Extensions of the INCL model to light ion induced reactions for medical and space applications

A. Boudard[1]*, B. Braunn*[1]*, J. Cugnon*[2]*, J.C. David*[1]*, P. Kaitaniemi*[1]*, S. Leray*[1]*, D. Mancusi*[1]
[1]CEA Saclay, Irfu/SPhN, 91191 Gif-sur-Yvette, FRANCE
[2]Université de Liège, AGO Department, Bât. B 5, B-4000 Liège, BELGIUM

Abstract
This contribution describes recent extensions of the Intra Nuclear Cascade code INCL to light ion projectiles and to low beam energies. Examples of carbon beam fragmentations at GANIL and at GSI energies on thick water or PMMA targets are compared with experimental data. The production of astatine isotopes from proton beams around 1 GeV on a thick Pb-Bi target (ISOLDE experiment) demonstrates the need of a good description of the helium production in the first interaction at the beam energy and of helium induced reactions at low energy in secondary interactions.

1 Introduction

Accelerator Driven Systems have renewed the interest for good models of spallation reactions describing especially the production of neutrons and of residual nuclei from proton beams on heavy nuclei in the GeV regime. This type of reactions is efficiently descried in terms of an Intra Nuclear Cascade - sequence of free and incoherent NN interactions in a realistic target nuclear density - followed by a de-excitation of the excited remnant nucleus mainly by evaporation of particles and possibly by fission.

The intra nuclear cascade code INCL originally built at Liège University [1] and more recently developed in collaboration with the CEA/Irfu/SPhN [2] is based on realistic physical ingredients and a very reduced number of parameters. This makes it a predictive semi-classical model of nuclear reactions. Coupled with modern de-excitation codes as ABLA [3], it fully specifies final states with all correlations and statistical fluctuations and is consequently also well adapted as a realistic event generator. It has been recognized as one of the best cascade in the frame of an inter-comparison of many codes organized by IAEA [4] and dealing with nuclear reactions induced by nucleons of 60 MeV to 2.5 GeV mainly on thin Iron and Lead targets.

We have recently tested and improved the model in other sectors. Composite projectiles up to alpha particles were already implemented with promising results at the GeV per nucleon [2]. We have extended the capabilities up to projectiles of mass sixteen and we have paid attention to the low energy domain, interesting in itself and really needed for most of applied calculations of thick target configurations. Potential applications are in the medical domain (tumor treatment by carbon beams) and in the evaluation of irradiation by cosmic rays (including heavy ions) on men and electronics in space vehicles.

There are presently a Fortran version of the code INCL4.6 coupled with the de-excitation ABLA07 in a still private version of MCNPX [5] and a fully redesigned C++ version INCL++5.1 implemented in GEANT4 [6] and using the GEANT4 de-excitation handler.

2 Treatment of light projectiles (4<A<17)

Light composite projectiles are treated in the following way. The ion comes from infinity at a random impact parameter (see Fig. 1a). It is described as a set of (A,Z) nucleons in the ion rest frame whose positions and momenta are randomly chosen in a realistic spacial and momentum density. A constraint is applied to have the sum of the vectors equal to zero in both spaces. For each configuration the depth of a binding potential is determined so that the sum of the nucleon energies is equal to the tabulated mass of the projectile nucleus.

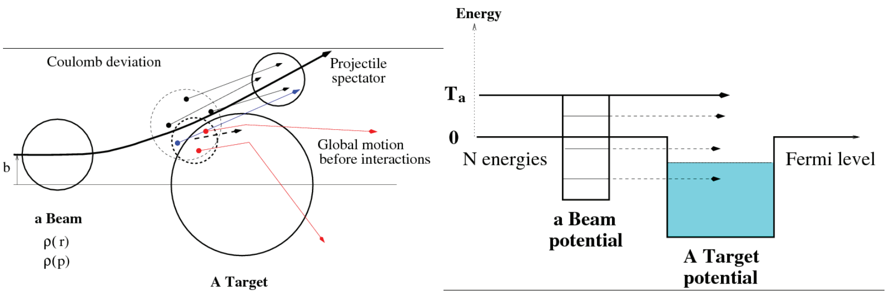
A Lorentz boost with the nominal projectile velocity is applied to the off-shell nucleon four-vectors to define them in the laboratory system (target at rest). Nucleons are no more on mass shell but the sum of energies and vector momenta are equal to the nominal energy and momentum of the projectile.

