INCL INTRA-NUCLEAR CASCADE AND ABLA DE-EXCITATION MODELS IN GEANT4

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We present INCL intra-nuclear cascade and ABLA de-excitation (evaporation/fission) models that can be used to calculate collisions between projectile particles and nuclei at energies from 0.2 to 3 GeV. Supported projectiles are proton, neutron, pions and light ions up to alpha. The optimal target materials range from carbon to uranium.

We have extended the INCL model light ion projectile support up to carbon-ions and compared the results against experimental data and Geant4 Binary cascade. The thin target results of the INCL model are in good agreement with experimental data.

KEYWORDS: *Geant4, intra-nuclear cascade, Monte Carlo, ion-ion collisions*

I. Introduction

INCL[1] intra-nuclear cascade model calculates the reactions between nucleon, pion or light ion projectiles with target nuclei. After the cascade an excited remnant nucleus is de-excited using the ABLA[2–4] evaporation/fission code. INCL/ABLA alone is a thin-target simulation code. In order to perform calculations that involve complex geometries and multiple composite materials INCL must be embedded into a transport code that can offer this functionality. Two such transport codes are Geant4[5] and MCNPX[6]. The original FORTRAN version of INCL4.2 has been included in MC-NPX. The same version of INCL was later translated to C++ and included in Geant4[7].

The combination of INCL/ABLA with transport code has opened new possibilities for practical applications. Some of the more traditional applications for intra-nuclear cascade models are nuclear waste transmutation and Accelerator Driven Systems (ADS) studies which mainly deal with heavy target materials and nucleon beams. In recent years there has also been an increasing interest in medical applications of these Monte Carlo codes. One such application is the treatment of tumors using light ions, especially carbon beams with energies of a few hundred MeV per nucleon. Another interesting application for ion-ion collisions are the spacecraft radiation shielding studies. In this case the relevant ions range from protons to iron ions with energies up to a few GeV.

This has motivated us to extend the light ion projectile supported by INCL. In the previous release of INCL4.2 we supported light ion projectiles up to alpha. In this new version we have extended this support up to carbon. In this paper we present our first results and compare against Geant4 Binary

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cascade which offers similar support for light ion projectiles as INCL.

In the future we hope to further extend the ion-ion support of the INCL intra-nuclear cascade model and make it more realistic. This, and many technical shortcomings of the INCL codebase that have their roots in the FORTRAN77 legacy of the original code, have motivated us to perform a complete redesign of the INCL simulation code in object oriented C++. We will discuss some of our motivations and main ideas of the redesign work and how they will help us to develop our model further.

II. INCL4.2 light ion extension

The INCL light ion extension consists of two main parts: handling of the projectile as a collection of individual nucleons and de-excitation of the projectile fragments after the reaction.

1. Projectile as a collection of nucleons

TODO: Improve the explanation of gaussian potential and rms values (see JMQ comments) The projectile is modeled as a collection of independent nucleons with gaussian momentum and position distributions[8]. For the position distribution we use the realistic r.m.s. of the projectile ion. The r.m.s. of the momentum distribution is fixed to 100 MeV/c. The sum of the energies of the projectile nucleons is equal to the projectile total energy, but the momentum is slightly biased because all projectile nucleons are on mass shell. **TODO:** Clarify what "on mass shell" means (see JMQ comments)

Some projectile nucleons miss the target. These are considered *projectile spectators*. Some of the nucleons that enter the nucleus can pass through it without any collisions at all and

are also considered as projectile spectators. The rest of the projectile nucleons proceed to produce an intra-nuclear cascade as described in ref[1].

At the end of the cascade all projectile spectators are combined into a *spectator nucleus*. The mass, charge and momentum of this nucleus are directly determined by summation. The excitation energy is determined in the following way. In the initialization of the cascade, a list of A-projectile Fermi momenta has been randomly chosen corresponding to individual kinetic energies. The removal of some projectile nucleons by the interaction with the target nucleus is interpreted has holes for the the projectile spectator nucleus. Its excitation energy is simply the energy released in packing the spectator nucleons in the lowest energy states of the individual kinetic energy list.

2. De-excitation

After the cascade we need to de-excite both the projectile spectator nucleus and the remnant of the target nucleus. The spectator nucleus is always de-excited using the Geant4 Fermi break-up model. Fermi break-up is also used for the light cascade remnants (below mass 17) as well. The heavy remnants are treated with the ABLA fission/evaporation code. The ABLA version in Geant4 provides us with evaporation of protons, neutrons and alphas that competes with fission channel for sufficiently heavy remnant nuclei.

