Results with INCL4

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Abstract. The new version INCL4.5 of the Liège intra-nuclear (INC) model is presented. All the new ingredients compared to the standard version INCL4.2 are given with some detail. They bear on the mean potentials of nucleons and pions, the included cluster production model, the Pauli blocking, the treatment of soft collisions and a somehow relaxed definition of participants. Except for the first modification, which is determined by known phenomenology, these modifications introduce some parameters which are being fixed by comparison with illustrative experimental data. A comparison with the intermediate version (standard +simplified cluster emission module) of the INCL model concerning the prediction of most representative data is provided.

1. Introduction

The standard version of the INCL model, designated as INCL4.2 [1], is quite successful for the description, without relying on any fitting parameters, of a large set of experimental data for nucleon-induced spallation reactions in an incident energy range extending from 0.2 to 2 GeV. However, it is nevertheless suffering from systematic small deficiencies: it cannot accommodate light charged particle emission; it somehow underestimates the production yield of deep spallation products; the isotopic distributions of residues close to the target nucleus are not always satisfactory; pion production is somehow overestimated for heavy targets. Furthermore, the predictions of the model at lower energy are not always very good. Of course, this point deserves some explanation. It may not be appropriate or legitimate to apply INC models below 200 MeV, where the theoretical conditions of validity are not satisfied. Let us first stress that these conditions are sufficient but not necessary conditions. This question is discussed in another contribution to this meeting [2]. On the practical side, INC models can give good results for neutron and proton spectra, down to ~40 MeV. See for instance Ref. [3]. On the other hand, they may fail on other observables, such as the total reaction cross section. This suggests that INC models are probably valid, below to 200 MeV down to a lower limit still to be found, to describe satisfactorily the energy-momentum flux and are able, after some limited corrections, to describe a large set of observables.

2. From INCL4.2 to INCL4.5

Since the release of the INCL4.2 model, a constant effort has been made to palliate these deficiencies. First a dynamical coalescence model has been implemented to allow for emission of light clusters in the cascade stage [4]. This version is known as INCL4.3. Several further improvements have been included. It is the purpose of this paper to present the most recent version of the INCL model, labelled INCL4.5 but not yet released. Actually, we will limit ourselves to presenting the new features of INCL4.5, in comparison to INCL4.2. For a description of INCL4.2 itself, see Ref. [1]. Some intermediate versions have been used (see an example in another contribution to this Conference [5]). We will also compare the predictions of the INCL4.3 and INCL4.5 models. Since INCL4.5 is still under development, the values of the parameters will not always be given. To make the comparison meaningful, the same de-excitation code is used. We chose the standard ABLA version[6,7], named also KHSv3p [1], since the new ABLA version is still under (final) development [8].

3. Main new features of INCL4.5

3.1. Including known phenomenology

A. *Isopin and energy-dependent potential well.* In INCL4.2, the nucleon potential has a constant depth. Now, we have introduced an isospin-dependent and energy-dependent average well, inspired from the phenomenology of the real part of the optical-model potential. This is described in Ref. [9].

B. *Average potential for pions.* An average (isospin-dependent) potential well is introduced for the pions, as well as pion transmission to the Coulomb barrier. The nuclear average potential is largely (but not totally) consistent with the phenomenology of the pion optical model. For the detail, see Ref. [10].

C. *Deflection of charged particles in the Coulomb field.* Once an impact parameter is selected for the incident nucleon, the cascade process is initiated with this nucleon located at the intersection of the Coulomb trajectory with the nuclear periphery (defined as before by a radius R_{max}, see Ref.[1]). The same procedure is used to connect the direction of an outgoing particle at the nuclear periphery and its asymptotic direction.

These three modifications can be considered as mandatory. They do not introduce parameters.

3.2. Cluster emission

Since this feature has changed from the INCL4.3 version, we will describe it in more detail. In both versions, the basic idea is the same: an outgoing particle is able to carry along other nucleons to form a cluster, provided they are lying sufficiently close by in phase space. The details of the implementation has substantially changed. They can be summarized as follows.

