INCL4.5 and Abla07 - Improved versions of the intranuclear cascade (INCL4) and deexcitation (Abla) models

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Abstract

The two codes INCL4.2 (Intra-nuclear cascade) and Abla (deexcitation), combined to describe spallation reactions, have been improved in the last years. The main points were the light charged particle emission and IMF (Intermediate Mass Fragment) emission. The new versions, INCL4.5 and Abla07, give now good results in particular on tritium and helium production. An international benchmark, where these two codes participated, shows that this spallation model combination is one of the most reliable to reproduce particle and residue production in a wide projectile energy range. These two models have been implemented recently in MCNPX2.7 (beta version).

Significant improvements in microscopic results will be shown and new calculations for the Megapie target will be compared to the previous results.

Introduction

Spallation reactions exist in space and are studied for basic research (e.g. cosmogenic isotopes) and for application (e.g. activation of space-borne devices). Thanks to high-intensity proton beams such reactions can be used to produce radioactive ion beams or intense neutron fluxes, for spallation neutron sources or accelerator-driven system. These proton accelerators and spallation targets have to be optimized to reduce the risks (cost, safety) and get the best results. This can only be achieved via reliable spallation models.

Spallation reactions are a two-step process: A first and fast stage called Intra-Nuclear Cascade (INC) and a second and slower one called deexcitation. Several models exist to describe both step, but this paper focus on one model combination: The Intra-Nuclear Cascade Liège (INCL, for the INC part) followed by the Abla code from GSI (for the deexcitation phase).

Around 2000 the INCL4.2 [1] and AblaV3p [2] versions gave good results for neutrons and the residual nucleus production was really improved especially for nuclei close to the target mass and charge and for fission fragments (case of heavy target). For these reasons they were implemented in the transport code MCNPX2.5 [3]. Nevertheless the light charged particle and Intermediate Mass Fragments (IMF) productions were not or poorly predicted. With other refinements, a coalescence mechanism in INCL4.5 and a comprehensive evaporation process including IMF emission in Abla07 improve significantly the results obtained by this combination.

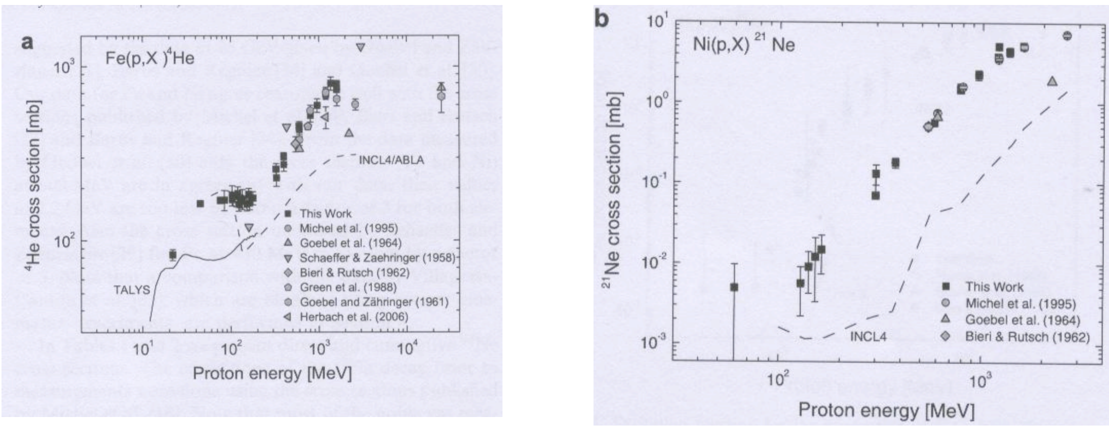
In the first section we will remind the main results obtained by the previous versions (INCL4.2 and AblaV3p) focusing on the shortcomings. The second section will present the main new physics ingredients in both codes and the third section will be devoted to the results with thin targets (microscopic reactions), and also for the Megapie target, since these new versions have been very recently implemented in a beta version of MCNPX2.7.

