-}_B \ << \ r_0 \leq vt_{coll} \leq d. \tag{2}$$

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On this basis, it is generally considered that the INC model could not be valid for collisions induced by projectiles with a kinetic energy per nucleon of less than 250 MeV. Occasionally, applications of the INC model at lower energy produce however satisfactory agreement with experimental data (see for instance [4, 5]), but the conventional wisdom continues to restrict the applicability of the INC to incident energy larger than 200 MeV.

Surely enough, condition (2) should be considered as a sufficient, but not a necessary condition. However, it is hard to establish the lower limit of validity of the INC model by relying solely on the present theoretical knowledge. Below, we investigate this issue (for nucleon-induced reactions) on a purely empirical basis, just by comparing INC predictions with experimental data for various systems and various energies. We will use the version of the Liège INC model described in sect. 2. Whenever necessary, we add the evaporation model of Dresner [6].

In sect. 2, we recall the most prominent features of the Liège INC model. Sect. 3 is devoted to an extensive comparison with experimental data and to an evaluation of the predictive power of the model at low energy. Sect. 4 contains a comparison of our results with those of the alternative models used for nucleon-induced reactions in the energy range under interest. We present also a tentative connection between the INC and the exciton models. We give our conclusions in sect. 5.

2 The Liège INC model

The original Liège INC model for nucleon-induced reactions is described in ref. [7]. Recent improvements have led to the successive versions INCL2 [8], INCL3 [9] and INCL4 [10]. In the next section we will use INCL3, but it is worth to present the results at high energy obtained with the latest version INCL4. A complete description can be found in ref. [10] and in references cited therein. It is sufficient here to recall that the collision mechanism is assumed to proceed from a succession of binary collisions well separated in space and time. The fate of all particles is followed as time evolves. The particles travel along straight-line trajectories until two of them reach their minimum distance of approach, in which case they can be scattered provided the value of this distance is small enough, or until one of them hits the border of the potential well, supposed to describe the target nuclear mean field. Additional features are: (1) initial positions and momenta of target nucleons are generated stochastically; (2) relativistic kinematics is used; (3) isospin degrees of freedom are introduced for all types of particles and isospin symmetry is respected; (4) Pauli principle is enforced by means of statistical blocking factors and some other prescription to be described below; (5) spectator nucleons are not allowed to collide [1]; (6) inelasticy of nucleon-nucleon collisions is taken into account by the introduction of Δ and pion production and destruction mechanisms; (7) there is a "self-consistent" determination of the stopping time for the cascade. We elaborate a bit on this point. For a reaction induced by a nucleon of incident kinetic energy T_{lab}, energy conservation implies:

$$T_{lab} = K_{ej} + W_{\pi} + E^{*} + S, \tag{3}$$

where K_{ej} is the kinetic energy of the ejectiles, W_{π} is the total energy of the produced pions, E^{*} is the excitation energy of the remnant and S is the separation energy, *i.e.* the minimum energy necessary to remove the ejected nucleons. Within the INC model, the quantities in eq. 3 can be evaluated at any time. On the average (over runs) the time dependence of E^{*} displays a typical behaviour: it first increases sharply when the incident particle hits the nucleus, then decreases rather fastly, due to the emission of fast particles and further decreases at a much slower pace, very much like an evaporative process. The change in the rate of decrease is rather sharp. The time at which this change occurs determines the stopping time of the cascade. It has been parametrized once for all and is used as such in the numerical simulations.

We complete this description by mentioning the differences between the INCL3 and the INCL4 versions. In INCL3, a nuclear density with a sharp surface is assumed, whereas in INCL4, a Saxon-Wood

[1] Nucleons are divided into participants and spectators. A participant is either the incident particle or any particle which has been hit by the latter or by another participant. The other particles are spectators.