- A outgoing nucleon arriving at the periphery is selected as a possible leading nucleon for cluster emission when its energy is higher than the threshold energy (otherwise it is reflected).
- Potential clusters are then constructed. The leading nucleon is backed to a radial distance D (slightly larger than the half-density radius) and clusters are built by searching target nucleons which are sufficiently close in phase space. Clusters of different sizes are built successively. All potential clusters up to a maximum size are considered: there may be different clusters of same size (all containing the leading nucleon, of course) and a cluster of a given size may or may not be embedded in a cluster of larger size). For the moment,

clusters up to A_{cl}=12 can be handled. The criterion of sufficient proximity is applied to Jacobian coordinates:

$$r_{i,[i-1]}\, p_{i,[i-1]} \leq h_0, \quad \text{for } i=2,3,\ldots,A_{cl} \tag{1}$$

where the quantities are the relative position and momentum of nucleon *i* with respect to the subgroup of the *i-1* first nucleons. The parameter h_0 is given different values for different clusters, but , for $A_{cl}<5$, it is of the order of unity in natural phase space units. For larger clusters, a smooth $A^{2/3}$ law is adopted.

- The less "virtual" cluster is selected. The 4-momentum of a cluster is defined by the sum of the 4-momenta of the nucleons of which it is composed. Let $\sqrt{s}$ be the c.m. energy of the nucleons and let us consider the quantity

$$v=\left(\sqrt{s}-\sum m_i\right)/A_{cl}-B_{cl}/A_{cl}=E^{*}/A_{cl}-2\ B_{cl}/A_{cl} \tag{2}$$

where B_{cl} is the (nominal) binding energy of the cluster and E* its excitation energy. The cluster with the minimum value of *v* is selected.

- The selected cluster is emitted provided three conditions are satisfied. First, it should have sufficient energy to escape, i. e. $T_{cl}=\sum\left(T_i-V_i\right)-B_{cl}>0$, where the T_i 's are the kinetic energies of the nucleons and where the V_i 's are the depths of their potential wells. Second the cluster has also to fulfil the test for penetration of the Coulomb barrier. Third, the cluster cannot be emitted too tangentially. If θ is the angle between the direction of the cluster (defined as the direction of its total 3-momentum) and the radial outward direction at the point where the leading nucleon is checked, it is required that cos θ > 0.7. The idea behind this condition is that if a nascent cluster spends too much time in the nuclear surface, it likely gets dissolved. It is however applied to $A_{cl}<5$ clusters only and the condition is slightly different on the first collision (cos θ > 0.3). These choices are admittedly made to improve the results at low energy, though some supporting arguments can be produced.
- If these tests are successful, the cluster is emitted with the kinetic energy T_{cl} in its initial direction. If they are not, the leading nucleon is emitted alone provided it succeeds the test for penetration of the Coulomb barrier. If not, the leading nucleon is simply reflected.
- At the end of the cascade process, short-lived clusters (e.g. ^{5}Li) are forced to decay.

3.3. Modifications concerning the Pauli blocking

A. *A strict Pauli blocking is applied to the first collision*: the nucleons should lie outside the Fermi sea after the first collision. In INCL4.2, the Pauli blocking is applied stochastically, according to the products of the final blocking factors. Conjugated with the fact that constructing the target with nucleons at random generates a nonuniform Fermi sea, this procedure has the drawback of allowing sometimes collisions which otherwise would be strictly forbidden. On the other hand, it allows to account for the effects of the depletion of the Fermi sea as the cascade process evolves. It is found in Ref. [11] that a good compromise is achieved when a strict Pauli blocking is adopted for the first collision and when the usual procedure is kept for the forthcoming ones.

B. *In addition, collisions between two nucleons below the Fermi levels are now forbidden.* This was already the case for spectators but now collisions are forbidden when one of the nucleons or both are participants. This modification, which has minor effects, has been introduced along the same lines as the previous one, i.e. to "harden" the Pauli blocking.