INCL4.2/AblaV3p

The two codes INCL4.2 [1] and AblaV3p [2] gave very good results on neutron spectra with projectile energy higher than 150 MeV, on residue yields for nuclei close to the target and on fission fragments and rather good results for proton spectra. Due to the overall quality of the obtained spallation results with this model combination the two codes had been implemented in MCNPX2.5 and used for different spallation target project (Megapie [4], Eurisol-DS [5] or ADS benchmarks [6]).

Nevertheless this combination was not able to predict all types of observables. INCL4.2 emitted nucleons and pions, but no cluster. On the Abla side nucleons and alpha were the only particles evaporated and fission was the only other way to deexcite the remnant nucleus. As a result the light charged particles, except proton, were badly or not predicted and the IMF were produced only via fission, which is for sure not the main channel to get them especially for the light targets that don't undergo fission. Some examples are given below. Fig. 1 shows that alpha production is too low within a factor 2 (left part) and IMF are strongly under predicted (right part).

Figure 1: alpha excitation function with proton on Fe on the left side and ^{21}Ne excitation function with proton on Ni on the right side. INCL4.2-AblaV3p results are plotted in dashed line. These figures are from [7].



INCL4.5/ABLA07: physics ingredients

The main new ingredients included in the last versions are presented briefly. The reader is invited to find more details in the references given in the following sections and in [8].

INCL4.5

To fix the problems mentioned previously several improvements have been made in INCL4.2 to end up in INCL4.5: composite particle emission, nucleon and pion potentials (isospin and/or energy-dependence), extension to low-energy projectile, and other minor modifications.

The mechanism used to predict composite particle (or cluster) emission is based on the idea that a nucleon escaping from the nucleus can drag with him other nucleons which are sufficiently close (in phase space), and form an emitted light charged cluster (surface coalescence). All possible clusters up to a mass 8 are considered. Going beyond this mass number would increase dramatically the calculation time since all possible clusters are built in the given phase space. The less *virtual* cluster, according to the definition given in [9], is selected and emitted if it has enough kinetic energy to penetrate Coulomb barrier. Thus this new version is able to emit nucleons and pions, but also d, t, ^{3}He, α and all nuclei with a mass number below or equal to 8.

Compared to other models INCL4.2 gave not too bad results concerning quasi-elastic and quasi-inelastic peaks in particle spectra. Nevertheless refinements of the nucleon potential have been performed, taken into account its dependence upon the isospin and its more or less linearly decreasing when nucleon energy increases [10].

Pion production was previously not so good, so this motivated the implementation of a pion potential which was set to zero before and of a pion transmission through the barrier. The nuclear part that is described by two fitted parameters is isospin-dependent like the Coulomb part [10].

Below 150 MeV INC models are not supposed to be reliable since then nucleon should be sensitive to the nuclear structure. Nevertheless transport codes used them below these energies when evaluated data files for the considered nuclei do not exist. Thus, in order to be *usable* at low energies, in particular concerning the total reaction cross-section, special attention has been paid to the treatment of the first nucleon-nucleon collision and Coulomb distortion in the entrance channel has been introduced.

Finally other minor modifications have been made. Two of them are i) the strict Pauli blocking for the first collision (which was before statistical) and ii) to save computing time (~25%), in addition to the stopping time criterion, when all particles are below a given energy (E_F + 10 MeV) the cascade is stopped.

