New features of the INCL model for spallation reactions

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Abstract.

The recent developments of the Liège intranuclear cascade model INCL are reviewed. The INCL4.6 version of this model was able when coupled with the ABLA07 de-excitation code, to describe rather well a huge set of experimental data in an incident energy range spanning between 200 MeV and 3 GeV, as it has been testified by an intercomparison of spallation codes organized by the IAEA. Since that time, the model has been implemented in several nuclear particle transport codes. Therefore, the possible applications of INCL have been enlarged to focus on diverse fields, and in the recent years, the model has been further developed to be applicable to these new issues and also to cope with remaining deficiencies. The new features include: i) a sophisticated dynamical model for light cluster emission (up to O ions), ii) the accommodation of light nuclei as projectiles, iii) a new procedure to take account of the fuzziness of the Fermi surface, and iv) an extension of the model to higher energy. The aim of this contribution is to present for the first time and to discuss the physics of the added features, and to give a hint about the performances of the new model.

1. Introduction

Spallation reactions are nuclear reactions between a light projectile and a target nucleus at energies roughly around one GeV, i.e. where no nuclear structure needs to be taken into account and when hadron degrees of freedom are relevant. The numerous applications where these reactions happen, such as hadrontherapy, radioprotection in space missions, radioprotection in nuclear installations, interactions with cosmic rays, etc., motivate the development of simulation tools as INCL. The Liège intranuclear cascade model INCL[1] simulates the first part of those reactions and is often combined to the ABLA07[2] code, which treats the second phase, i.e. the deexcitation of the remnant nucleus. It was recognized as one of the best cascade models especially when combined to ABLA07 during the IAEA benchmark (2010), where reactions between a nucleon below 3 GeV and any kind of targets were compared to experimental data. Since then, and based on this sound model, new improvements and extensions have been added.
Here four are them are presented: clusters as projectile, light cluster emission, few nucleon removal and the high-energy extension.

2. Clusters as projectile
Whether it is the development of hadrontherapy, with carbon beams for example, or helium nuclei which represent 12% of cosmic ray (∼1% for the heaviest ions), light nuclei as projectile in INCL were both useful and exciting. The model was primarily used with nucleon and pion projectiles. All the details on the implementation of incident light clusters was published in [1, 3]. Here we give only the main aspects. Unlike proton, neutron or pion, in this case the projectile is made of several nucleons and should be treated on the same footing as the target. However, for technical (e.g. computing) reasons it is not exactly the case in INCL. The main difference is that no nuclear cascade happens in the projectile. This is justified a priori for incident light nuclei at the spallation energy regime where few nucleons are emitted during the first phase. A simple particle-hole model is used then to estimate the excitation energy of the projectile-like prefragment. This is also justified a posteriori with the results given below. During the cascade phase, in the target, and depending upon the impact parameter, several scenarios appear. All (or some of the) nucleons of the projectile can be absorbed by the target, this is the (incomplete) fusion case. The nucleons that do not enter the target are called geometrical spectators. Another type of spectators, named dynamical spectators, are also considered. Those are the nucleons of the projectile that enter the target, but leave it without interaction with any nucleons of the target. The projectile-like prefragment is made then of all those nucleons from the projectile which did not interact with the target.

The results are pretty good, even if, obviously, the model can still be improved. Fig. 1 shows the mass distribution for the reaction $^{86}$Kr + $^9$Be at 500 A.MeV. INCL fits very well the experimental data, except around the mass A=75 and for some specific low masses. Isotopic distribution are not shown, but here again the results are very good. At a lower energy, and for a symmetric reaction, our results show sometimes some deficiencies. Fig. 2 plots the angular distributions for two nuclei, $^4$He and $^{11}$C, for the reaction $^{12}$C+$^{12}$C at 95 A.MeV. While INCL is doing rather well, and even better than other models also mentioned, for $^4$He production, it does not do a good job concerning the $^{11}$C production. For this isotope substantial improvements are needed.

![Fragmentation cross sections](image_url)

**Figure 1.** Fragmentation cross sections for the 500A MeV $^{86}$Kr + $^9$Be reaction, as a function of the fragment mass number. INCL-ABLA calculations are compared to experimental data. More details in [3].
3. Light cluster emission

With increasing energy, emission of light clusters appears, both in the first and the second phase. Moreover, the most energetic ones can induce secondary reactions. Therefore, their implementation in an intranuclear cascade is mandatory for a good description of spallation reactions. Here, the difficulty is that the degrees of freedom in a cascade are hadrons: baryons (nucleons and resonances) and mesons (pions, ...). An ad-hoc model must be then used to built the emitted clusters. INCL relies on a dynamical coalescence model. Basically, when a nucleon is leaving the target nucleus during the cascade, all nucleons close by in phase space of the escaping nucleon are then candidates to aggregate and build a cluster. Criteria on the excitation energy of the candidate clusters, on the size of the cluster, on the capability to overpass the Coulomb barrier define the cluster, if any, which will be eventually emitted.

Fig. 3 shows two double differential cross sections of clusters emitted during the reaction $p + ^{197}$Au at 1.2 GeV. The green curves are the spectra calculated by INCL. They fit rather well the measurements, both for $^6$He and $^7$Be, but, especially for $^6$He, the high-energy tail is a bit overestimated. This must be cured. A cut on the momentum of the nucleon candidate to aggregate could improve the results. More details can be found in [4, 5].

