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Recent Developments of the Liège Intranuclear Cascade Model in View of its Use into High-energy Transport Codes

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Recent extensions of the Liège Intranuclear Cascade model, INCL, at energies below 100 MeV and for light-ion (up to oxygen) induced reactions are reported. Comparisons with relevant experimental data are shown. The model has been implemented into several high-energy transport codes allowing simulations in a wide domain of applications. Examples of simulations performed for spallation targets with the model implemented into MCNPX and in the domain of medical applications with GEANT4 are presented.

I. INTRODUCTION

The Liège Intranuclear Cascade model, INCL4 [1], has originally been developed to describe spallation reactions, i.e. nucleon-induced collisions in the 100 MeV - 3 GeV energy range. Coupled to the ABLA de-excitation code from GSI [2], INCL4 has been extensively compared with experimental data covering a wide range of reaction channels and continuously improved during the last years. In the benchmark of spallation models organized recently under the auspices of IAEA [3], the combination of the INCL4.5 and ABLA07 [4] versions was found [5] to be one of the models giving the best overall agreement with the experimental data.

A new version, INCL4.6, very similar to INCL4.5 for nucleon-induced reaction above 100 MeV but significantly improved for composite projectiles and energies below 100 MeV, has recently been released [6]. It is now implemented into PHITS [7] and in a version of MCNPX [8], coupled respectively to the GEM and ABLA07 de-excitation models. A version fully re-written in C++, INCL++, extended to light-ion beams up to ^{18}O has also been developed and is included into GEANT4 [9].

II. NEW POTENTIALITIES OF THE MODEL

A. Low-energy Composite-particle Induced Reactions

Although from the origin, the INCL4 model was designed to handle reactions with composite particles up to alpha, little attention had been paid to those up to recently. However, when the model is used in transport codes to simulate for instance a complex spallation target, secondary reactions induced by composite particles generated in primary collisions can occur. Since the data libraries available to the public transport codes do not consider yet reactions induced by complex particles, models are used instead. It is therefore necessary to ensure that they correctly predict at least the gross features of these interactions, although this falls well beyond the alleged theoretical limit of validity of INC models. This is why the treatment of low-energy composite particle induced reactions has been improved in [6].

Let us summarize the main modifications: i) the composite projectile is described as a collection of off-shell nucleons with Fermi motion, ensuring full energy and momentum conservation; ii) geometrical spectators, i.e. nucleons not passing through the target volume, are put on-shell and the energy needed to preserve a correct balance is taken from the participant nucleons; iii) if one nucleon tries to enter the target below the Fermi level, all geometrical participants are assumed to fuse with the target nucleus and produce a compound nucleus, which is subsequently passed over to the de-excitation model; iv) the projectile Coulomb deviation is now explicitly taken into account; v) experimental mass tables are used to ensure correct Q-values for all the reaction channels.

The model is now able to rather well predict helium-induced total reaction cross sections [6]. It also reasonably reproduces the different reaction channels that open with increasing incident energy. This is illustrated in Fig. 1, which shows experimental ^{209}Bi(α,xn) cross sections as a function of the incident particle kinetic energy, from the EXFOR experimental nuclear reaction database [10], compared with the model.

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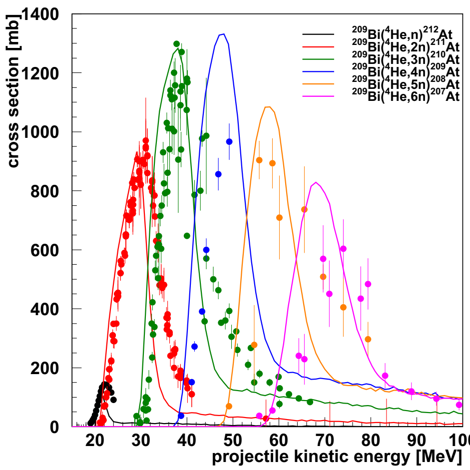

FIG. 1. ^{209}Bi(α,xn) cross sections for x=1 to 6 as functions of the helium kinetic energy compared to the INCL4.6+ABLA07 model. Experimental data come from the experimental nuclear reaction database EXFOR. From [6].