The ion follows globally a classical Coulomb trajectory until one of its nucleon impinges on a sphere of calculation around the target nucleus, large enough for simulating all reaction events in practice. Considering the individual nucleon velocities, some of them will never interact with this sphere and will be combined together in the "projectile spectator".

All other nucleons are entering the calculation sphere. They will move globally (with the beam velocity) until one of them interact, being close enough to a target nucleon. The NN interaction is computed with the proper nucleon momenta, and if not Pauli-blocked, outgoing nucleons propagate independently until further collisions. Nucleons having crossed the sphere of calculation without any NN interaction are combined also in the "projectile spectator" at the end of the cascade.

This projectile spectator nucleus is kinematically defined by its nucleon content and its excitation energy obtained by an empirical particle-hole model based on the energy configuration of the current projectile and the removed nucleons (interacting with the target). This nucleus can then be de-excited by any model; typically a Fermi Breakup for the light projectiles considered up to now.

It is quite clear that this "projectile spectator" has not received any explicit contribution from the zone of interaction which is entirely contained in the target remnant. This has two consequences. The calculation is not at all symmetric (if we compute C on C for example) and we believe that the residue of the target is more realistic than the "projectile spectator" at this stage of the model.



(a) Coulomb deviation (b) Compound nucleus at low energy

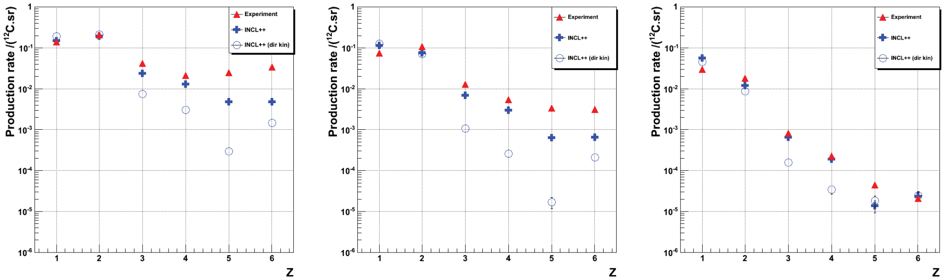
Fig. 1: Composite projectile treatment in INCL

3 Very light projectiles (d, t and He) and low energy

At very low energy, the nuclear reaction proceeds by a total absorption of the projectile and the formation of a compound nucleus which will then decay. To account for this, we have introduced a smooth empirical description of the transition between the full absorption and the usual intra nuclear cascade regime (actually only for projectiles with A<=4) in the following way.

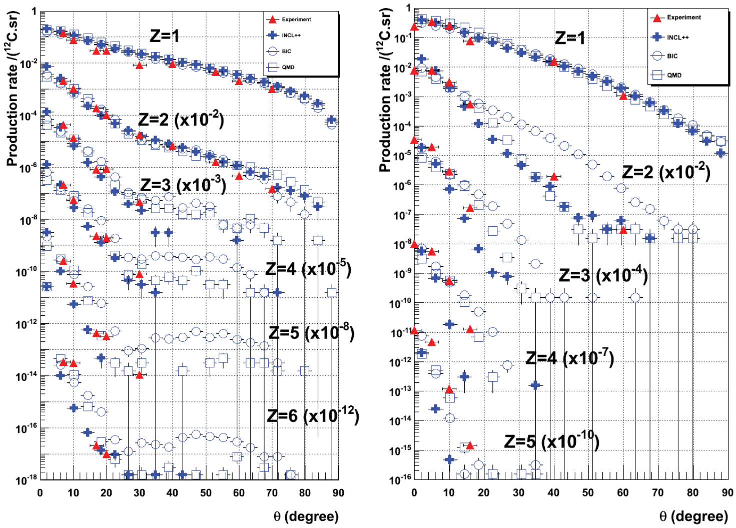
The projectile content in terms of nucleons and the Coulomb deviation is realized as described above, but the kinetic energy of individual nucleons can be negative and some times can even be lower than the Fermi level in the target nucleus (see Fig. 1b), a situation hardly acceptable in the cascade picture. Up to alphas, nucleons missing the sphere are put on shell and the necessary energy for this is equally taken from all nucleons entering in the sphere and named participants.

