Theoretical Description of Proton and Light Ion-Induced Reactions Within the HINDAS Collaboration

J. CUGNON[1], TH. AOUST[2], P. HENROTTE, B. VAN DEN BOSSCHE
University of Liège, Physics Department B5
B-4000 Sart Tilman Liège 1, Belgium
A. BOUDARD, S. LERAY and C. VOLANT
DAPNIA/SPhN, CEA/Saclay, F-91191 Gif-sur-Yvette Cedex, France

Abstract. The HINDAS collaboration put forward the improvement of the intranuclear cascade (INC) plus evaporation model for spallation reactions in the 200 MeV to 2 GeV range. This effort has led to the construction of the recent version INCL4 of the Liège INC model, which is briefly described here. Current developments of the model are also presented.

1 Introduction

One of the tasks of HINDAS was "to develop a theoretical model for p-induced reactions in the 200 MeV to 2 GeV range, to be validated on benchmark experiments, and to be included in the particle transport code HERMES". The choice of the HINDAS collaboration turned towards the model resulting from the coupling of the Liège intranuclear cascade model INCL[1−3)] and the Karl-Heinz Schmidt evaporation-fission model ABLA[4)]. The present paper reports on the developments of the INCL model during the period of the HINDAS program.

Prior to HINDAS, the INCL2[1)] and INCL3[2)] versions of INCL were able to give good results for neutron double differential cross-sections, but suffered of some shortcomings: (i) they failed on the quasi-elastic peak, (ii) residue cross-sections close to the target mass were underestimated and (iii) the statistical implementation of the Pauli blocking led to unphysical results. We explain below how these shortcomings are cured in the new version INCL4[3)] developed within the frame of the HINDAS program. We will comment on some selected important results and say a few words on the developments of the INCL model outside HINDAS.

2 Description of INCL4

Let us first describe the main features of the INCL model. Its basic premise is the description of the nucleon-nucleus interaction as a sequence of binary collisions (and decays) well separated in space-time. In fact, all the particles are followed in time, move on straight-line trajectories until two of them reach their minimum distance of approach (when collision is decided or not on a minimum distance of approach criterion), or until a particle hits the surface (when it can be transmitted or reflected), after which straight-line motion is resumed, and so on. Collisions are subjected to Pauli blocking, stochastically, according to a probability linked with phase space occupancies evaluated on the neighbourhood of the candidate final states of the particles. Cross-sections are supposed to be as in free space. Pion and Δ degrees of freedom are introduced. The target is supposed to occupy a sphere with a sharp surface, in which nucleons undergo the effect of a constant attractive potential. An important aspect of the INCL model is the "self-consistent" determination of the stopping time, at which an evaporation model is to be cranked: the average evolution of many physical quantities exhibits a change of rate roughly at the same time, which is chosen as the stopping time.

[1]e-mail:J. Cugnon@ulg.ac.be
[2]Also at SCK-CEN, Mol, Belgium

The description of INCL4 is completed by the following additional points.

1. *Introduction of a smooth surface.* Target nucleons are positioned at random according to a Saxon-Woods distribution for the density $\rho(r)$, cut at $R_{max} = R_0 + 8a$. Their momentum is randomly generated in a sphere of radius p_F; $r - p$ correlations are introduced in order to account for the fact that fast nucleons travel farther out than slow nucleons. Nucleons with momentum between p and $p + dp$ are assumed to contribute to the density $\rho(r)$ by the layer

$$\delta\rho(r) = (\rho(R(p)) - \rho(R(p + dp)))\theta_H(R(p) - r), \tag{1}$$

where θ_H is the Heaviside function. This defines the correlating, monotonously increasing, function $R(p)$. This prescription amounts to take first momentum p at random and then position at random in a sphere of radius $R(p)$. Furthermore, particles of momentum p are feeling a potential of constant depth V_0 and of radius $R(p)$. It is shown in Ref.[3)] that this leads to a total stabilization of the target (in terms of r and p distributions) in absence of collisions. This procedure is basically equivalent to putting particles in a Saxon-Woods potential well, but keeps the simplicity of the straight-line motion, which allows to propagate particles in a single time step between collisions.

2. *Consistent dynamical Pauli blocking.* The combination of the statistical generation of the initial state and the statistical implementation of the Pauli blocking leads to unphysical effects. Because of fluctuations the phase space occupancy f (measured by counting particles in a small phase space volume) can be smaller than one, even in the initial state. As a consequence, even the first collision made by the incoming particle may lead to a decrease of the energy of the colliding target particle, if the foreseen position of the latter in phase space is just in a region where $f < 1$. In such a case, the target excitation energy may become negative. In most events this deficiency is cured by subsequent collisions. To remove this undesirable effect we do not allow collisions which could lead to a negative excitation energy of the current Fermi sea, i.e. the energy of all particles with momentum below p_F cannot be smaller than the ground state of the current Fermi sea, defined as the energy of the original Fermi sea minus the separation energy of the nucleons which have escaped from it.