III. Results

We have compared the new version of INCL against experimental data and the Geant4 Binary cascade. These calculations have been done using a test version of INCL and Geant4 version `geant4-09-03-ref-05` which is an internal Geant4 development release from May of 2010.

1. Thin target calculations

Double-differential energy spectra for neutrons produced in reaction C + C at 135 MeV/nucleon are shown in **Figure 1**. INCL combined with Geant4 Fermi break-up reproduces the quasi-elastic peak very well, as can be seen in the energy spectrum for angle 0 °. The agreement with experimental data is worse for angles above 30 °.

In the case of C + C at 290 MeV/nucleon (**Figure 2**) INCL performance is still fairly good, but not quite perfect, in the forward region. For larger angles INCL seems to reproduce the shape of the distribution slightly better than Binary cascade.

We have also compared some projectile fragmentation results of INCL and Binary cascade against experiments. The results of these comparisons show that the combination of INCL and Geant4 Fermi break-up perform quite well when compared against Binary Cascade and the FORTRAN version of INCL that uses Fermi break-up taken from the LAHET code[9].

The projectile fragmentation plots in **Figure 3** show a slight disagreement between the FORTRAN version INCL4.3 and the C++ version of INCL4.2. This difference can be mostly attributed to the main difference between INCL4.2 and INCL4.3: light cluster emission in the cascade stage. It should

also be noted that the Fermi break-up models used in the calculations come from different sources. In the FORTRAN version INCL4.3 we use Fermi break-up implementation from the LAHET package and in INCL4.2 Geant4 version we use the Geant4 Fermi break-up model.

2. Thick water target

We have started doing preliminary tests using a full Geant4 simulation with thick water target. For this purpose we use a modified version of the Geant4 hadron therapy example application included in the standard Geant4 distribution.

In our simulation setup we shoot a 200 MeV/nucleon carbon beam to a 12.78 cm thick water target and record the outcoming particles behind the target. A preliminary neutron production comparison between INCL and Geant4 Binary cascade is shown in **Figure 4**.

The physics performance of both INCL (using physics list `QGSP_INCL_ABLA`) and Binary cascade (using physics list `QGSP_BIC_EMY`) is quite similar as far as neutron production is concerned.

IV. Ongoing development: INCL redesign in C++

The design of the INCL FORTRAN code has remained relatively stable for more than a decade while physics performance and modeling features of the code have been significantly improved. This has made the codebase monolithic and difficult to develop further. It has become apparent that the current design has reached the end of its life. Since the Geant4 version of INCL4.2 is basically only a minimal translation of FORTRAN code to C++, sort of "FORTRAN in C++ syntax", it inherits all the problems of the FORTRAN version. Additionally the monolithic nature of the code makes it difficult to utilize the full potential of C++ capabilities.

Another important problem in the current development model of INCL is that we have several "forked" versions of the code: the main line of development (version INCL4.6) and the MCNPX version (currently INCL4.2, INCL4.5 interface under development) in FORTRAN and INCL4.2 translation in C++ for Geant4. Additionally the light ion extension that was first introduced in INCL4.3 has now been added to the Geant4 version of INCL and will be released in 2010. The MCNPX version of INCL is essentially the same code as the standalone version, except that it has been modified to work inside of a transport code. The redesign project gives us an opportunity to unify all these different versions under a single source tree and allows us to deliver the same physics features consistently for Geant4, MCNPX and as a standalone thin-target calculation code without duplication of effort. **TODO:** This maybe requires some more clarification... (see JMQ comments)

