Improvements of Intra-Nuclear Cascade model stimulated by recent spallation data

A. BOUDARD[1,*], J. CUGNON[2], S. LERAY[1] and C. VOLANT[1]
[1]DAPNIA/SPhN, CEA-Saclay, 91191 Gif-sur-Yvette Cedex,France
[2]University of Liège, 4000 Sart-Tilman Liège 1, Belgium

In high-energy transport codes used to design Accelerator Driven Systems or spallation neutron sources, elementary interactions are computed through nuclear physics models. Among these, Intra-Nuclear Cascade models play a major role since the excitation energy at the end of the INC stage determines the number of evaporated particles. Therefore, in simulation of spallation targets, INC influences the total number of emitted neutrons and the isotopic distribution of produced nuclei. Recent data regarding the production of neutrons and residual nuclei in proton induced reactions make it possible to test the reliability of INC models and to improve them. A new version (INCL4) of the Liège INC model including especially a realistic nuclear density and a consistent treatment of the Pauli principle is presented.

KEYWORDS: Intra Nuclear Cascade; spallation

I. Introduction

To design Accelerator Driven Systems, it is necessary to predict with precision the energy spectrum and angular distribution of neutrons produced in the spallation target. This is important for the optimization of the target geometry in terms of useful neutron production and spatial distribution of the neutron flux. The spallation residue production has also to be well understood since these nuclei contribute to the radioactivity or/and to the possible structure material embrittlement.

The spallation processes are generally described in two steps: the incident light particle first interacts with the target nucleus through successive nucleon-nucleon hard collisions modeled by the so called Intra Nuclear Cascade (INC), leading to the emission of high energy nucleons which will induce subsidiary spallation reactions in a thick target. At the end of this stage, the remaining nucleus is left with some excitation energy and then de-excites either by evaporation or by fission. The reliability of the available numerical code systems is not yet sufficient to assess all the parameters required to design spallation targets. Moreover, the revival of interest in the spallation physics has allowed the availability of very precise new measurements[1–6] which put strong constraints on the models. Details in the calculations which were considered so far as refinements become now crucial to correctly describe the data.

II. New ingredients in the Liège INC model

The Liège INC model for proton-nucleus interactions[7] has been revisited[8] especially with more realistic elementary cross-sections, when accurate neutron spallation data from SATURNE became available[1]. In this version called INCL2, applied in [1], the interplay between the stochastic implementation of the Pauli blocking and the fluctuations of the phase space occupation in the initial state, inherent to its stochastic generation, introduces unphysical results for certain events with a negative excitation energy of the residual nuclei for which zero excitation energy was assumed. Latter in a more recent version, INCL3, applied in ref[3], the cascade events were considered as complete when the excitation energy was vanishingly small.

The nucleons were moving in a sharp spherical potential with a realistic radius. This had two consequences. First the total reaction cross section was too small (20% to 30%), and the calculations had to be renormalized with the experimental value. Second, large discrepancies were observed for peripheral reactions very sensitive to the nuclear surface. This is the case for the production of residual nuclei close to the target mass and is disturbing since they are the most produced ones.

The new ingredients of the version called INCL4 are the following ones:

- A smooth nuclear surface is introduced. The shape of the matter density is described with a two-parameter Fermi model, the parameters being obtained from electron scattering data.

- A consistent dynamical Pauli blocking is now used. The statistical procedure is still used but the final acceptance of a collision is submitted to the condition that this collision does not lead to a negative excitation energy.

- The collision between spectator nucleons are now forbidden, but spectators are still moving in the potential. This avoids the "spurious boiling" of the Fermi sea. Participant nucleons are particles having collided with at least one other participant, the incident particles being the only participant at the beginning of the reaction.

- An energy dependence has been adopted for the Δ-particle lifetime to take into account the phase space variation of the pion-nucleon system with energy.

- A correction factor has been applied to the $N\Delta \rightarrow NN$ cross-section which was formerly deduced from the detailed balance. A factor of 3 has been adopted as justified in[9] to describe correctly pion absorption in nuclei.

- The intrinsic angular momentum of the residual nuclei is now calculated from angular momentum conservation. This is of some importance for the evaporation-fission stage of the spallation.

- The stopping time formulation of[8] has been revisited now taking into account the diffusivity of the target nuclei. Due to the extension of the nucleus, it is now about two times larger

* Corresponding author, Tel. (33-1) 69 08 43 44, Fax. (33-1) 69 08 75 84, E-mail: aboudard@cea.fr

than before, but the results are less sensitive to small variations of this parameter.