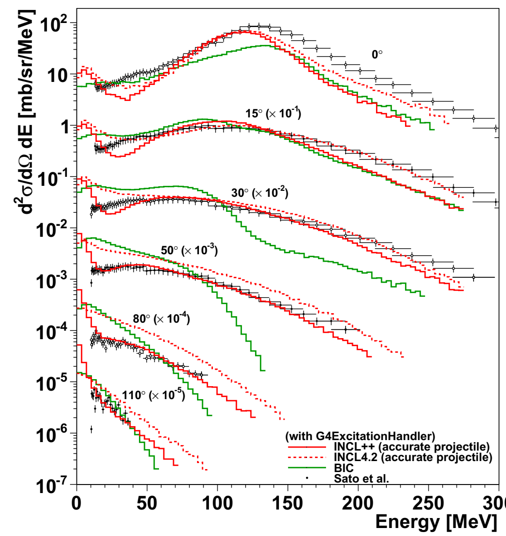

FIG. 2. Neutron production double differential cross sections in the ^{12}C + ^{12}C system at 135 MeV/u [13] compared to INCL++, INCL4.2, both in inverse kinematics, and BIC, all INC coupled to the GEANT4 de-excitation handler.

B. Light-ion Induced Reactions

A first attempt to extend INCL to light-ion induced reactions was done in [11]. Recently, the model has been revisited on the basis of the INCL4.6 version and totally rewritten in C++. This version, denoted as INCL++, has been included in the last GEANT4 release.

In this model, the projectile is described as a collection of nucleons whose positions and momenta are drawn from realistic distributions and satisfy the centre-of-mass constraint of zero total momentum. For each configuration, the depth of a binding potential is determined so that the sum of the nucleon energies is equal to the mass of the projectile nucleus. The projectile is then boosted with the nominal beam velocity. The nucleons that do not interact with this sphere are combined together in the "projectile spectator". The nucleons entering the calculation sphere move globally (with the beam velocity) until one of them interacts with a target nucleon. The NN interaction is then computed with the individual momenta, and Pauli blocking is tested. Nucleons crossing the sphere of calculation without any NN interaction are also combined in the "projectile spectator" at the end of the cascade. A fusion mechanism, as above described is also included.

The excitation energy of the projectile spectator nucleus is obtained by an empirical particle-hole model. This nucleus is then given to the de-excitation model. In this model, this "projectile spectator" has not received any explicit contribution from the zone of interaction which is entirely contained in the target. Therefore, the calculation is not symmetric and the residue of the target is a priori more realistic than the "projectile spectator". This means that to compare with experimental data, if emanating from projectile fragmentation, the results of the calculation should be done in "inverse kinematics" with the target fragments from the calculation Lorentz-boosted to become projectile fragments. Comparisons of ^{12}C+^{12}C experimental data to both "direct" and "inverse kinematics" simulations confirmed that the latter provides a better agreement [12].

Fig. 2 shows neutron production cross-sections measured in the ^{12}C+^{12}C system at 135 MeV by Sato *et al.* [13] compared with the present model, the former version INCL4.2, both in inverse kinematics, and the binary cascade (BIC) [14], all models being coupled to the GEANT4 de-excitation handler [15]. It can be observed that the present model better reproduces the data than the former version and that BIC is definitely less good.

III. EXAMPLES OF APPLICATIONS

A. Radioactive Inventory of the ESS Target

We have used INCL4.6-ABLA07 implemented into MCNPX to simulate the helium-cooled rotating tungsten target foreseen for the ESS facility, in which the radioactive inventory has been determined [16]. The major contributors to the radiotoxicity and their production channel have been identified. In order to estimate the reliability of the simulation, the model has been compared, when possible, with elementary experimental production cross-sections (excitation functions).

Examples of such excitation functions are displayed in Fig. 3 for two nuclides that pose issues for radioprotection: ^{148}Gd, which is an alpha emitter, and tritium. In most of the cases where elementary experimental data are available, the model reproduces them generally within a factor smaller than 2, implying a similar degree of confidence for the estimation of the radioactive inventory.