3. *Incident light clusters.* Incident light clusters, up to ^4He, can now be accommodated by the INCL4 code.

4. *Improved pion dynamics.* The dynamical picture of pion production has been improved on some points. In particular, a corrected detailed balance formula, which accounts for the finite lifetime of the Δ resonances, is used to determine the $N\Delta \rightarrow NN$ cross-section.

5. *Remnant angular momentum.* This quantity is provided as an output of the code. It is calculated as the difference between the initial angular momentum and the angular momentum carried by the ejectiles.

6. *Spectators and participants.* Spectators are moving, which generates a physical rearrangement of the density, but are not allowed to collide among themselves.

The numerical code INCL4 is basically a parameter-free code. Input data are taken from experiment (target radius, cross-sections, etc) or fixed once for all (e.g. Fermi momenta). Technically only two parameters (potential depth and stopping time) are left free, although they cannot reasonably changed much from their optional values.

In Ref.[3)] INCL4 predictions are shown to be quite successful when compared with a large body of experimental data including total cross-sections, neutron and proton differential cross-sections, neutron and charged particle multiplicities, residue mass and charge distributions, isotopic distributions and residue recoil energy distributions.

3 Some significant results

The amplitude of the quasi-elastic peak both in n and p spectra is well described by INCL4. This is basically due to the introduction of a smooth nuclear surface, which enhances the rate of single scattering events. However, if the position of the peak is well reproduced in p spectra (see Fig.1), it is located at a too high energy for n spectra. This probably reflects the effects of collective degrees of freedom, which show up coherently in single scattering events, but are wiped out in multiple scattering events, which are dominated by incoherent effects.

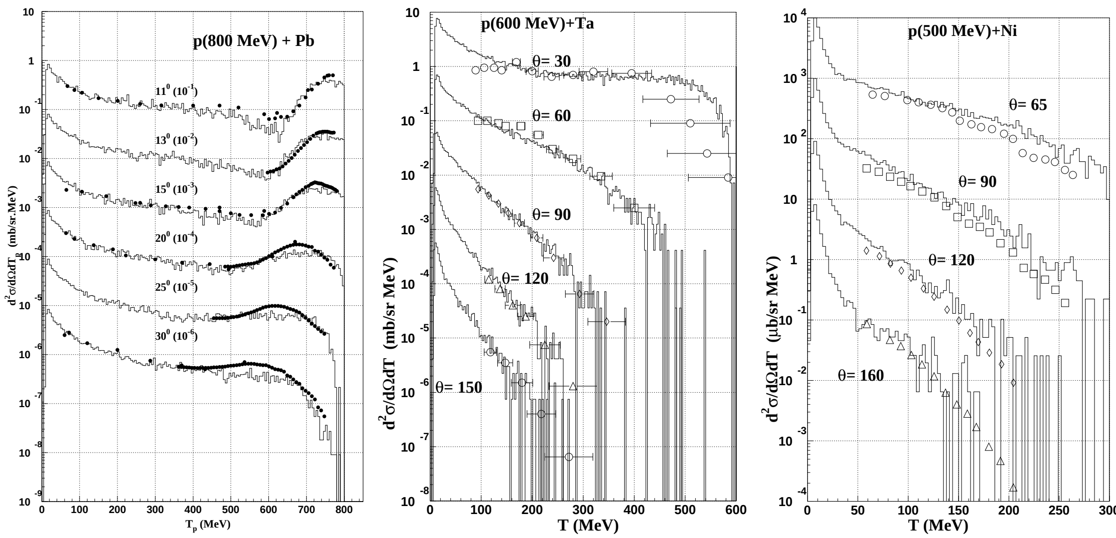

Figure 1: *Comparison of the INCL4+ABLA predictions with experimental proton double differential cross-sections for the indicated systems. Data are from Refs.*[5–7]*. Adapted from Ref.*[8]

The residue mass spectra are considerably improved in INCL4 (see Ref.[3]), especially for residues with mass close to the target mass. This is also due to the introduction of a smooth surface, which enhances the rate of events with a small excitation energy. The fission yield is usually well described, a result which is mainly attributable to the use of the fission model contained in ABLA, but also to the excitation distribution generated by INCL4.

We would like to comment on the recoil energy of the residues. Its value is overwhelmingly determined by the cascade stage. It is well described by INCL4, as depicted by Fig.2. More importantly, longitudinal recoil velocities have been measured. It is found[9] that their mean value for a given mass loss increases linearly with this mass loss and that their variance is also a linear function of the mass loss (at least for not too large mass losses). Therefore, variance and mean value are proportional. This is akin to the fingerprint of a random walk process, which can readily be identified with the sequence of successive collisions: each collision produces another recoiling participant which ultimately transfers its momentum to the remnant. The observed proportionality thus provides us with a justification of the basic assumption of the INC approach, namely the independence of the successive collisions.