The redesign project gives us an opportunity to revisit the physics ideas of INCL and experiment with features that would be very difficult to implement in current versions of INCL. Some examples of things that are difficult with the current codebase are changing the way particles are tracked or collisions are detected and implementing more realistic handling two of nuclear potentials in ion-ion collisions.
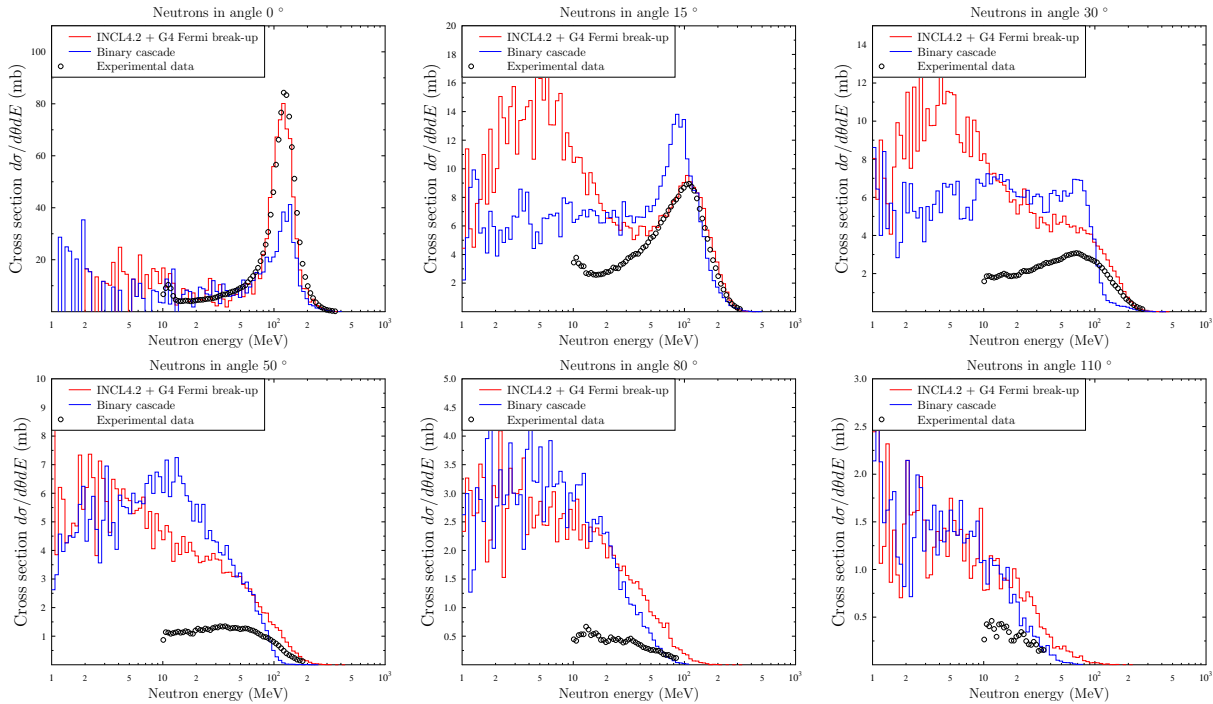
Fig. 1 Double-differential neutron energy spectra for C + C at 135 MeV/nucleon. Agreement of the INCL4.2 model with experiment is very good in the forward region. The quasi-elastic peak is reproduced very well.

V. Conclusions

We have presented the INCL intra-nuclear cascade model implementation in Geant4 and the INCL light ion projectile extension. The first results are in good agreement with experiments and physics performance of INCL is competitive with Geant4 Binary cascade.

We are now in good position to perform thick target studies and comparisons of INCL against experimental data in the case of light-ion collisions. Our first results are quite encouraging. However, there are still some open questions with regards to the physics list we should use with INCL. An especially important question is what to do for low energy collisions. In the physics list we used in this study we use INCL for nucleon, pion and ion projectiles from energy 3 GeV/nucleon down to 0 MeV/nucleon. Unfortunately some of the basic assumptions of intra-nuclear cascade start breaking down when energies fall significantly below 100 MeV/nucleon. One available option is to investigate the use of other potentially more suitable Geant4 models for low energy collisions and compare their results against those given by INCL.

The validation of the light ion extension will continue and it will be included in the Geant4 9.4 release in December 2010.