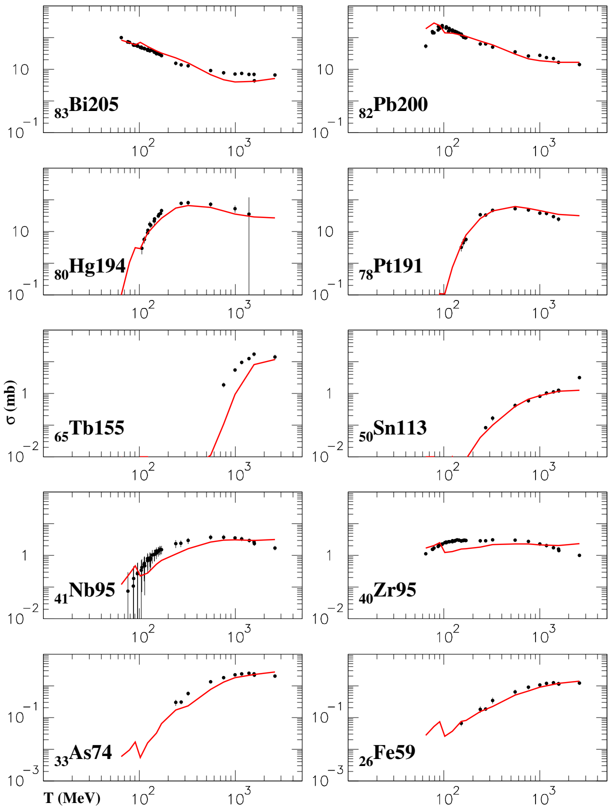

Figure 1: Cross-sections (in mb) for production of various residual nuclei in p+Pb reactions as functions of the proton incident energy (in MeV). Data (points) are from ref. [13]. Curves are the results of the INCL4+KHS[11] calculations.

distribution is assumed and r-p correlations are introduced in order to maintain this distribution in absence of interactions for moving nucleons (see detail in ref.[10]). In INCL3, a statistical Pauli blocking is implemented, i.e. the phase space occupancies are evaluated for the positions in phase space of the two nucleons in phase space; the collission is allowed stochastically according the product of the the two occupation probabilities. This sometimes gives rise to unphysical effects, because of the fluctuations in the Fermi sphere, inherent to its stochastic initial filling. In INCL4, besides this statistical Pauli blocking, a further criterion is applied which forbids the excitation energy of the remaining Fermi sphere to become negative. The version INCL4 can accomodate light clusters $(d, t, ^3He, ^4He)$ as incident particles, which is not the case in INCL3. Both INCL3 and INCL4 record the excitation energy, the momentum and the recoil energy of the remnant (to be introduced into the evaporation module), but INCL4 calculates also the intrinsic angular momentum of the remnant. Finally, pion dynamics is slightly improved in INCL4 (see ref.[10] for detail).

Typical results of INCL4 for spallation reactions in the 200 MeV to 2 GeV range can be found in ref.[10]. Therein it is shown that the model gives very good description of the total reaction cross-sections, of the proton and neutron double differential cross-sections and of their multiplicities, of the residue mass and charge cross-sections and of the isotpotic distributions, and an excellent description of the recoil energy of the residue as well as of its fluctuations. Recently, the INCL4 has been supplemented with a surface coalescence model for composite production. Very good results are obtained[11] for the production yields of high energy (cascade) light composites in $p(2.5GeV) + Au$ reactions, as measured by the NESSI collaboration[12]. Let us finally complete this enumeration by the predictions obtained for the excitation function for the production of selected residues. An illustration is provided by fig. 1. The data are taken from ref. [13]. They are obtained by activation of natural lead and γ-decay identification and counting. Proper corrections, in particular those for the cumulative production of the identified residue, are applied to the calculation. This comparison provides a stringent test to the reaction models, as the excitation functions results from a delicate and changing balance between many open channels. This is reflected by the very different shapes of the excitation functions. The agreement with the data is rather convincing. The kick observed at 100 MeV results from a change of the total cross-section: above this energy the proper reaction cross-section of the model is used, whereas the experimental reaction cross-section is used below.

3 Comparison with experimental data at low energy

For the study of the low-energy behaviour of the Liège INC model, we used INCL3, simply because this investigation had started before the version INCL4 was completed. We used the total reaction cross-section as given by experiment, the numerical code giving the sampling of the collisions in the impact parameter range. This is a common procedure when such codes are used in transport models, such as LAHET [14]. We do not expect significant differences when INCL4 is used, as our preliminary checks indicate.