Finally, we say a few words about the stopping time. We checked that, by changing the stopping time by a few fm/c's, the results are not modified sensitively. Of course, if it is changed more sizably, results may change drastically. In particular, if it is diminished by more than, say, 10 fm/c's, neutron spectra can be substantially depleted in the region between 20 and 50 MeV. It looks as our stopping time has just the value which makes the introduction of an intermediate so-called pre-equilibrium stage[10] unnecessary (there is no missing feature in our predicted nucleon spectra just above the

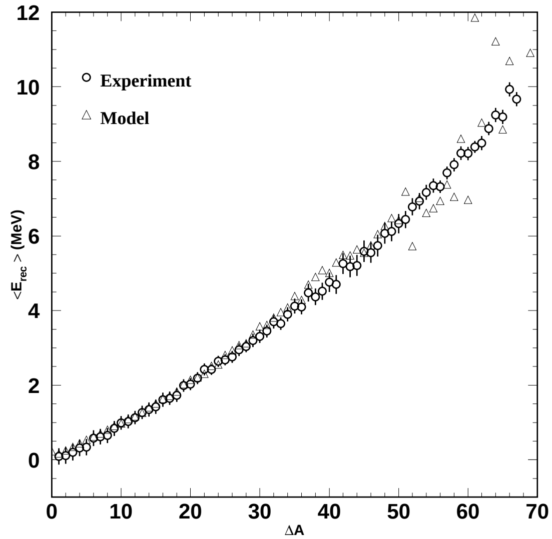

Figure 2: *Comparison of the INCL4+ABLA predictions (triangles) with experimental average residue recoil energy(circles), as a function of the mass loss. Data are from Ref.*[9]*. Adapted from Ref.*[3]

evaporation part, see Fig. 3). Perhaps it is appropriate to say that our cascade model exhibits two important features: it is able to describe the features usually attributed to pre-equilibrium models (except for cluster emission, but see below the extensions of our model) and it picks up (by the 'self-consistent' determination of the stopping time) the time at which the system is sufficiently randomized for evolving further by evaporation.

4 Developments outside HINDAS

4.1 Cluster emission

Since this topic is largely covered by A. Boudard[12] in his contribution at this meeting, we just explain briefly the model used to accomodate cluster emission during the cascade stage. When a particle is checked for leaving the nucleus (and provided it has fullfilled the test for transmission through the Coulomb barrier), it is verified whether it can drag along a cluster, in which it is embedded. A cluster is defined as a group of nucleons close to each other in phase space. Actually, the candidate cluster is constructed, starting from the considered particle, by finding a second, then a third, etc, nucleon satisfying the following condition

$$r_{i,[i-1]}p_{i,[i-1]} \leq P_0 \qquad (2)$$

on the Jacobian coordinates of the i-th nucleon, i.e. the relative coordinates of this nucleon with respect to the subgroup constituted of the first $[i-1]$ nucleons. A cluster is emitted if its (kinetic+potential) energy is sufficient to give an asymptotic bound cluster with positive kinetic energy and if it succeeds the test for transmission through the Coulomb barrier. Of course, energy is conserved during the emission of the cluster.

Clusters up to ^4He are considered. If a large cluster is built and if it does not succeed the tests for emission, the next largest cluster in the building process is then tested for emission, and so on. In other words, we adopt the following hierarchy: $^4He >^3 He, t > d > n, p$. Finally, as nucleons are checked for emission at the outer fringes of the nucleus, i.e. in a region where the density is very

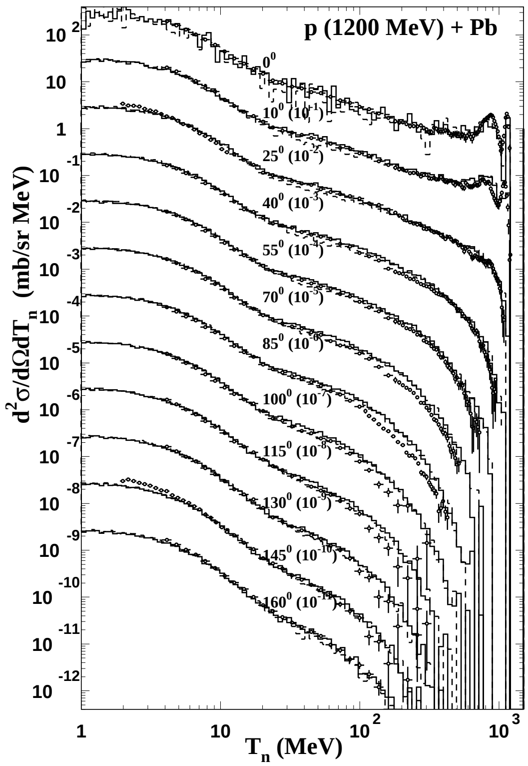

Figure 3: *Comparison of the INCL4+ABLA predictions with experimental neutron double differential cross-sections for the indicated system. Data are from Refs.*[11]*. Adapted from Ref.*[8]

small, we get it back by a small distance d before building the cluster. In summary, this model is a sort of surface coalescence model, relying on the instantaneous phase-space occupancy, dynamically generated by the INC itself. It is quite different from pure (momentum space) coalescence.