3.4. Soft collisions and low-energy behaviour

A. *Soft collisions*. In INCL4.2, the soft collisions (with c.m. energy less than $\sqrt{s_0} = 1925\ MeV$) are neglected. Historically, this choice was made to avoid inconveniences linked with the raising NN cross sections at low energy. More profoundly, the argument goes as soft collisions (with low momentum transfer) do not change significantly the energy-momentum content of the system and their effect is likely to be more accounted for by the nuclear mean field. Furthermore, the effect of changing the boundary between soft and hard collisions is of small importance. The reason is that soft collisions occur mainly when the nucleons are lying close to the Fermi energy and they are then largely Pauli-blocked [11]. This argument breaks down when a low-energy incident nucleon makes a collision in the nuclear periphery. We thus decided to lower $\sqrt{s_0}$ trying still to keep the results roughly equivalent and to save computation time. The new value is now $\sqrt{s_0} = 1910\ MeV$

B. *Special treatment on the first collision*. For the first collision, we even lowered the value of $\sqrt{s_0}$ to the minimum, twice the nucleon mass, in apparent contradiction with the arguments above. However, at low energy, only a few (1-3 on the average) collisions occur. Neglecting a soft collision, especially the first one, may amount to neglecting the event. This may have dramatic effects on the total reaction cross section, since the latter involves all kinds of events, be them hard or soft. It should be stressed that this procedure does not change the results at high energy (say, above 200 MeV). Furthermore neglecting a soft collision after a hard one is most of the time harmless. See Ref.[12] for more details. In addition, a special procedure, named 'local E', is applied to the first collision. In INCL4.2, the momenta of the target nucleons are too large in the nuclear surface, compared to the semi-classical models for the nuclear density. In the 'local E' procedure, when two nucleons are selected for the first collision, their momenta are "corrected". The minimum distance of approach criterion is introduced on the corrected momenta. After the collision, if it occurs, momenta are "corrected back" to the INCL4.2 prescription. Once again, this procedure is unimportant at high energy These two modifications are instrumental to give the predictions of the total reaction cross section in agreement with experimental data at low energy.

3.5. Modification of the status of the participants

If after a binary collision of after a Δ-decay, a nucleon (obviously a participant) has an energy smaller than the Fermi energy plus a small quantity ζ, taken as 18 MeV for the moment, it is considered thereafter as a spectator. This procedure, which is inspired from the Isabel code [13], may be supported by different considerations: in a nucleus, the Fermi sea is not sharply defined, nucleons cannot be localized with precision when their energy is low, correlations may make the difference between a nucleon above the Fermi level and a spectator rather fuzzy. In fact, there is no compelling argument in favour of this procedure. It is included here (as in Isabel) because it gives slightly better results in some cases, in particular for clusters at low energy.