First we noticed that the implementation of Pauli blocking should be changed if we wanted to deal appropriately with lower excitation energies. The usual statistical implementation used in INCL3 and INCL4 in the 250 MeV-2 GeV range is motivated by the need to take into account the depletion of the Fermi sea which occurs when nucleons are emitted. On the other hand, this method, coupled with the stochastic initialization of the nucleons can make spurious vacancies appear in the phase space of the nucleus. When the incident energy decreases the phase space of the nucleus gets tested more often and those vacancies begin to play a very important role. Moreover at low incident energy the number of ejectiles decreases and the need to take depletion into account becomes less important. That is why we introduced a strict implementation, which allows no final states whatsoever for which the momentum p is lower than the Fermi momentum p_F. This strict Pauli blocking has been used for all the results presented here.

What are the consequences of this choice ? By comparing the two Pauli implementations, we see that, first, statistical Pauli blocking produces an enhancement of the cross-section at the high-energy edge of the spectra, especially at forward angles. Second it generates a general increase at large angles. The first effect is easily attributed to fluctuations in the filling of the initial Fermi sphere. The second effect seems less easy to understand, as (high-energy) backward neutrons are expectedly produced after a few hard collisions, not so sensitive to Pauli blocking. We refer to [15] for tentative explanations of these observations.

The complete list of the reactions that have been studied for this work can be found in the reference [15], alongside many figures. Here we will only display some selected results. We refer the reader to the original article for more results and more extensive analyses.

For proton-induced reactions we display in fig 2 the results of our calculation for 80.5 MeV protons on a Pb target. The agreement is quite good and the shape of the spectrum is nicely reproduced for the angular range displayed here (for angles lower than 20 or higher than 140 it is usually less good).

Similar agreement is found for most (p,xn) reactions.

Moving on to (p,xp) reactions we present in fig. 3 results for a Bi target at 90 MeV. In this energy range, results turn out most of the time to be noticeably less good than for (p,xn) reactions, especially for heavy targets where the calculations predict too many low-energy ejectiles, probably because of a crude treatment of the Coulomb barrier. As we show in fig. 4 results are much better for lighter targets. Agreement increases with incident energy, being very good at 200 MeV. As it was already the case for (p,xn) reactions double-differential cross sections are not well reproduced for angles lower than 20^o and are noticeably underestimated for energies of the emitted protons lying around half the incident energy.

Let us now look at neutron-induced reactions for which only few reliable data are available. Extensive and reliable data have been obtained recently at 62.7 MeV [17]: they refer to proton production and are displayed in fig. 5. Globally, the agreement with data is similar to, but slightly less good than the one prevailing in proton-induced reactions at the same incident energy (see fig.2). For all angles there is a systematic overestimation of the cross-section around 15-20 MeV. This feature seems to come from a too