If at least one participant has an energy lower than the target Fermi level and one participant will cross the "hard" part of the target density, a target-participants compound nucleus is produced and treated



(a) $Fragments\ emitted\ at\ 7^{\circ}$ (b) $Fragments\ emitted\ at\ 10^{\circ}$ (c) $Fragments\ emitted\ at\ 16^{\circ}$

Fig. 2: Production of fragments identified in charge (Z) and produced by a ^{12}C beam of 95 MeV per nucleon on a PMMA target. For three angles, the measured production rate [8] (red triangles) is compared with calculations using INCL++ in GEANT4 with the "direct" mode (open blue circles) or the recommended "reverse" mode (blue crosses).

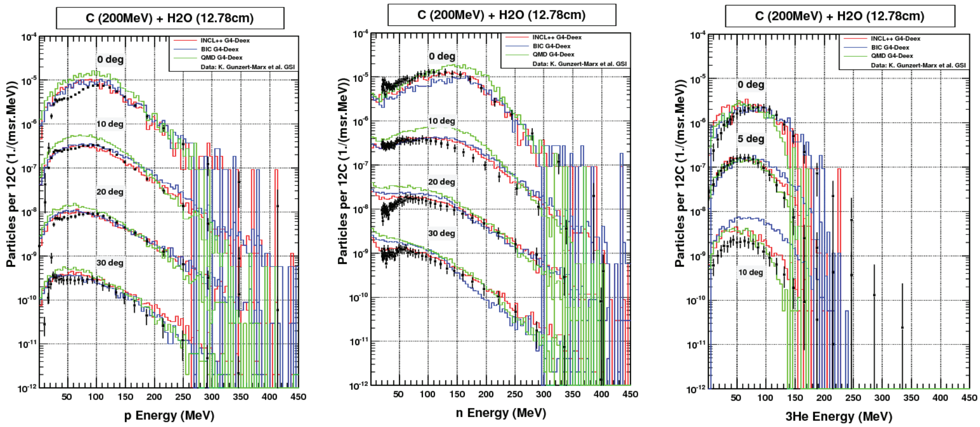


(a) $target\ thickness : 5mm$ (b) $target\ thickness : 25mm$

Fig. 3: Angular distributions of fragments identified in charge (Z) and produced by a ^{12}C beam of 95 MeV per nucleon on a PMMA target. Data measured at GANIL [8] (red triangles) are compared to calculations with INCL++ (blue crosses), BIC (blue circles) and QMD (blue squares) in GEANT4.

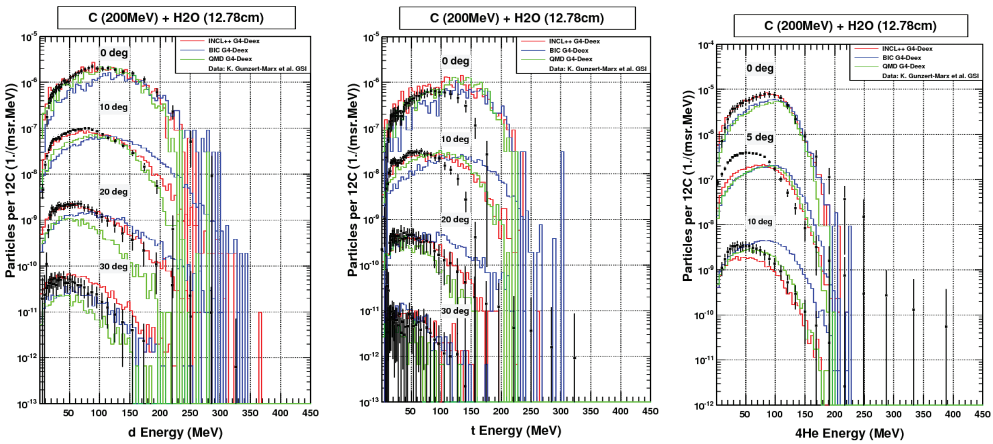
by the de-excitation as the usual remnant nucleus of the cascade. There is no more "cascade" calculation in that case.