4. Few nucleon removal

Emission of nuclei resulting from the transfer of one, and only one, proton or neutron, in addition to the projectile, is expected to be well described by an intranuclear cascade model, since the mechanism is very simple. However, in INCL, but also in other cascade models, the one-proton removal yield is overestimated while the one-neutron removal yield is more correctly estimated. This was possibly due to not enough neutrons evaporated, because of a too low excitation energy. The classical picture for the energy density of the nucleus used in INCL, i.e. a strong correlation between the position of a nucleon in the nucleus and its momentum, could explain this defect. Only the most energetic nucleons could reach the surface, where the few-nucleon removal reaction take place. Therefore, only energetic nucleons were emitted, leaving the nucleus with a too small excitation energy. In addition, the one-nucleon removal occurring at the surface of the nucleus, the neutron (proton) skin should be also refined. These works have been published in two papers. The first one [6] stated the hypotheses which were tested with a simple shell model, replacing the classical picture, on two specific cases. Fig. 4 illustrates the difference between the classical picture (top) of the energy content in the nucleus and the refined picture (bottom) based on a shell model, which exhibits a fuzzy surface. The second one [7] refined and extended the idea.
Figure 3. Double-differential cross sections for $^6$He (left) and $^7$Be (right) cluster production in p + $^{197}$Au collisions at 1.2 GeV. The green histograms indicate the INCL component. More details in [1].

with the use of single-particle wave functions from Hartree-Fock-Bogoliubov calculations, and gave the very good results which now fit the experimental data (Fig. 5).

Figure 4. Space–kinetic-energy density of protons in $^{208}$Pb in the classical picture (top) and in the refined and fuzzy picture (bottom). The dotted vertical lines indicate the region of impact parameters which dominates one-proton removal. More details in [6].

Figure 5. One-proton removal cross sections from proton-induced reactions at kinetic energies of 1 GeV as a function of the target mass number (solid circles). The open squares represent the standard INCL calculations and the open triangles take into account the proton and neutron density profiles obtained with the Hartree-Fock-Bogoliubov model. The open circles correspond to calculations where the two refinements, density profiles and surface fuzziness, are simultaneously applied. More details in [7].
5. High-energy extension

Until year 2010, INCL was applied in the energy domain ranging from a few MeV up to 2-3 GeV, basically the domain of the ADS’s and spallation neutron sources. Extension of INCL up to 10-20 GeV was motivated by the galactic cosmic ray spectrum that peaks roughly around one GeV, but with a non-negligible component up to 10-20 GeV.

The more energetic the projectile, the more energetic secondary particles are produced, and thus a greater cascade of secondary reactions. Moreover, with increasing energy new particles are produced like, for example, strange particles (kaon and hyperon) and new types of residue, like hypernuclei.

The first step toward 10-20 GeV was the implementation of the multiple pion channels. Whereas most of the models open resonances when the energy increases, INCL includes only the decay products, i.e. principally the multipions. At least three reasons drove this approach. First, due to large widths some resonances overlap making difficult the choice, second, the half-lives are short making the transport useless, and third, the parameters related to the resonance interactions are not known. This is explained in [8]. Fig. 6 shows the need of the multipion channels. The excitation function of the $^{47}$Sc from the reaction p+Fe was rather well described by INCL up to 2-3 GeV, but to fit the high-energy point at 12 GeV, the implementation of the 2, 3 and even 4-pion emission is necessary.

![Graph showing Sc production cross sections from proton-induced reaction on natural Fe.](image)

**Figure 6.** $^{47}$Sc production cross sections from proton-induced reaction on natural Fe. Calculation results from INCL4.6[1], where multipion channels were implemented, combined to ABLA07[2]. Experimental data come from [10, 11, 12, 13].

The second step toward the high energies was the implementation of strange particles. Here again no new resonances were added, but only the decay products, kaons and Λ and Σ hyperons, were accounted for. This is explained in details in [9]. The main difficulty, in addition of the computing time due to low cross sections, was to get the values of the elementary cross section (production, scattering, absorption) related to those new particles. Experimental data were too scarce, thus isospin symmetries and models were necessary to complete the data base. On Fig. 7 are plotted rapidity spectra of kaons produced with 14.6 GeV/c protons on four different targets (Be, Al, Cu and Au). Experimental measurements are well fitted by INCL, except for the highest rapidities and the heaviest nuclei. This encouraging results is only one example and more plots will be published soon.
Figure 7. K⁺ production cross sections in p(14.6 GeV/c)+A collisions as a function of rapidity. The experimental data[14] (black) are compared to INCL predictions (red).

6. Conclusion
Since the IAEA benchmark in 2010 where INCL was recognized as a sound and reliable model, new features have been added to extend its capabilities. We presented here four of them. The clusters as projectile allow to use INCL in hadrontherapy as well as in all interactions of galactic cosmic ray in the GeV energy domain. Light cluster emission (A ≤ 8) is required to cope with secondary reactions when energy increases. The study and improvement of one-proton removal via a more realistic energy content of the target nucleus enabled to also better described the residue yields close to the target mass, sometimes important in radioprotection. Finally, the high-energy extension with multipion channels and strange particles, have extended the energy range of INCL up to 10-20 GeV and given the possibility to account for hypernuclei production. ABLA07 has been also improved in this sense with the possibility to evaporate Λ and to manage hyperfission. In those four topics INCL gives now interesting results, and the remaining deficiencies are well identified. INCL is available, on request, as a stand-alone version, but can also be used within the particle transport code GEANT4.

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