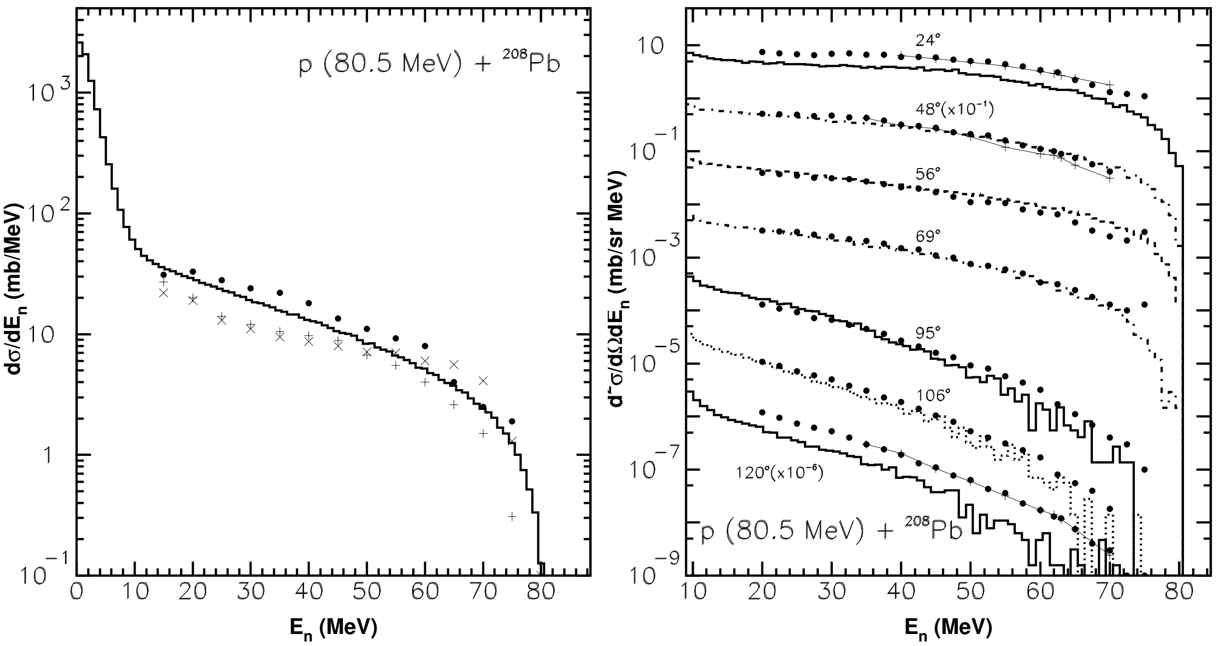

Figure 2: Energy differential (left panel) and double differential (right panel) neutron cross-section for proton-induced reactions on ^{208}Pb at 80.5 MeV. Data (dots, with an uncertainty of about 20 %) are taken from ref. [16]. On the left panel, data are compared with the predictions of our model (histograms) and with those of the Hybrid (H) and Geometry-Dependent Hybrid (GDH), as quoted in ref. [16]. They are indicated by the + and the × symbols, respectively. On the right panel, data are compared with the predictions of our model (histograms) and with the ones of the Multi-Step Direct (MSD) model of ref. [24] (continuous lines, as quoted in ref. [16]). The experimental data at 95 and 106° are underestimated by a factor between 1.5 and 2.

high Coulomb barrier in the cascade, which is accompanied by a probably too low barrier in the Dresner evaporation model (responsible for the small peaks around 6 MeV in some of the proton spectra). The lack of data for low-energy produced particles did not allow us to investigate a possible removal of this deficiency.

As a summary we can say that the INC model yields surprisingly good results well below the often quoted lowest incident energy where it could be valid. The agreement looks sometimes a little bit erratic, pointing to a possible dependence of the data on the detail of the structure of the target nuclei (of course, an erratic dependence upon the target mass or upon the energy cannot come from our model where both the description of the initial target state and the elementary cross-sections are smooth functions). But, these "accidents" are small fluctuations on a smooth variation. Trying to summarize the general trend, one can say our model give good results for (p, xn) reactions above 45 MeV. The agreement improves with increasing incident energy and with increasing target mass. It is also generally better for intermediate angles than for forward and backward angles. For (p, xp) reactions, the trends are the same, but a little bit more pronounced: when varying the parameters mentioned above, the agreement worsens faster than in the (p, xn) case. For neutron-induced reactions, the number of cases investigated is much lower and does not really entitle to draw precise conclusions, but presumably the same trends are present, with a systematically slightly less good agreement.

4 Comparison with other models

First our results have been compared with those of the Hybrid (H) and Geometry-Dependent Hybrid (GDH) model. For more information on these models, see [25], [26] and [27]. Let us just say here they

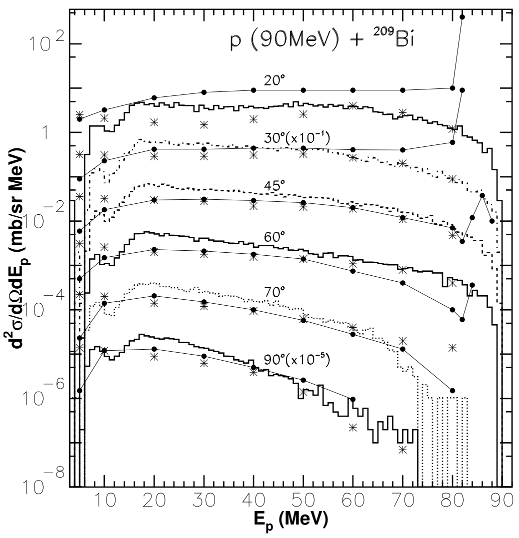

Figure 3: Double differential proton cross-section for proton-induced reactions on ^{209}Bi (right panel), at 90 MeV. Data (dots) are taken from ref. [28] and are compared with the predictions of our model (histograms) and those of ref. [29] (crosses). The experimental uncertainty is of the order of 10%.

are based on the Griffin exciton theory and that the GDH model includes a dependence on the impact parameter, which gives more importance to peripheral collisions.