- The extension to incident light clusters has been realized, namely to incident deuterons, tritons, ^{3}He and ^{4}He. A gaussian shape for the spatial distribution is used with a width dictated by the charge r.m.s. radius. The same is done for the momentum distribution, with widths taken from literature, except for deuterons. For this loosely bound nucleus, the momentum distribution is taken from the wave function in momentum space as calculated with the Paris potential[10)].

III. Comparison with data

One of the interesting consequences of the introduction of the smooth nuclear surface is that the calculated reaction cross-sections are now in good agreement with the measurements. This is illustrated in fig. 1, where the predictions (full lines) are compared to a compilation of measurements [11,12)] for protons on iron, lead and uranium.

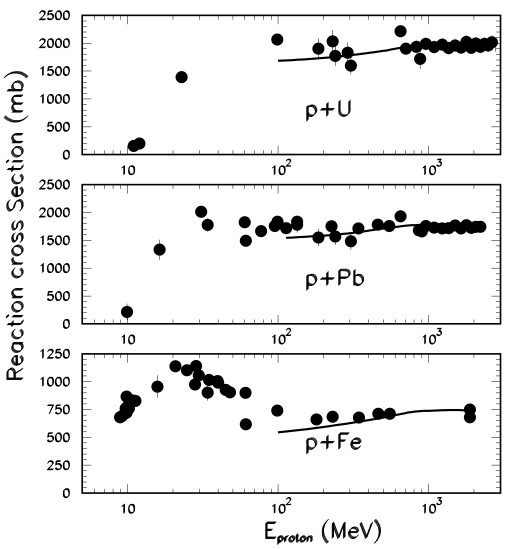

Fig. 1 Calculated reaction cross-sections (full lines) compared to the data (points).

A significative improvement is obtained on the cross section of residual nuclei close to the target mass as measured at GSI in reverse kinematics. This is illustrated for proton-lead interaction at 1 GeV [3,6)] on fig. 2 where the measured mass distribution (top) and the isotopic distributions of Pb, Tl and Hg (bottom) are compared with calculations performed with INCL3 and INCL4 coupled with the evaporation-fission code developed at GSI[13,14)] . The realistic density is here crucial for heavy residues produced in peripheral reactions. Note also that the fission part is very well reproduced due to the GSI model using a delayed fission and to the intrinsic angular momentum as computed at the end of the cascade. The mean value of this momentum is about a factor 2 larger than the one computed in abrasion-ablation codes developed for heavy ion collisions[17)] .

The same conclusions are also valid for the proton-gold interaction[5)] at 800 MeV (per nucleon) fig. 3. Note here that

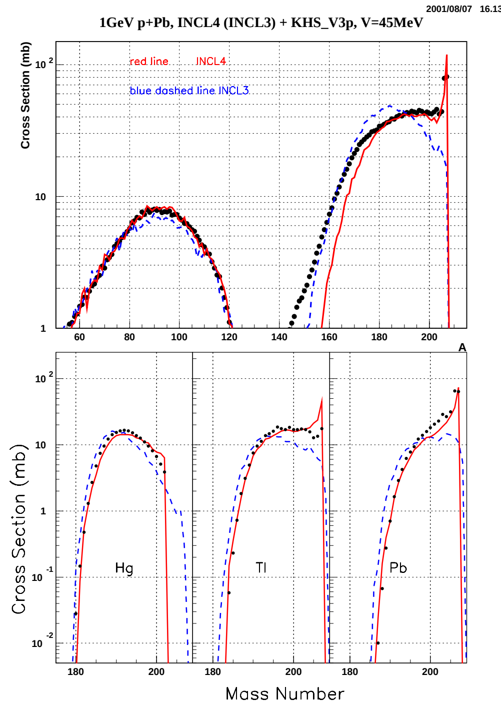

Fig. 2 Improvements mainly due to the realistic nuclear density compare to residual nucleus cross sections measured at GSI in proton-lead interaction at 1 GeV per nucleon (dots).