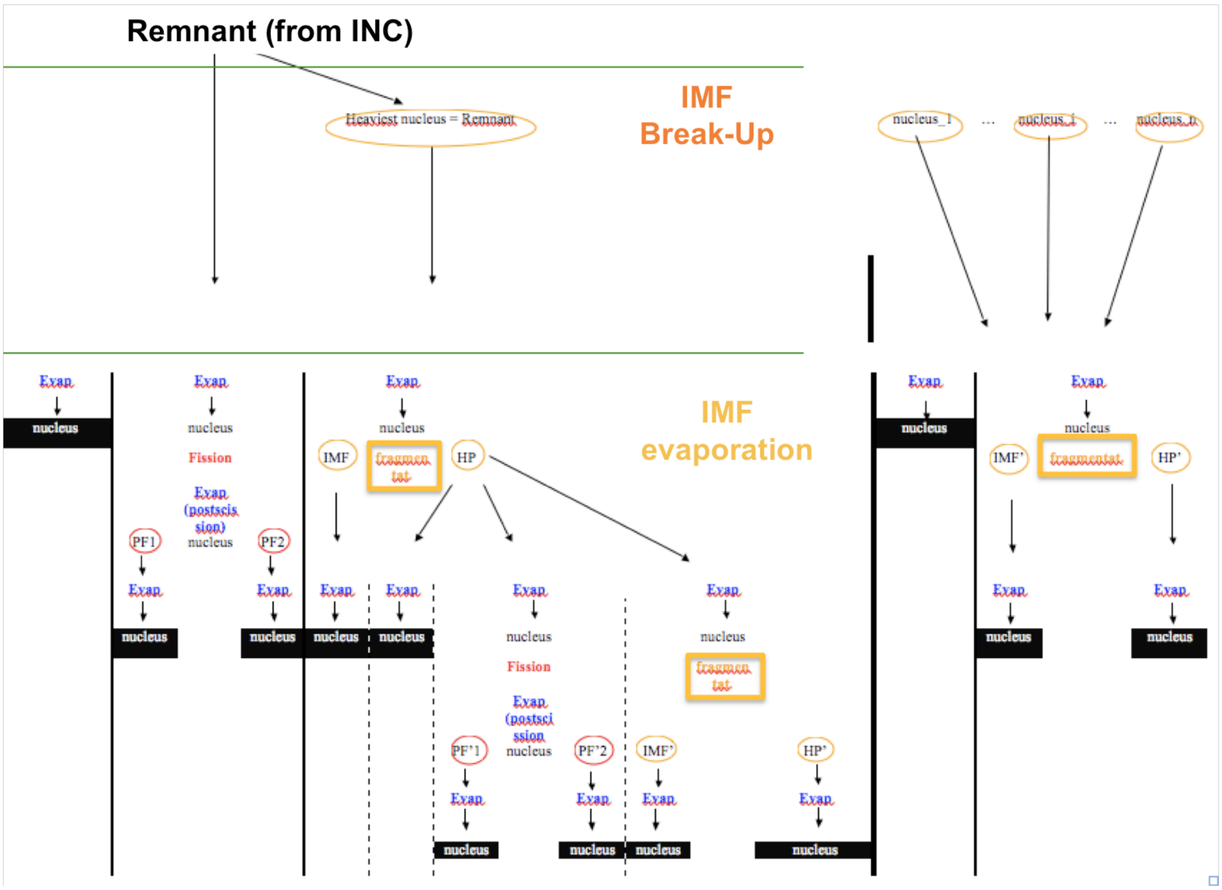
Abla07

The main improvements in Abla are the evaporation of particles from nucleons up to alpha and the emission of IMF via two processes: Breakup (or multifragmentation), when temperature of the remnant is high enough, and evaporation (or binary fragmentation). Evaporation mechanism has been refined with much more sophisticated Coulomb barrier and inverse cross sections. IMF evaporation is different from the particle evaporation only in the way to calculate the emission widths. They are obtained in IMF case with a power law to avoid a too huge calculation time. This is the same type of law that is used in the Breakup phase.

Fission has also been improved via for instance a dissipation based on an approximated solution of the Fokker-Planck equation, replacing the previous step function, and a possible evaporation step between saddle and scission points.

Fig. 2 gives a schematic view of the different deexcitation channels in Abla07.

Figure 2: Schematic view of all possible ways to deexcite a remnant nucleus in Abla07



INCL4.5/Abla07: Results

Thin targets (No transport)

Some results on tritium, helium and IMF production with the new versions are presented below.