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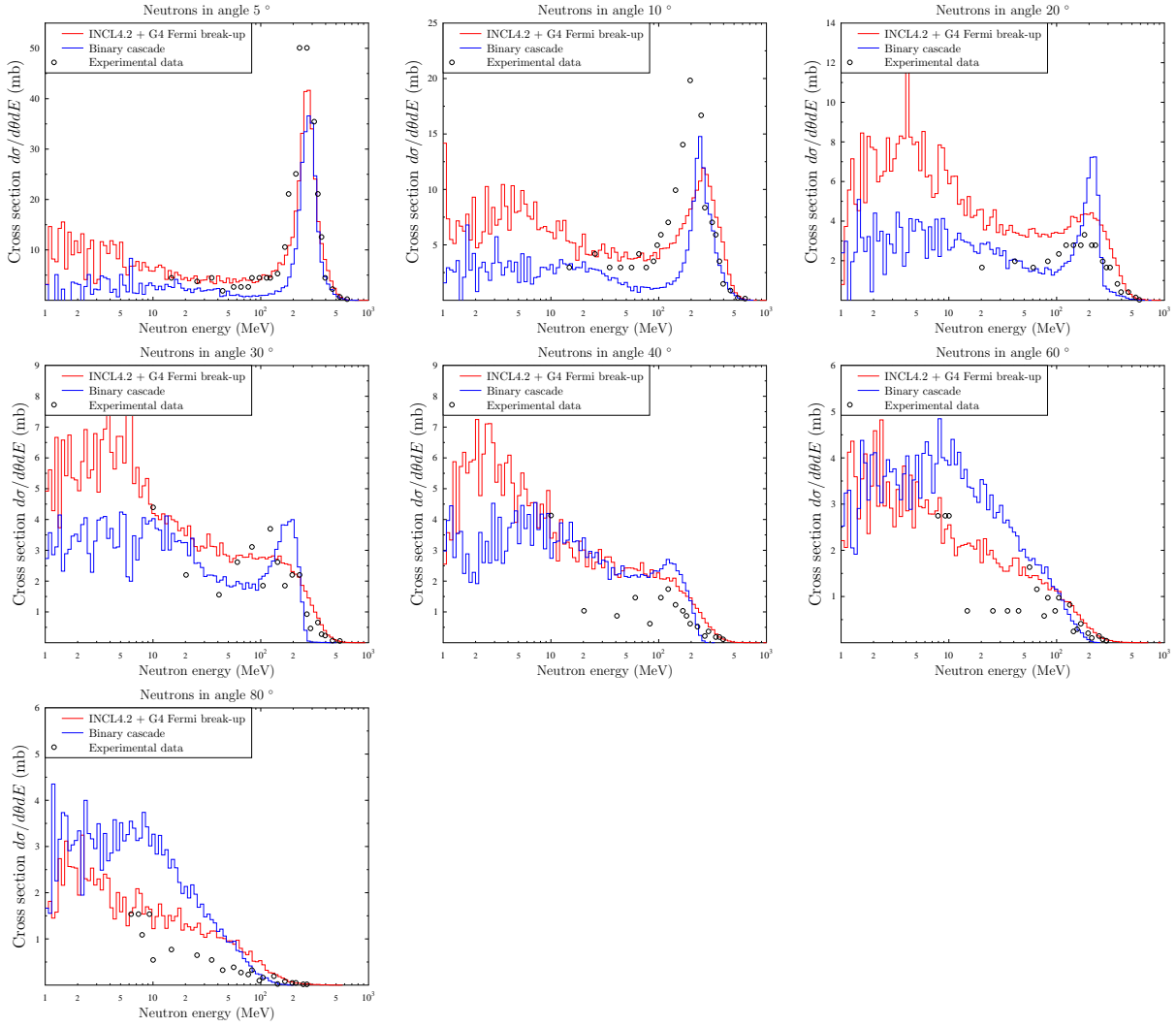
9) **TODO:** Add LAHET reference