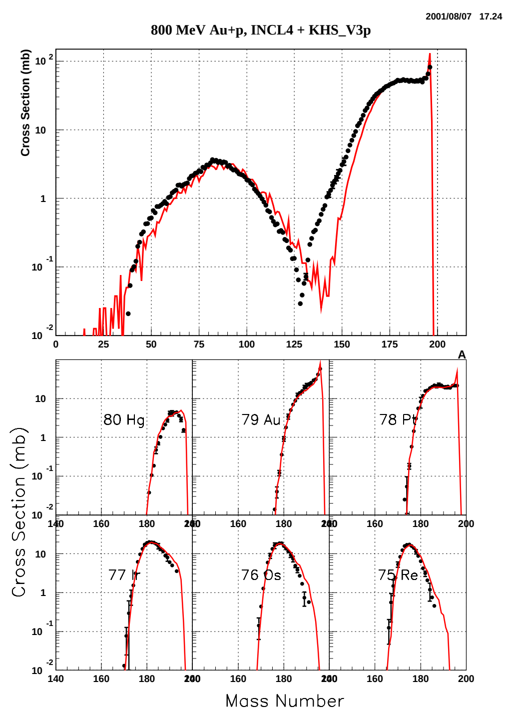

Fig. 3 INCL4-KHSV3p calculation of residual nucleus cross sections compare to data measured at GSI in proton-gold interaction at 800 MeV per nucleon (dots).

even the isotopes of Hg, one more charge than the target, are convincingly reproduced in shape and magnitude. Another conclusion is that the light fragmentation residues are under-predicted by the model, but both cascade and evaporation play here a role.

The double differential cross-sections of produced neutrons as measured at SATURNE (LNS) provide disentangled observables since the neutrons above 20 MeV are purely produced at the cascade stage of the calculation. As an example, fig. 4 presents the cross-sections for Pb(p,xn)X at 1200 MeV [1] compared to the same calculations. The quasi-elastic peak and

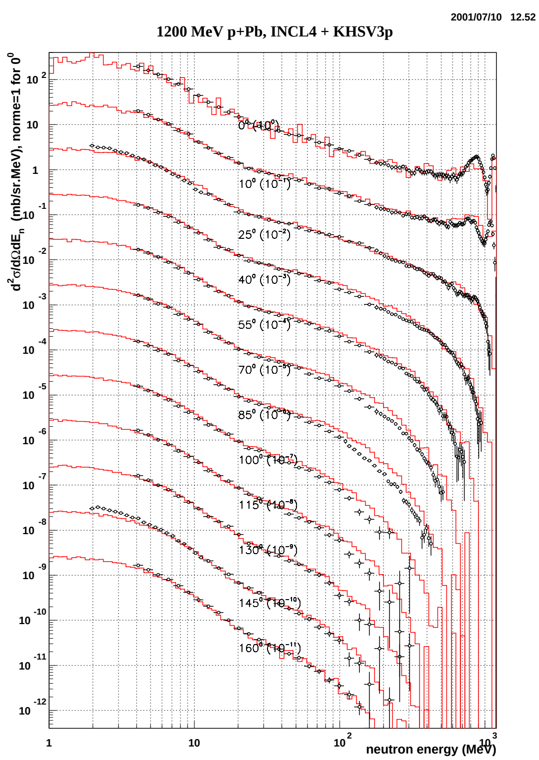

Fig. 4 Comparison of a INCL4-KHSV3p calculation with the double differential cross sections of neutrons produced in a proton-lead interaction at 1.2 GeV and measured at LNS (dots).

the region of the Δ excitation are slightly improved (compare to INCL3). The overall agreement is satisfactory above and bellow 20 MeV, especially if we consider that the transport in the target (2cm thick) is not evaluated here. It is known [18] that it de-populates slightly the high energy part to the benefit of the low energy (30% increase bellow 3 MeV). The evaporative part (GSI) gives an agreement comparable to the previous calculations presented in [1] and done with the evaporation treatment of Dresner [19] . This last code was shown in [3] unable to reproduce the isotopic distributions of residual nucleus and the fission cross section. The coupling of INCL4 with Dresner evaporation gives however a much better mass (A) or charge (Z) dependence of the fragmentation residues, showing the importance of the evaporation-fission stage for the light fragments. However, we have now the possibility to propose with INCL4 coupled with the GSI model a more coherent description of the full data base.