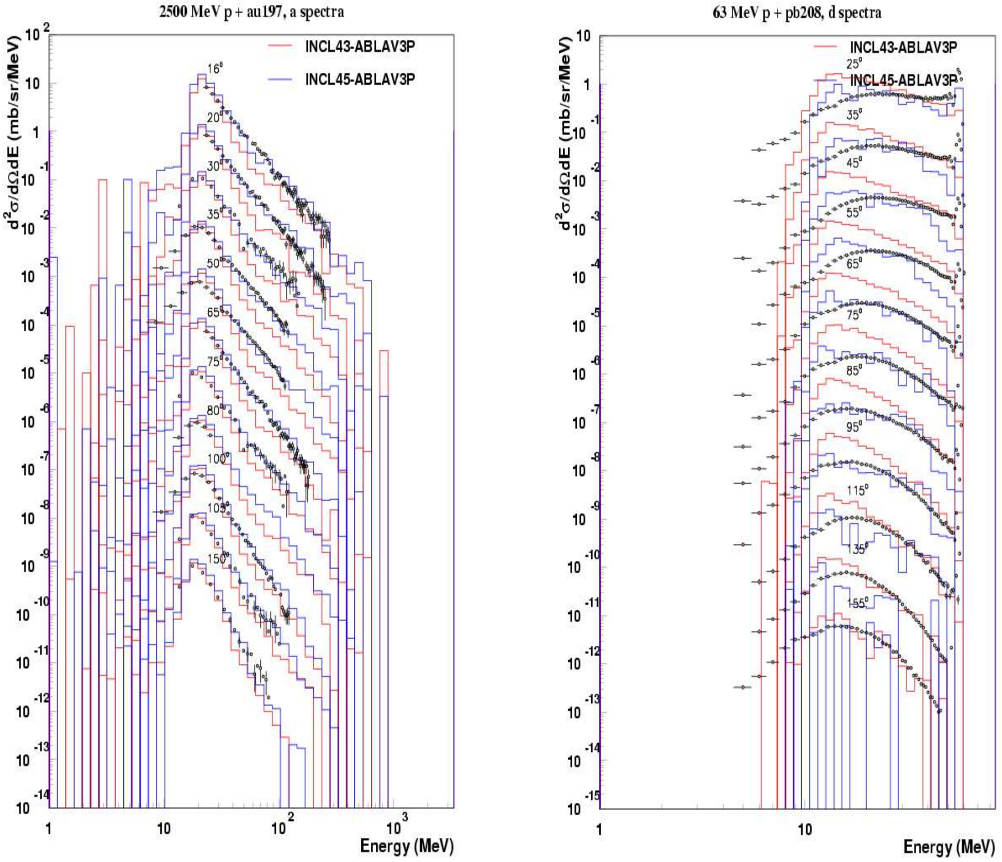

Fig. 1. Comparison between the predictions of INCL4.2 (red) and INCL4.5 (blue) and the data (black symbols) for the production of alpha particles in p (2.5 GeV)+^{197}Au collisions (left) and for the production of deuterons in p(63 MeV)+ ^{208}Pb collisions (right). Data are taken from Refs. [14-15].

4. A few illustrative results

4.1. Introduction

Due to lack of space, only a few results are shown here. We have deliberately chosen to favour results when the difference between INCL4.5 and INCL4.3 is important. We will give without illustration a general survey of the comparison in the next Section.

4.2. Particle spectra

Fig. 1 refers to the production of α particles at high energy and deuterons at low energy. It can be seen that the results are remarkably good and substantially better for INCL4.5. This is mainly due to the sophistication of the cluster production model.