We have also taken into account the tabulated [7] masses of nuclei and particles so that the Q-values in all outgoing channels are now correct and the global conservation of energy-momentum is at



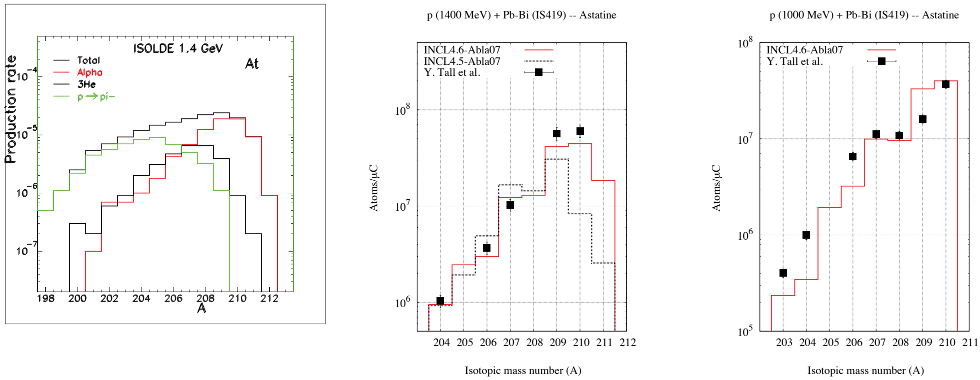
(a) *proton production* (b) *neutron production* (c) ^{3}He *production*

Fig. 4: Proton, Neutron and ^{3}He double differential production rates from a ^{12}C beam of 200 MeV per nucleon stopped in a thick water target. Data measured at GSI [9] (black points) are compared with INCL++ (red line), BIC (blue line) and QMD (green line) models in GEANT4. Convenient powers of 10 are used to display the various angles on the same picture.



(a) *deuteron production* (b) *tritium production* (c) ^{4}He *production*

Fig. 5: Same as Fig. 4 for deuteron, tritium and ^{4}He production except that all calculations are divided by 3 for d and t and by 10 for ^{4}He.



(a) *Contributions* (b) *At production at* 1.4 *GeV* (c) *At production at* 1.0 *GeV*

Fig. 6: Production of astatine isotopes by a proton beam of 1.4 GeV and 1.0 GeV on a 20 cm thick Pb-Bi target as measured at ISOLDE [10] and compared to INCL4.6-ABLA07 predictions with MCNPX.

the tenth keV level at the end of the cascade.

4 Ganil experiment

A collaboration has measured [8] at GANIL the fragmentation of a ^{12}C beam of 95A MeV stopped in a PMMA ($C_5H_8O_2$) target. In Fig. 2 the production of fragments emitted at 7° , 10° and 16° is compared with INCL calculations in GEANT4 either in the "direct" mode or the "reverse" mode. In "direct" mode the ^{12}C is really the beam particle interacting with the target nucleus (C or O here) and due to the asymmetric beam/target treatment as discussed above, fragments of the projectile are poorly described. So for each interaction the actual calculation ("reverse" mode) in GEANT4 is done with a Carbon target and a C or O projectile with all produced particles boosted in the correct system after each interaction for further transport. More precisely, the choice is dependent of the observable. The "direct" mode is an "accurate target" mode and the "reverse" an "accurate projectile" mode.

In Fig. 3 the angular distribution of fragments for a 5mm and a 25mm thick PMMA target measured by the same collaboration are compared with INCL, BIC (Binary Cascade) and QMD (Quantum Molecular Dynamics) calculations in GEANT4 [6]. The INCL calculation is better than the BIC one and quite comparable to the QMD one but much faster.