Fig. 2 Double-differential neutron energy spectra for C + C at 290 MeV/nucleon. Both models show fairly similar levels of agreement with experiment. Overall INCL seems to reproduce the shape of the distribution slightly better.
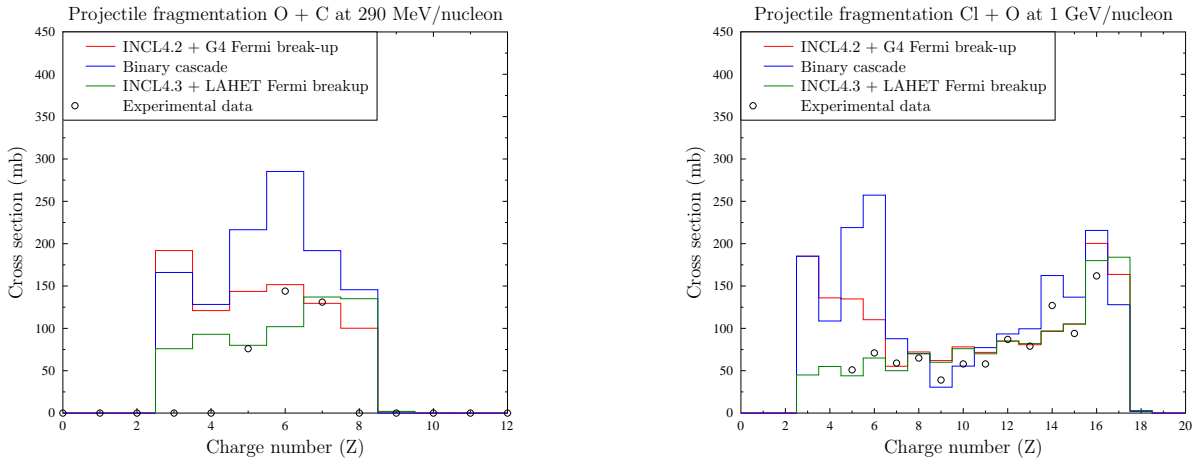
Fig. 3 Projectile fragmentation of INCL4.2 (C++), Binary cascade, INCL4.3 (FORTRAN) compared against experimental data. Both versions of INCL are in quite good agreement with the experiment. The differences in INCL results are presumably caused by the lack of light cluster emission in the INCL4.2 (C++) version.
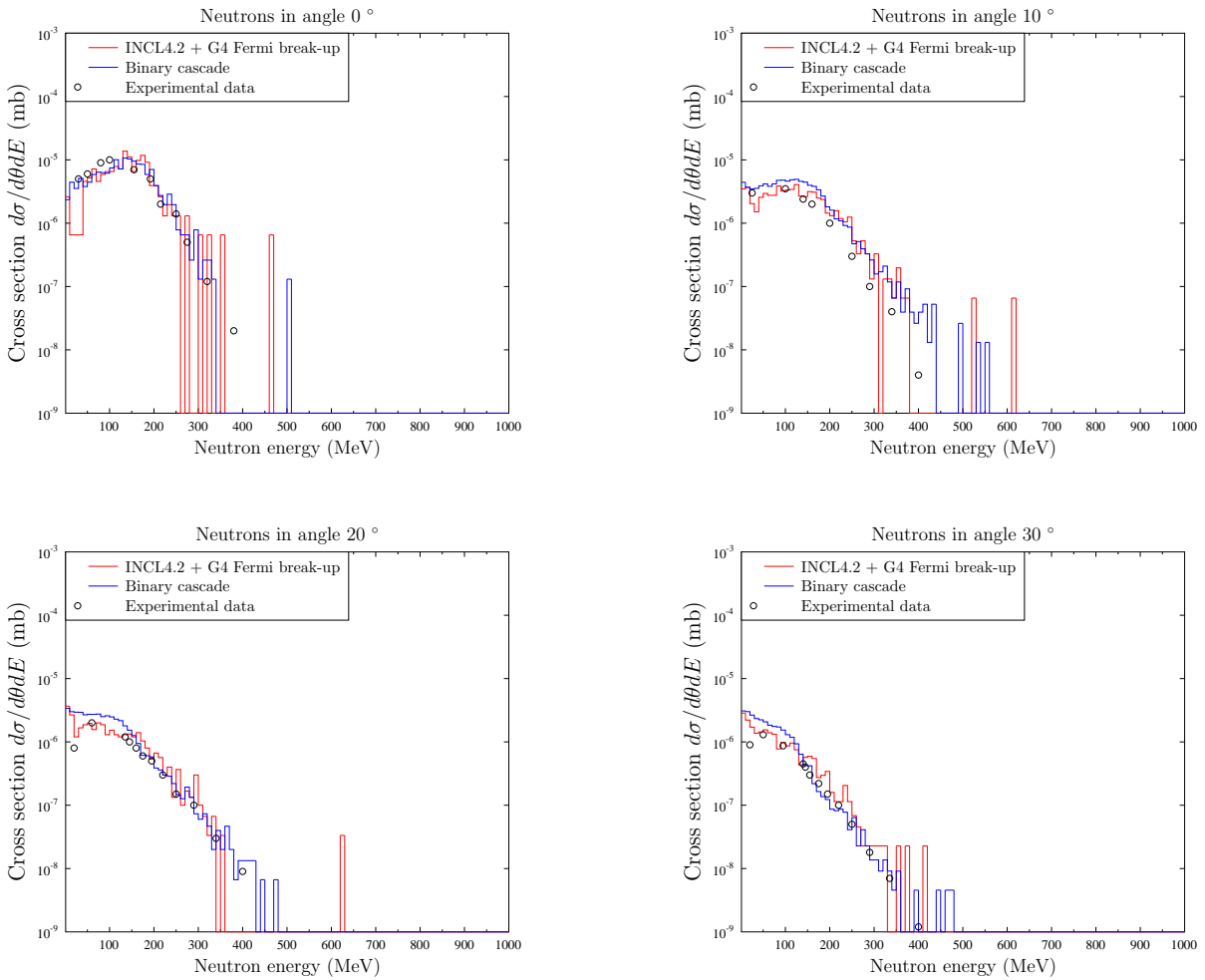

Fig. 4 Neutron double-differential energy spectra in C + water with target thickness of 12.78 cm at 200 MeV/nucleon. Both INCL and Binary Cascade show similar agreement with the experiment.