We did not try to fit the parameters P_0 and d. The adopted values are P_0=387 MeV/c and d=2.6 fm. They allow us to give a reasonable account of cluster production cross-sections, as shown in Ref.[12] .

4.2 Low-energy limit of validity of INCL

It is commonly stated that separability of the successive nucleon-nucleon collisions cannot be guaranteed for incident energies below ~200 MeV. Occasionally INC models have been used at lower energy, with some success. In a recent work[13], the validity of INC has been systematically tested below 200 MeV, just by comparing the INCL predictions with the existing data for n and p double differential cross-sections. The conclusions of this investigation are: (*i*) total reaction cross-section is underestimated under 100 MeV; (*ii*) predicted energy and angular distributions, down to 40-50 MeV incident energy, are generally well described, provided a strict Pauli blocking (instead of the statistical implementation) is adopted; (*iii*) better results are obtained when Pauli blocking is strictly enforced for the first collision and statistically for the succeeding ones; (*iv*) in many cases, INCL3 gives as good results (even, sometimes, better) as multi-step direct models. The latter, somewhat surprising, result presumably arises from the fact that, for multiple collisions, what really matters is the average energy-momentum flow, which can be described by mean (classical) trajectories and cross-sections.

4.3 Isospin and momentum dependences of the mean field

The isospin dependence of the mean field is introduced by adopting different Fermi momenta k_F^i, $i = n, p$ and by requiring the Fermi energies to be equal to minus the separation energies S_i:

$$\frac{(\hbar k_F^i)^2}{2M} - V_i = -S_i, \tag{3}$$

where V_i is the potential depth. The following energy dependence $V_i = \alpha_i - \beta_i E$ is introduced, with parameters taken from the optical potential phenomenology[14)] (see Ref.[15)] for details). The main effect of these dependences is to drive the quasi-elastic peak towards lower energies in neutron spectra at small angles, partly curing one of the shortcomings of INCL. This effect has been confirmed by an analytical model assuming single scattering[16)], which is a good approximation in the quasi-elastic region.

5 Conclusions

In the frame of the HINDAS collaboration, the Liège INCL model has reached a high level of predictability in the 200 MeV to 2 GeV range. It has been confronted successfully with a large body of experimental data, especially with those obtained by the HINDAS groups. This new version (INCL4) has been introduced or will soon be introduced in the transport codes HERMES, LAHET3 and MCNPX. The INCL model is under constant improvement. We only mentioned three of them, related to cluster emission, extension to low energy and detailed properties of the mean field.

Acknowledgments.

The development of the INCL4 model, the building of the INCL4 code, its inclusion in the HERMES transport code and some further studies have been performed in the frame of the HINDAS collaboration (European Union Contract N° FIKW WCT-2000-00031). We are grateful to our HINDAS colleagues for helpful discussions and for having participated to various tests of INCL4.

References.

1. J. Cugnon, C. Volant and S. Vuillier, Nucl. Phys. **A620** (1997) 475.
2. J. Benlliure et al, Nucl. Phys. **A700** (2002) 469.
3. A. Boudard et al, Phys. Rev. C**66** (2002) 044615.
4. J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. **A531** (1991) 709.
5. R. E. Chrien et al, Phys. Rev. C**21** (1980) 1014.
6. K. R. Cordell et al, Nucl. Phys. **A352** (1981) 485.
7. G. Roy et al, Phys. Rev. C**23** (1981) 1671.
8. A. Boudard et al, contribution to the AccApp03 Conference, San Diego, 2003.
9. T. Enqvist et al, Nucl. Phys. **A686** (2001) 481.
10. K. K. Gudima, S. G. Mashnik and V. D. Toneev, Nucl. Phys. **A401** (1983) 329.
11. S. Leray et al, Phys. Rev. C**65** (2002) 044621.
12. A. Boudard et al, contribution to this meeting.
13. J. Cugnon and P. Henrotte, Eur. Phys. J. A**16** (2003) 393.
14. P. E. Hodgson, "The Nucleon Optical Potential", World Scientific, Singapore, 1994.
15. T. Aoust and J. Cugnon, Preprint University of Liège, September 2003.
16. J. Cugnon and B. Van den Bossche, in preparation.