We present in the left panel of fig. 2 a comparison of the predictions of the H and GDH models with our results for a typical case. As often quoted in the literature [16], the GDH model is generally better than the H model, especially for the high energy part of the spectrum. This is expected since the corresponding particles are mainly produced in quasi-elastic collisions which are more represented in the peripheral collisions. Fig. 2 shows that our INC model gives a reasonable agreement, similar to the one achieved by the exciton models.

Some authors [19, 20, 21, 22] noticed that the most important contributions come from low exciton numbers. Smith and Bozoian [30] have built a model where the lowest contribution of the GDH model is replaced by a quasi-free scattering (QFS) contribution, calculated microscopically, with some "effective" nucleon number. This model gives better results than the standard GDH model, as shown in [30], except at small angles and high energy loss, similarly to our INC results.

It is also interesting to compare the various contributions of this model and those of ours. For this we introduce the activation number n_a which indicates whether a nucleon participating to the cascade process has been activated early or late in the arborescent structure of the collision process (see fig. 6). At the beginning, $n_a = 0$ for all nucleons. After the first collision, n_a is put equal to unity for the two nucleons involved. Later on, in a collision between a participant ($n_a \neq 0$) and a spectator ($n_a = 0$), the activation number of the participant is increased by one unit and the one of the former spectator is given the same value. It is easy to see from fig. 6 that n_a labels the bifurcations of the graph representing the successive collisions. It may happen however that branches of the graph coalesce, which occurs through collisions between two participants. After such a collision, the lowest activation number is increased by one unit and the same resultant value is set for the other one. Let us add that the activation number is not modified by the reflection of the nucleons on the nuclear surface. We finally recall that spectator nucleons are not allowed to collide with each other in the INCL3 model.

The different contributions of the Smith and Bozoian model and of the INCL3 model are given in fig. 5 of ref. [30] and fig. 7, respectively. The shape of the QFS contribution is similar to the $n_a = 1$ contribution of our model. The shapes of the 3p-2h, 4p-3h,... contributions are rather similar to each other and quite similar to the shapes of the n_a=2,3,... contributions in our model. This more or less

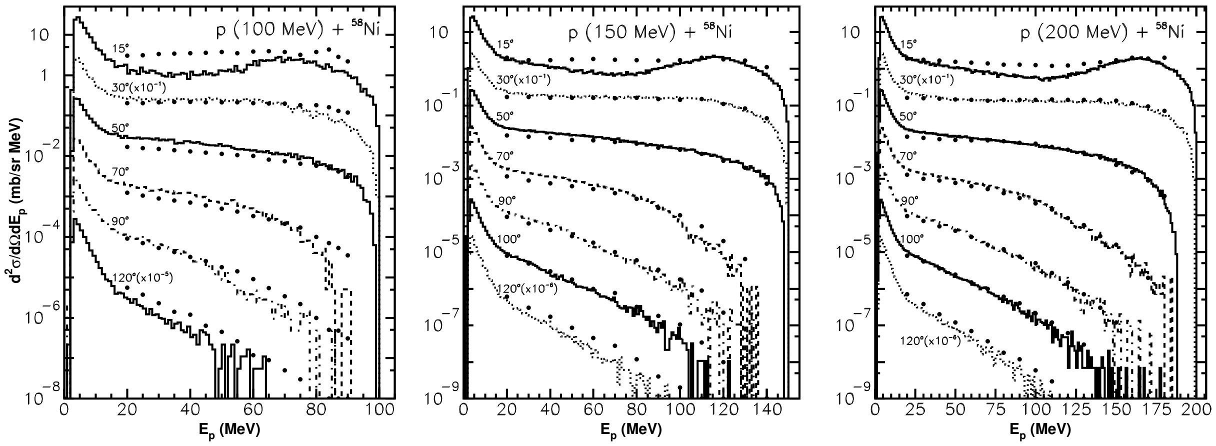

Figure 4: Double differential proton cross-section for proton-induced reactions on ^{58}Ni at 100, 150 and 200 MeV. Data (dots) are taken from ref. [31]. They are compared with the predictions of our model (histograms). The experimental uncertainties are lying between 10 and 20 %.