5 GSI experiment

At GSI, double differential production rates of n, p, d, t, ^3He and ^4He produced by a ^{12}C beam of 200A MeV stopped in a 12.8 cm thick water target have been measured [9]. In Fig. 4 and Fig. 5, data are compared with the same 3 dynamical models available in GEANT4 (INCL, BIC and QMD). All calculations are divided by 3 for deuterons and tritons and by 10 for ^4He but are absolute for neutrons, protons and ^3He. We don't understand the origine of these factors but these detailed observables are rather precisely described in shape, and on the overall better by INCL than by the other models.

6 ISOLDE experiment (At production)

The production of astatine isotopes released from a 20 cm thick Pb-Bi target and produced by proton beams of 1.4 GeV and 1.0 GeV has been measured [10] at ISOLDE. To increase by 2 units the charge of the bismuth target, a one step process by a $Bi(p,\pi^-)At + xn$ reaction or a two step process $Pb - Bi(p, He)X$ followed by a $Bi(He, xn)At$ reaction are possible.

The total production (black curve in Fig. 6a) is decomposed into these various contributions showing that the one step process is dominant for the light isotopes whereas the two step is dominant for the heavy ones. Taking into account the history of irradiation (decay of nuclei during irradiation) leads to the final rather satisfactory calculations of Fig. 6b and Fig. 6c.

Fig. 6b illustrates the effect of a better treatment of He projectiles at low energy between the version INCL4.5 in blue and the present one INCL4.6 in red.

7 Conclusion

We have explained how the cascade code INCL has been improved in the sector of composite beams up to oxygen nuclei and for low beam energies. This led to a Fortran version (INCL4.6 soon publicly available in MCNP6, projectiles up to ^4He) and a fully redesigned C++ version (INCL++5 already available in Geant4, projectiles up to ^{16}O).

We have shown promising first results on the fragmentation of ^{12}C beams on thick targets at 95A MeV and 200A MeV. INCL calculations are here better than the BIC model and comparable to but faster than the QMD model. Energy distributions of light particles (up to ^4He) are very good. The correct prediction of astatine production measured at ISOLDE illustrates the importance of a good He production and of the low energy treatment in the code.

The new open sector has certainly to be more systematically tested especially to disentangle the contribution of the de-excitation. The main drawback is at the moment the asymmetric treatment between the projectile and the target nuclei. This force a choice of the kinematics (beam nuclei as target or as beam in the INCL calculation) favoring the fragmentation of the beam and will be the subject of future developments.

References

[1] J. Cugnon, *Nucl. Phys. A462 (1987) 751*

[2] A. Boudard, J. Cugnon, S. Leray and C. Volant, *Phys. Rev. C66 (2002) 044615*

[3] A. Kelić, M.V. Ricciardi and K.-H. Schmidt, *arXiv_ nucl-th 0906.4193v1*; Proc. of Joint ICTP-IAEA Adv. W. on Model Codes for Spal. Reac., Trieste, 2008, report INDC(NDS)-530, Vienna, August 2008, Editors: D. Filges et al.

[4] *http://www-nds.iaea.org/spallations/* and Report IAEA INDC(NDS)-530, Vienna, August 2008, Editors: D. Filges et al.

[5] D. B. Pelowitz. MCNPX User's Manual - Version 2.6.0. LA-CP-07-1473, 2008

[6] GEANT4-S. Agostinelli et al. *Nucl. Inst. and Phys. A506 (2003) 250* and Geant4.cern.ch (Physics Reference Manual).

[7] J.K. Tuli, *Nuclear Wallet Cards 2010*, Broohkaven Nat. Lab. USA

[8] B. Braunn et al. *Nucl. Inst. and Meth. B269 (2011) 2676*

[9] K. Gunzert-Marx et al. *New Journal of Phys. 10 (2008) 075003* and D. Schardt private communication.

[10] Y. Tall et al. *Proceeding of Internat. Conf. on Nucl. Data for Science and Tech., April 2007 Nice, France, Editors: O. Bersillon et al., EDP Science (2008) p1069*