Fig. 3 deals with two tritium excitation functions: The left part with an iron target and the right part with a lead target. INCL4.5/Abla07 is the solid line and two other models are plotted also (CEM03 [11] in dashed line and Bertini-Dresner [12,13] in dashed-dotted line). If on iron the production is slightly overestimated, but with values within a factor lower than 2, results obtained with lead are very good.

Same type of comparison has been made for helium production on iron (Fig. 4). The alpha production (solid line) is still underestimated, but significantly improved compared to Fig. 1 and ^{3}He is now produced (dashed line) and very well estimated, which gives a much better confidence in helium production. With a lead target (not shown here but in [14]) the previous good results for alpha have not been changed and ^{3}He production is rather well described.

Figure 3: Tritium excitation functions: Fe(p,xt) on left, and Pb(p,xt) on right. INCL4.5/Abla07 is plotted as solid line, CEM03 is dashed and Bertini-Dresner is dotted. References on Data in [14].

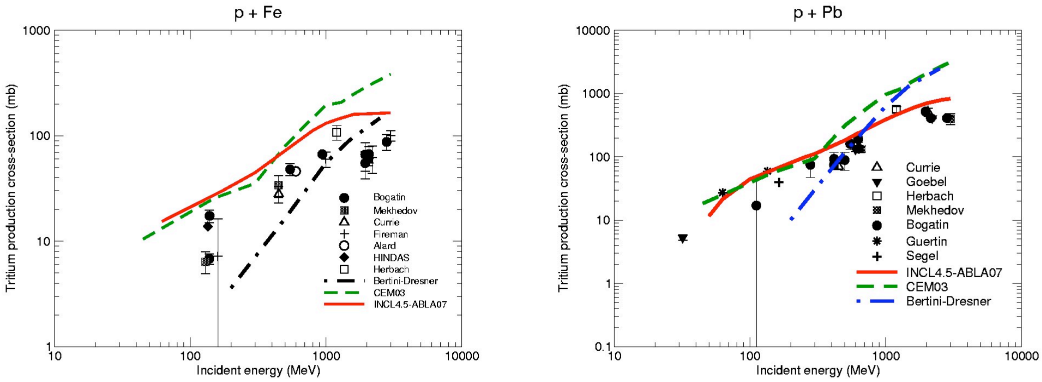
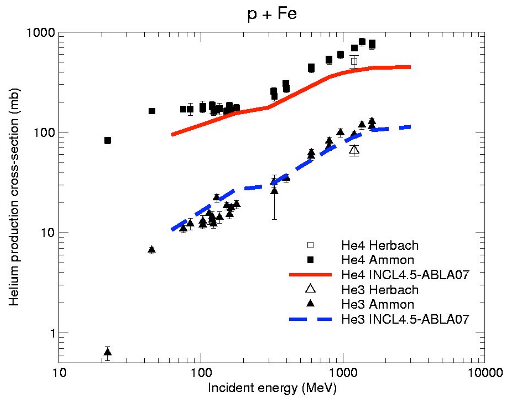
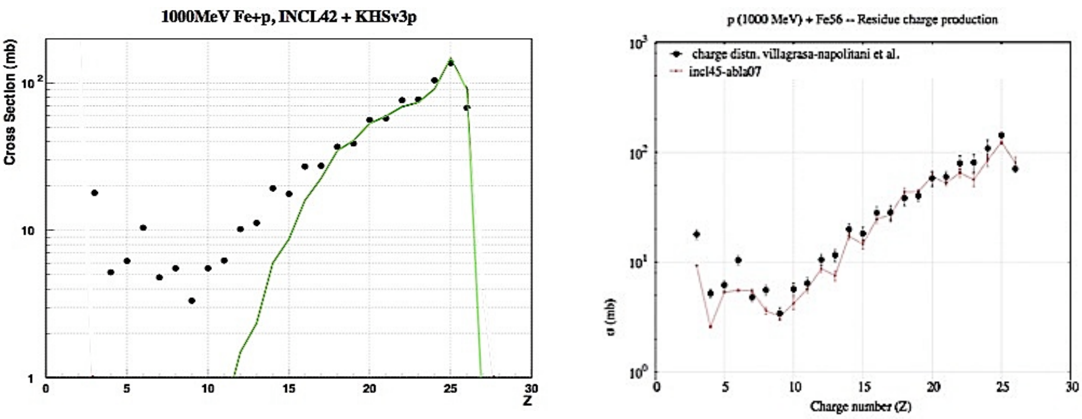


Figure 4: Helium excitation functions: Fe(p,xα). INCL4.5/Abla07 is plotted as solid line for ^{4}He and as dashed line for ^{3}He. References on Data in [14].