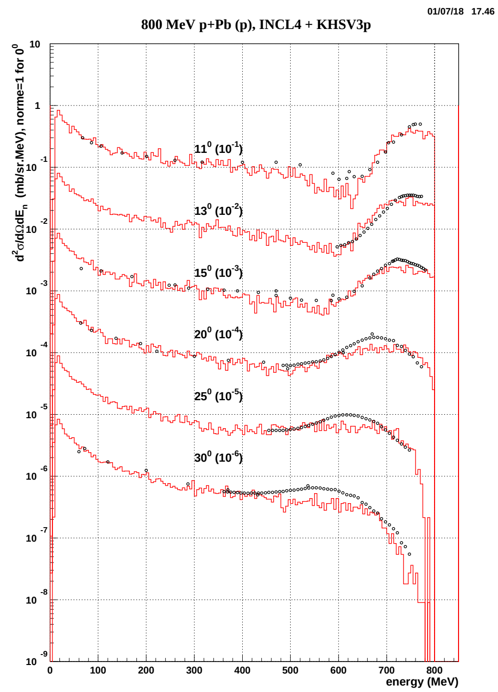

Fig. 5 Comparison of a INCL4-KHSV3p calculation with the double differential cross sections of protons produced in a proton-lead interaction at 800 MeV and measured at Los-Alamos (dots).

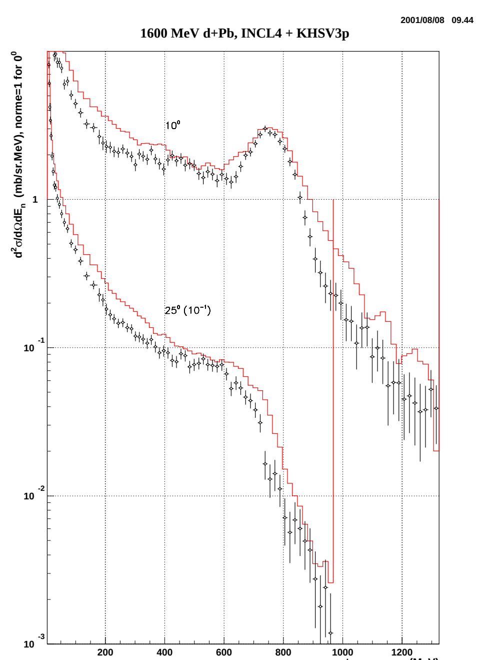

Fig. 6 Comparison of a INCL4-KHSV3p calculation with the double differential cross sections of neutrons produced in a deuteron-lead interaction at 1600 MeV and measured at LNS (dots).

The same quality of agreement is obtained for other targets (Al, Fe, Zr, W and Th) and energies (800, 1200 and 1600 MeV) measured at SATURNE [20] . Data at lower energies (597, 256 MeV)[15] are also reasonably reproduced. The outgoing protons measured at 800 MeV[16] are shown in fig. 5 for the lead target. The quasi-elastic peak is here especially well accounted for.

The possibility to use light clusters as projectile has not yet been fully exploited. However neutrons produced by deuteron induced reactions have been measured at SATURNE[20–22] . The calculations agree reasonably well with the data (see fig. 6). In particular the high energy tail of the neutron spectra above the beam velocity is well accounted for when using the deuteron momentum distribution obtained with the Paris potential.

Residual nuclei production from lead[23] and uranium[24] beams at 1 GeV/nucleon bombarding a liquid deuterium target has been also measured at GSI. Comparison of these data with the code predictions is encouraging (see fig. 7).

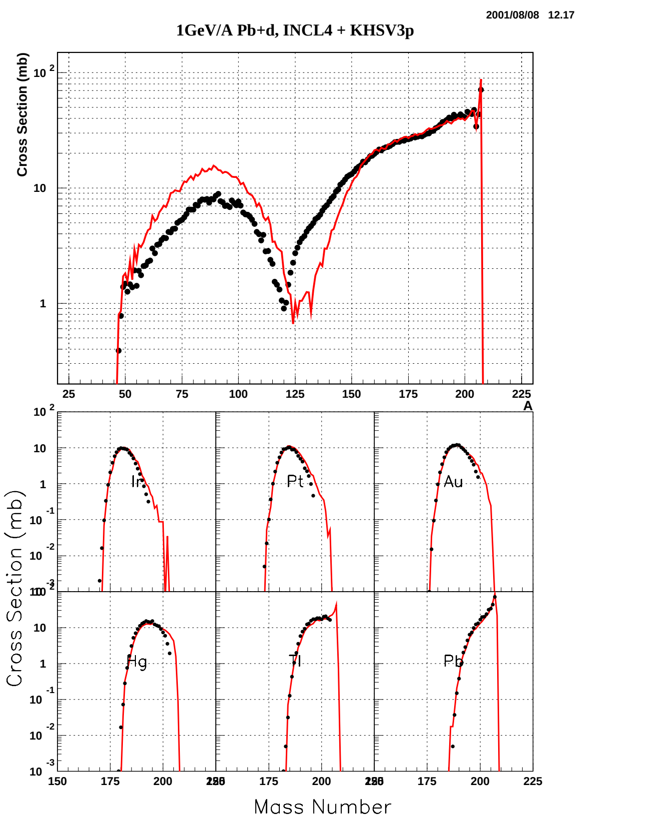

Fig. 7 INCL4-KHSV3p calculation of residual nucleus cross sections compare to data measured at GSI in deuteron-lead interaction at 1 GeV per nucleon (dots).