4.3.Residue mass and charged spectra

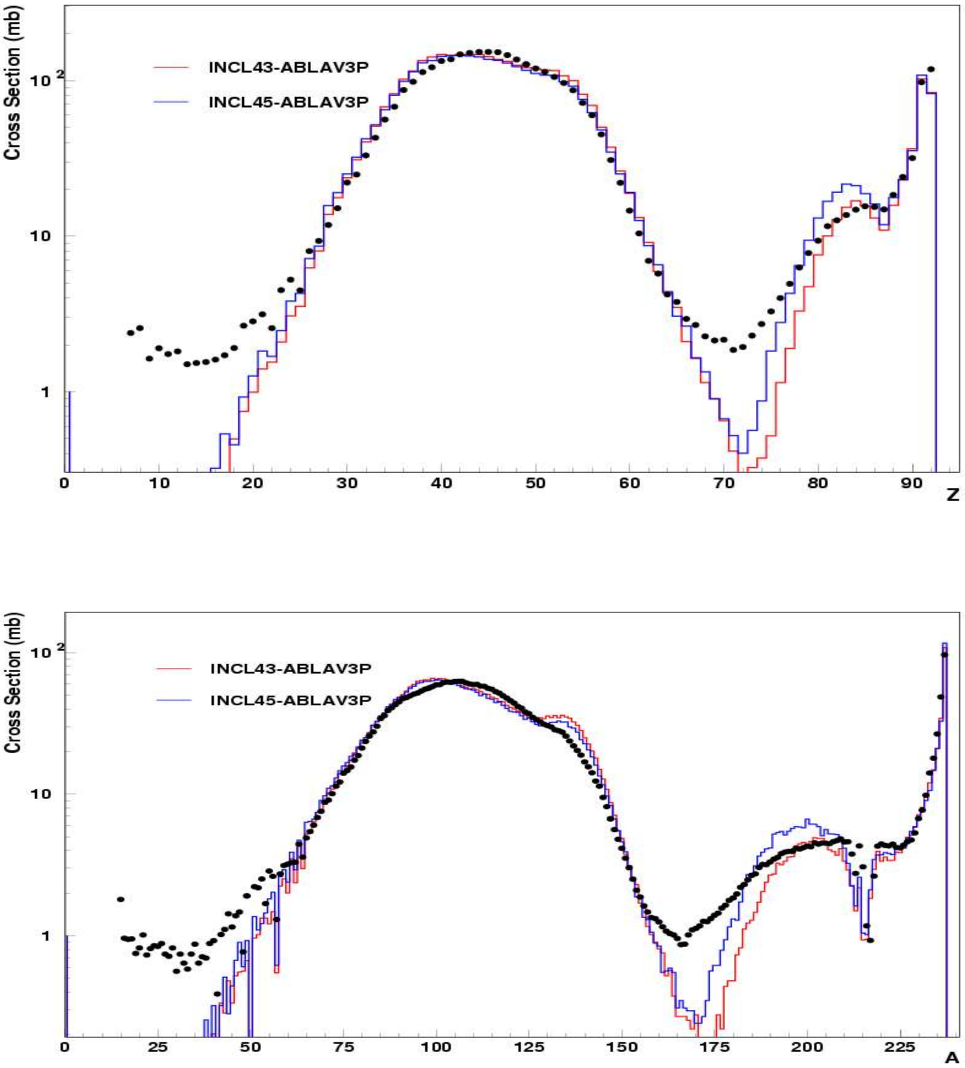

Fig.2. Residue charge (upper panel) and mass (lower panel) spectra in p(1GeV)+ ^{238}U collisions (left). Same convention as in Fig.1. Data are taken from Refs. [16-17].

Fig.2 shows the charge and mass spectra of the residues in p (1 GeV)+^{238}U collisions. For the fission, there is no real difference. This is easy to understand as the fission yield is quite large and thus very similar in the two versions. The details of the peak is thus solely determined by the fission-evaporation code, which is the same in the versions. One should notice a theoretical overestimate around A=140, which very likely corresponds to too strong shell effects. For the deep spallation residues, the yields predicted by INCL4.5 are larger than those of INCL4.3. This is due to a larger fraction of high excitation events, presumably due to the new cluster module, mainly. In p(1GeV)+ ^{208}Pb (not shown here), the deep spallation yield is correctly reproduced by INCL4.5.

5. Conclusion

Let us first give a survey of the results. The predictions for the cluster emission are much better and generally quite satisfactory with INCL4.5, in the whole range of incident energy stretching from 63 to 2500 GeV. Neutron spectra are not really changed at high energy. At low energy, the predictions of INCL4.5 are definitely better since the predictions of INCL4.3 were renormalized on the experimental reaction cross sections. Concerning the shape of the neutron spectra, the results of INCL4.5 are only and not always slightly better, though not sufficiently. The shapes of the proton spectra are not very much changed either. However, they have the tendency to be underestimated (in the cascade stage). Pion production is somehow improved with INCL4.5. Concerning residue production, the deep spallation side of charge and mass spectra, which was underestimated, is significantly improved with INCL4.5 in p+Fe and in p-Pb. In p+U, the improvement leads even to some overestimate. In p+Fe, the yield is still too low for the very low mass side. Concerning the isotropic distributions, if there is a slight improvement in INCL4.5, the shape of the distributions for residues of charge close to the target charge are only slightly affected and the discrepancy mentioned in the introduction persists.

It is hard to trace back the effects of one of the modifications introduced in INCL4.5 and to associate them with the improvement of one or the other of the predictions. Of course, it is clear that the modification of the cluster emission module is responsible for the improvement of the cluster production cross sections, especially at low energy. Similarly, the new treatment of soft collisions is responsible for better predictions of the particle spectra at low energy. Though less clearly, the modifications of the average potentials for nucleons and pions have contributed to the improvement of the pion production cross sections. The effect of the other modifications are too largely intermingled with those of the de-excitation models to draw any definite conclusion. It should be remarked that sometimes the modifications have a negative effect. For instance, the proton spectra are less good with the introduction of the cluster production module.

Finally, INCL4.5 offers a clear and substantial improvement of the standard INCL4.2 version. However, some of the deficiencies of INCL4.2 are resistant to the modifications introduced in this paper. The most noticeable case is the isotopic distributions for isotopes close to the target, which are still overestimated on the neutron rich side. Further work is still needed to obtain a model for an adequate predictive power for ADS applications.

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