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The INCL model for spallation reactions below 10 GeV

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Abstract

The Liège intranuclear cascade (INCL) model is shortly presented. The predictive power of its standard version concerning the description of nucleon-induced spallation reactions in the 200 MeV to 2 GeV range of incident energy is indicated. Current improvements of the model, in particular its extension to higher energies, are emphasized. The capabilities of the model for possible applications in astrophysics, space research and protontherapy are pointed out.

Keywords: Spallation reactions; Intranuclear cascade model; Radioprotection from cosmic rays

1. Introduction

Spallation reactions induced by either nucleons or light charged nuclei between ~100 MeV and ~2 GeV are best described by the intranuclear cascade (INC) plus evaporation model. There has been in the last decade a renewed interest in the study of such reactions, triggered by the appearance of projects for accelerator-driven systems or ADS (Gudowski, 1999). These devices are expected to be able to incinerate nuclear wastes. They will be composed of an accelerator delivering a high-intensity beam of protons on a spallation target, basically a piece of lead or bismuth, situated inside the core of a sub-critical nuclear reactor. Due to the interaction of the protons with the spallation target, neutrons are expelled from the spallation target, are multiplied in the sub-critical assembly and can be used to transmute nuclear wastes: long-lived radioactive isotopes can so be transformed into stable or short-lived isotopes. The most promising case seems to be the transmutation of so-called minor actinides (Np, Pu, Am, Cu) by neutron-induced fission. Neutron production inside the spallation target is the most profitable for proton beams of an energy around 1 GeV. More precisely, the number of emitted neutrons per incident proton and divided by the proton energy, a parameter which is basically proportional to the "cost" of production of a neutron, shows a broad maximum around this energy (Vassil'kov and Yurevich, 1991). The detailed design of the spallation target, including radiotoxicity aspects and chemical or mechanical behaviour under irradiation, requires a detailed knowledge of the transport of particles inside the target, which in turn requires good models for the elementary particle–nucleus interactions. In the last years, a large effort has been made in Europe, by the HINDAS Collaboration (Meulders et al., 2005), and elsewhere to provide with precise measurements which can serve as benchmarks for spallation reaction models.

We have been involved in the development of such a model, namely the Liège intranuclear cascade (INCL) model. Initially devoted to heavy-ion and antiproton-induced reactions, this model has been refined for nucleon and light-ion induced reactions. Recently, it has been shown that, when coupled with the ABLA evaporation-fission code developed by K.-H. Schmidt (Gaimard and Schmidt, 1991 and Junghans et al., 1998), this model is able

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to nicely reproduce, without adjustment of parameters, a whole bunch of experimental data in the 200 MeV to 2 GeV range, especially relevant for studies of transmutation of nuclear waste (Boudard et al., 2002). These data include total reaction cross-sections, particle multiplicities, double differential cross-sections, residue mass spectra, isotopic distributions and recoil energy spectra.

Since the energy range mentioned above is also relevant for other fields, the high predictive power of INCL4 could be useful for these fields, among which we can single out radioprotection in space missions, spallation targets (used as neutron sources for condensed matter physics) and radiotherapy. The purpose of this paper is threefold: to briefly describe INCL4, to present the recent improvements and extensions of the model and to illustrate by a few examples the potentialities of the model for space research.

2. A brief description of the INCL model

The INCL model is a time-like intranuclear cascade model. In the initial state, all nucleons are prepared in phase space. The target nucleons are given positions and momenta at random in agreement with a Saxon-Woods and a Fermi sphere distributions, respectively. They are moving in a potential well, describing the nuclear mean field. The incident nucleon is given the appropriate energy and an impact parameter at random. All nucleons are then set into motion and followed in space–time. They are assumed to travel along straight-line trajectories until two of them reach their minimum relative distance of approach or until a particle hits the nuclear surface. In the first case, the two nucleons can scatter if the relative distance is shorter than the square root of the total reaction cross-section (at the appropriate energy) divided by π. The outgoing momenta are then chosen at random in accordance with the experimental angular distributions and with the energy–momentum conservation law. In the second case, nucleons are transmitted or reflected, according to their energy and transmission probabilities for waves on a potential step. After the possible modification of the motion is applied, straight line motion is resumed until a new possibility occurs, and so on.

Other features of the model are: (i) collisions are subject to the Pauli principle (if the final momenta are already occupied, collision is avoided), (ii) relativistic kinematics is used, (iii) isospin symmetry is respected, (iv) nucleon–nucleon collisions can be elastic or inelastic (in the last case a Δ-resonance is produced which can further decay into a nucleon and a pion), (v) pions can escape or can further interact with a nucleon to form a Δ-resonance, (vi) Δ-resonances can scatter elastically on nucleons and on other Δ-resonances, (vii) the model can accommodate nucleons and light clusters (up to ^{4}He) as incident particles.

The INCL4 model should be supplemented by an evaporation model. An original feature of the model is that the stopping time, i.e. the time at which the cascade process is stopped to give place to evaporation is determined self-consistently, as explained in Boudard et al. (2002).