Intermediate Mass Fragment (IMF) production is now taken into account, both in INCL4.5 and Abla07. Fig. 5 shows clearly the great improvement in IMF prediction: On the right (left) part the new (previous) version is plotted. Isotopes with a charge around 10 were missing before and now are produced with a rather good rate compared to data.

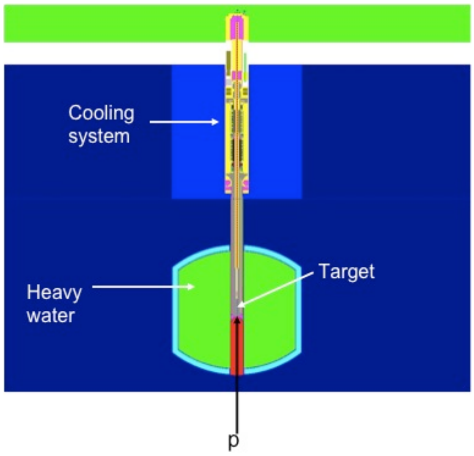
Figure 5: Charge distribution for the reaction Fe(1GeV.u) + p. On the left INCL4.2-AblaV3p and on the right INCL4.5-Abla07. Data from [15].



Megapie

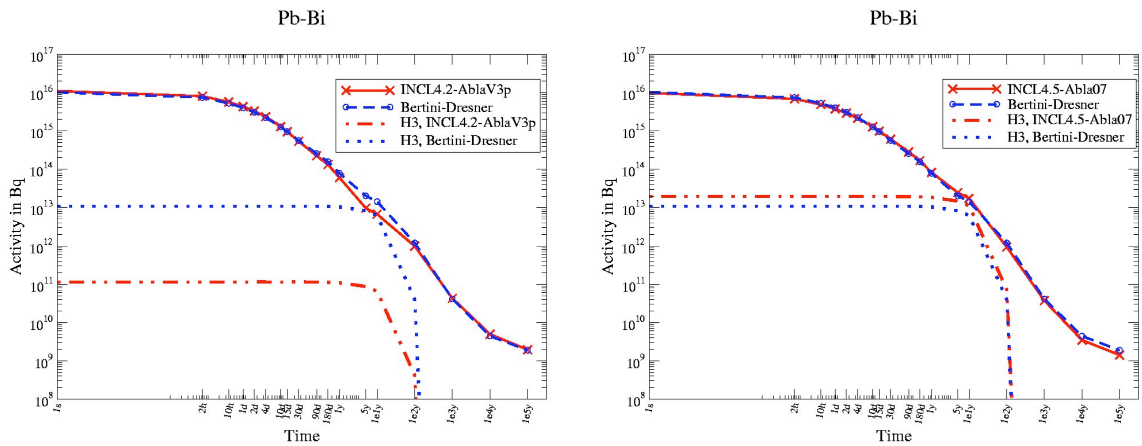
INCL4.5-Abla07 being strongly improved especially in tritium, helium and IMF production, they have been implemented very recently in a beta version of MCNPX2.7. This implementation allows then new predictions for the Megapie target. This spallation target was a demonstrator for a liquid lead-bismuth target. It was operated 123 days in 2006 at PSI (Switzerland). Fig. 6 shows the main parts with a proton beam (575 MeV - 0.947 mA) impinging the target surrounding by a water tank. Calculations on neutron flux and residue production in different places had been performed with several models like INCL4.2-AblaV3p available in MCNPX2.5 (more information in [4]).