confirms that the activation number n_a can be closely related to the exciton number. We have to stress however that the relative importance of the QFS contribution of ref. [30] is substantially larger than the $n_a = 1$ contribution in our model.

A step further was taken by Chiang and Hüfner [29] (and independently by Wu [32]). They assumed that the double differential cross-section can be decomposed into three terms, corresponding respectively to single (1), double (2) scattering and compound-nucleus (c) formation and decay. In other words, the authors postulate that only two collisions contribute to the pre-equilibrium emission, the third one leading already to the formation of an equilibrated system. Of course, this statement can be true only if the incident energy is low enough. Chiang and Hüfner argue that it holds up to ~100 MeV. This conjecture is supported to some extent by our work, which shows that components for $n_a \geq 3$ are indeed close to be isotropic.

A comparison between the predictions of our model and those of Chiang and Hüfner is provided by fig. 3. They are very similar. This is perhaps not surprizing as the average number of collisions in the cascade stage lies around 2. It seems that the "one, two, infinity" approach is close to reality. This approach, which was introduced in a pragmatic way, using plausibility arguments about mean free path, energy loss, Pauli blocking, etc, is supported by our model, where all these elements are treated equally by the INC dynamics.

Comparisons have also been made with MSD calculations (see fig.2) or with the TALYS code. The INCL model cannot generally compete with those elaborate models which, moreover, involve frequently a fair amount of parameter fitting. We refer the reader to ref. [15] for more on that subject.

5 Conclusions

We have investigated the low-energy limit of validity of the INC model by comparing the predictions of the Liège model (INCL3 version) to experimental data and to predictions by other models.

We first noticed that Pauli blocking should be modified in order to deal with low incident energies. A strict Pauli blocking has been used for all the results presented in this work but it seems that some sort of intermediate implementation should be investigated. At this stage the most promising results are obtained with a mix of both procedures where we switch from a strict to a statistical Pauli implementation after a given number of collisions (usually 1).

Contrary to what is generally believed, the predictions of our INC model are often reasonably good, well below the commonly accepted limit of validity, i.e. ~250 MeV incident energy. There are however systematic variations of the agreement as explained in sect. 3. We have also seen that the predictions

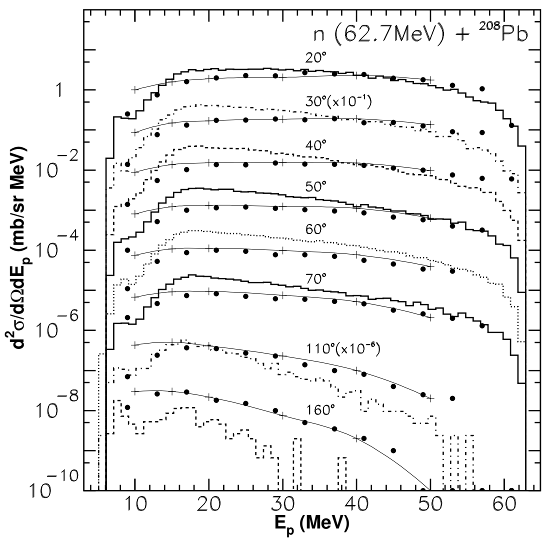

Figure 5: Double differential proton cross-section for neutron-induced reactions on ^{208}Pb at 62.7 MeV. Data (dots, experimental uncertainty of about 10 %) are taken from ref. [17]. They are compared with the predictions of our model (histograms) and those of the TALYS code system [18] (continuous lines with crosses, taken from ref. [23]).

of our model are comparable with and sometimes better than those of the exciton model or of its more elaborated versions like the GDH model and even those of the MSD model. This may not be after all so surprising: all these models carry the same basic physics, *i.e.* the physics of a Fermi gas lying in a potential well and subject to excitation by collisions and de-excitation by emission of particles. Only the methods for evaluating the different transition probabilities for the various steps of this complex process are different. The INC model presents this advantage that all transition probabilities are automatically fixed by the handling of collisions, giving it the unity which is somehow lacking in other models, where different methods are used for evaluating the various probabilities.