Although classical in nature, the model accounts for some quantum aspects: existence of a mean field, Pauli blocking of collisions, quantum transmission through the nuclear surface and stochastic determination of the final states in NN collisions. In the last respect, the model departs from molecular dynamics in which deterministic equations of motion are solved. Finally, we want to stress that the model does not include free parameters. There are, of course, parameters such as those characterizing the initial distribution or those entering the procedure for evaluation of the phase space occupancy, which have been determined once for all. But there is no adjustable parameter left to the user.

The INCL model, as described in Boudard et al. (2002) is embodied in a numerical code known as INCL4. It is included in particle transport codes such as LAHET (Prael and Lichtenstein, 1989) and MCNPX (Hendricks et al., 2003).

The INCL4 + ABLA model has been shown (Boudard et al., 2002) to give a quite good agreement with experimental data in the energy range stretching from 200 MeV to 2 GeV, covering reaction cross-sections, neutron and proton differential cross-sections, residue production cross-sections, fission cross-sections, isotopic distributions and target recoil energy distributions. Let us illustrate the predictive power of INCL4 by two examples. Fig. 1 shows the production cross-sections for several isotopes in proton-induced reactions on a thin Bi target. One can see that the agreement is fairly good for many different isotopes and for a broad range of incident energies. Fig. 2 refers to the target residue recoil energy. It shows the average recoil energy of the residue for a given mass loss, as measured in inverse kinematics experiments. The predictions of our model spectacularly agree with the measurements, except for very large mass losses, for which the productions cross-sections are very small. These kinds of results are important as they are closely related to the studies of damages inflicted by cosmic rays to materials in space mission vehicles and to the radioprotection of possible human passengers.

3. Recent developments

Since the release of INCL4, the model has been improved on several points, by implementing aspects of nuclear dynamics which had been left behind so far, either because they are still not totally clarified or because their implementation is not always obvious. We review some of them below, which bear on cluster production, pion dynamics and the extension toward lower energy.

3.1. Production of light charged clusters in the cascade stage

In the standard version of INCL (INCL4), only nucleons and pions are emitted during the cascade stage. Recently, we tried to alleviate this shortcoming by implementing

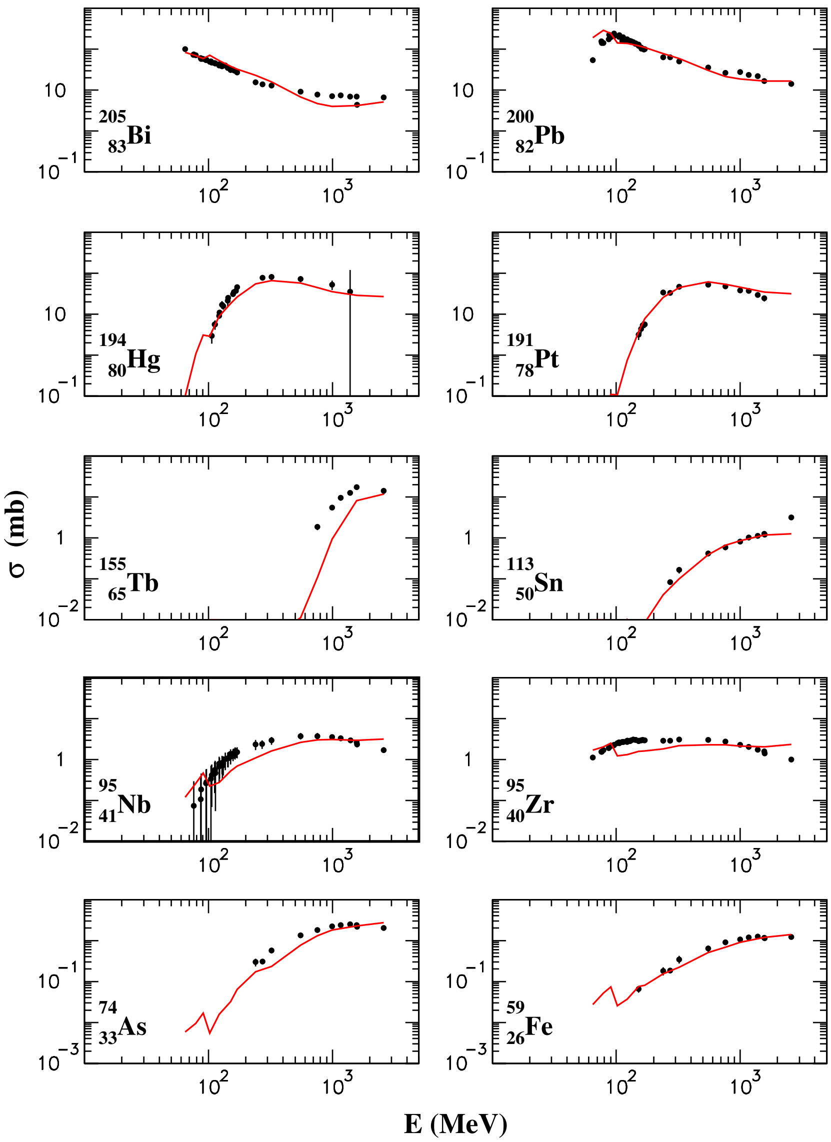

Fig. 1. Comparison of the results of the INCL4 model, coupled to the ABLA evaporation code, for residue production in the $p + \mathrm{Bi}$ system (full lines) with the experimental data (symbols) of Gloris et al. (2001). Adapted from Leya et al. (2005).