IV. Conclusion

The Liège INC model has been improved by the addition of necessary physics ingredients such as the smooth nuclear surface and a consistent dynamical Pauli blocking. In conjunction with a suitable evaporation-fission code developed at GSI, it is able to reproduce reasonably well a large set of recent data (neutron and proton production, residual nuclei for a wide set of incident energies from 200 to 1.6 GeV) without any change of parameters. The possibility to include light fragments as projectiles is being exploited and appears very encouraging for deuterons. Some remaining failures of the INCL4 model are still the excess of pion production although reduced by a factor ∼2 compare to previous versions (cross sections are ∼70% larger than the one measured at 730 MeV in proton on lead[25]) and the quasi-elastic peak in neutron production computed at 20 to 50 MeV above the data (whereas the proton one is correct). In an intricated interplay with the evaporation, the cross-section of light fragmentation residues is also under-predicted. An extensive confrontation of this model with data should be fruitful in future.

References

1) X. Ledoux *et al.*, Phys. Rev. Lett. 82 (1999) 4412.
Collaboration DSM-SPhN, DAM-SPN, LNS, LPC and Caen-Univ, Univ Libre Bruxelles,
IPN Orsay, IReS Strasbourg, Uppsala Univ.
2) M. Enke *et al.*, Nucl. Phys. A657(1999)317.
3) W. Wlazło *et al.*, Phys. Rev. Lett. 84 (2000) 5736.
Collaboration FRS-S184: GSI, DAPNIA-SPhN, Univ. Santiago de Compostela, IPN Orsay, CEN Bordeaux-Gradignan.
4) J. Benlliure *et al.*, Nucl. Phys. A683(2001)513.
5) F. Rejmund *et al.*, Nucl. Phys. A683(2001)540.
6) T. Enqvist *et al.*, Nucl. Phys. A686(2001)481.
7) J. Cugnon, Nucl. Phys. A62 (1987) 751.
8) J. Cugnon, C. Volant and S. Vuillier, Nucl. Phys. A620 (1997) 475.
9) J. Cugnon and M.C. Lemaire, Nucl.Phys. A489 (1988) 505.
10) M. Lacombe *et al.*, Phys. Rev. C21(1980) 861.
11) R. E. Prael and M. B. Chadwick, LA-UR-97-1744.
12) B. C. Barashenkov, Cross Sections of Interactions of Particles and Nuclei with Nuclei (JINR, Dubna, 1993).
13) J. Benlliure *et al.*, Nucl. Phys. A628 (1998) 458.
14) K. H. Schmidt *et al.*, private communication.
15) W. B. Amian *et al.*, Nucl. Sci. Eng. 115 (1993) 1 and references therein.
16) R. E. Chrien *et al.*, Phys. Rev. C21 (1980) 1014.
J. A. McGill *et al.*, Phys. Rev. C29 (1984) 204.
17) M. de Jong *et al.*, Nucl. Phys. A613 (1997) 435.
18) L. Donadille *et al.*, contribution to this conference.
19) L. W. Dresner, Oak Ridge Report ORNL-TM-196 (1962).
F. Atchison, Jül-Conf-34, paper II, 17 (1980).
20) F. Borne, PhD thesis, Bordeaux University, France 1998.
F. Borne *et al.*, Etude expérimentale de la spallation en cible mince, Rapport CEA-R-5887 (2000).
21) E. Martinez, PhD thesis, Caen University, France 1997.
22) P. Pras *et al.*, Internat. Meeting on Sub-Critical A.D.S., ITEP Moscow, Russia, oct 11-16 (1999).
23) T. Enqvist *et al.*, in preparation.
24) E. Casajeros, PhD thesis, University of Santiago de Compostela, Spain 2001.
25) D.R.F. Cochran *et al.*, Phys. Rev. D6 (1972) 3085