We want to recall that we use the INC model for describing the dynamics in the impact parameter range. We do not use it for the total reaction cross-section (in fact our predictions for this quantity are too small, by a factor between one and two). This is the way INC codes are often used in transport codes. The agreement that we obtain in this work would allow our model to be introduced in such transport codes for a large domain of energy. This is an important point: the simplicity of the INC model and the subsequent fastness of the associated numerical codes make it particularly appropriate for the modeling of nucleon-nucleus reactions in extensive applications. The accuracy of our results is admittedly not perfect and may sometimes be considered as insufficient, depending upon the application of the model. That is why we do not provide a definite figure for the lower limit of validity of the INC. But for transport codes which have to handle a series of complex processes with many different energy scales, the accuracy reached by the INC model in the 40-200 MeV range is very promising and the perspective of having a simple model in a large energy domain is certainly an attractive one.

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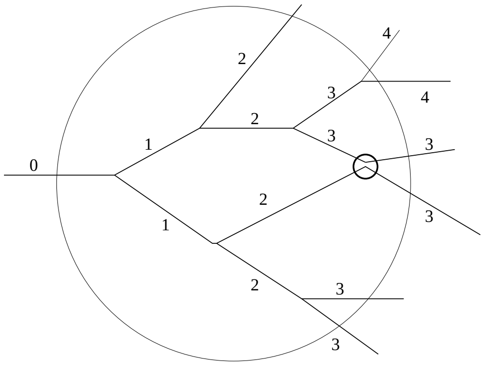

Figure 6: Schematic representation of the arborescent structure of the cascade process. The values of the activation numbers for the participant nucleons are indicated. The small circle indicates the collision between two participant nucleons. See text for detail.

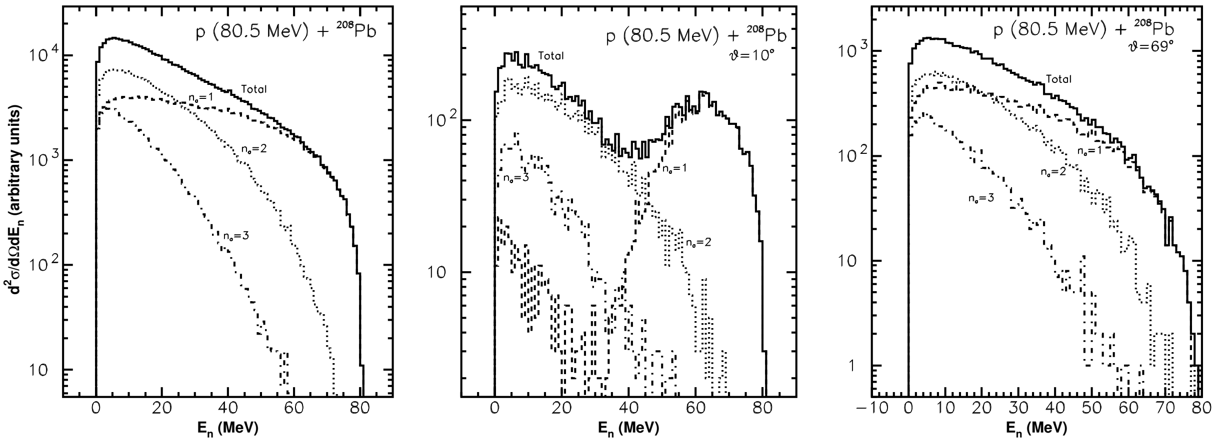

Figure 7: Splitting of the energy spectra according to the activation numbers of the emitted neutrons. The system under consideration is $p(80.5\text{ MeV})+^{208}Pb$. The distributions are given in arbitrary values. The left panel displays the integrated (over angles) energy spectrum, whereas the central and right panels refer to emission at 10° and at 69°, respectively.

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