Figure 6: Main parts of the Lead-Bismuth Eutectic (LBE) Megapie target



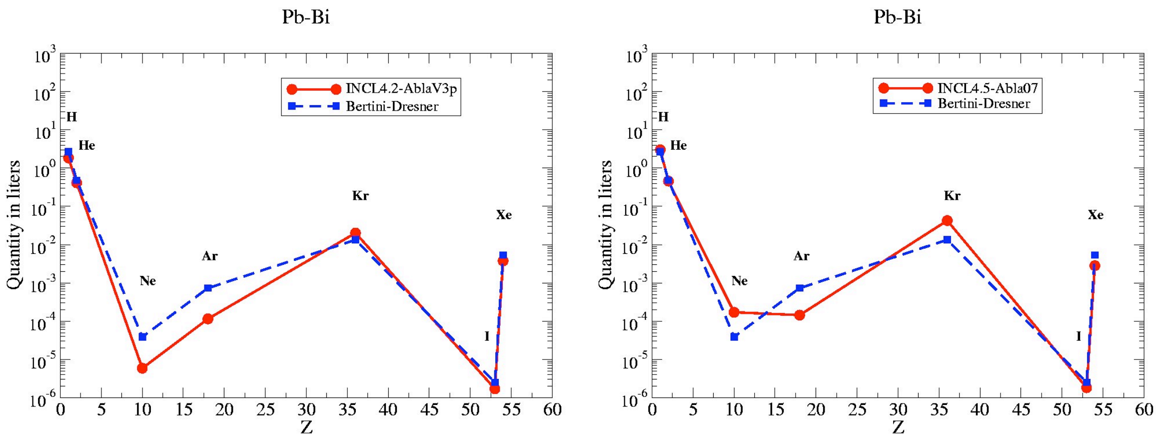
We show hereafter new results obtained in the target.

Figure 7: Total activity of the LBE target as a function of cooling time after 123 days of irradiation with 575 MeV protons at 0.947 mA using on the left part INCL4.2-AblaV3p and on the right part INCL4.5-Abla07. Bertini-Dresner, as default option in MCNPX, is also used as the contributions from Tritium.



Several models calculated time evolution of the total activity in the target previously and results were almost the same. The only difference was after around 10 years of cooling due to the production of tritium. Fig. 7 summarizes the results with the two versions (left for the old one and right for the new one) and Bertini-Dresner as default option in MCNPX. It is clear that the tritium production was missing which is fixed now. Moreover the difference between Bertini-Dresner and INCL4.5-Abla07, about a factor 2, can be explained by Fig. 3 (right part) where the INCL4.5-Abla07 model fits very well the experimental data while Bertini-Dresner underpredicts them in the Megapie energy range, i.e. below 575 MeV.

Figure 8: Quantity of volatiles (up to Xe) produced in the LBE traget after 123 days of irradiation with 575 MeV protons at 0.947 mA using on the left part INCL4.2-AblaV3p and on the right part INCL4.5-Abla07. Bertini-Dresner, as default option in MCNPX, is also plotted.



With Fig. 8 we see importance of IMF emission. If fission fragment production has not changed, Ne (Z=10) production has been significantly increased and the results obtained within the *Benchmark of spallation models* [16] give us confidence in these new predictions

Conclusions

INCL4 and Abla have been considerably improved. Emission of composite particle, isospin and/or energy-dependence of the nucleon and pion potentials, extension to low-energy projectile, and other minor modifications in INCL4.2 lead to the new version INCL4.5. On the Abla side, much more sophisticated inverse cross section description and coulomb barrier calculation for evaporation of all types of nucleons, light charged particles and IMF are the main new ingredients included in AblaV3p to end up in Abla07.

These new versions lead to much better prediction in light charged particle production, especially Tritium and He, and in IMF prediction. This makes INCL4.5-Abla07 one of the most reliable model combination to describe spallation reactions and then give more confidence when designing facilities like spallation neutron sources, Accelerator Driven Systems or Radioactive Ion Beams facilities from the two points of view: efficiency and safety.

References

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