emission of light charged clusters through the addition of a dynamical coalescence model, which can be viewed as a generalization of the standard coalescence model (Butler and Pearson, 1963; Gutbrod et al., 1976). When a nucleon hits the surface and is candidate for emission, it is checked whether it can drag other nucleons along, forming so an emitted cluster. Such an occurence is subject to conditions: (i) nucleons should be sufficiently close to each other in phase space when they are checked, (ii) the cluster should be stable (no cluster of two neutrons for instance), (iii) the total energy of the cluster should be larger than the emission threshold and (iv) the cluster should succeed the test for transmission through the appropriate Coulomb barrier. A preliminary account of this model is contained in Boudard et al. (2004). Therein candidate clusters are constructed starting from the initial nucleon by adding successively other sufficiently close-by nucleons. The closeness criterion corresponds to

$$r_{i,[i-1]}p_{i,[i-1]} \leqslant h_0, \tag{1}$$

where $r_{i,[i-1]}$ and $p_{i,[i-1]}$ are the Jacobian coordinates of the i-th nucleon, i.e. the relative spatial and momentum coordinates of this nucleon with respect to the subgroup constituted of the first $[i-1]$ nucleons. The quantity h_0 is a parameter of the order of the natural unit in phase space. In Boudard et al. (2004) only d, t, ^{3}He, ^{4}He clusters are considered. We are currently improving this approach and refining the choice of the parameter h_0.

3.2. Improvement of the pion dynamics

In INCL4, pions are produced through the reactions

$$NN \to N\Delta, \Delta \to \pi N, \tag{2}$$

and can be absorbed through the reverse reactions. Furthermore pion potentials are neglected. We recently

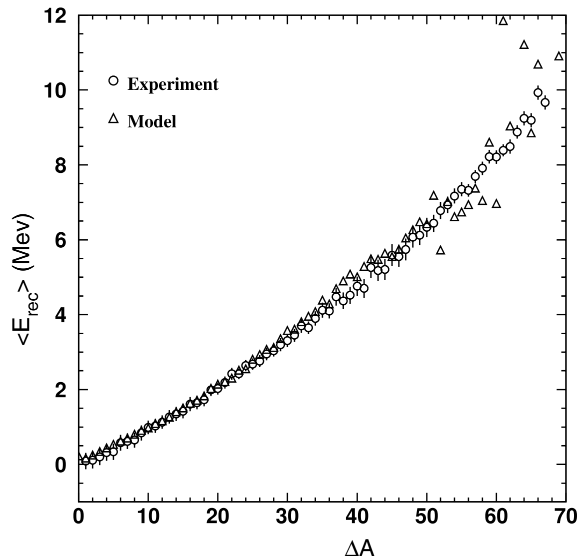

Fig. 2. Average residue recoil energy (vertical scale, in MeV) as a function of mass loss (horizontal scale) in proton-induced reactions on *Pb* at 1 GeV. Comparison between the INCL4+ABLA model (△) and the experimental data (○) of Enqvist et al. (2001). Adapted from Boudard et al. (2002).

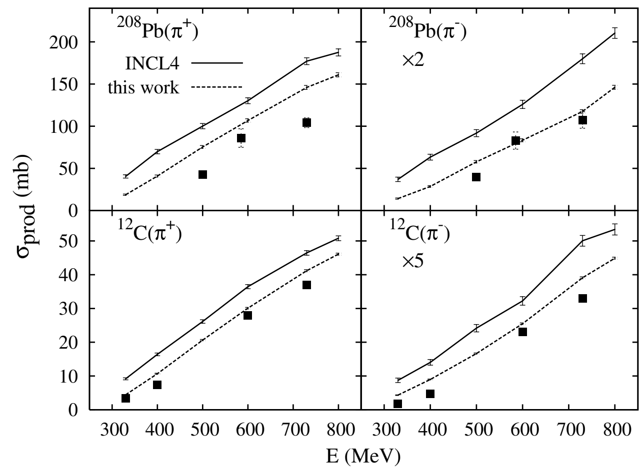

Fig. 3. Production cross-section of π^+'s (left) and π^-'s (right) in proton-induced reactions on ^{208}Pb (up) and ^{12}C (down), as function of the incident proton kinetic energy *E*. Experimental data are from Cochran et al. (1972) and Crawford et al. (1980). Full lines are the standard INCL4 predictions, with indications of the statistical uncertainty (error bars). Dotted curves are obtained after introduction of pion potentials.

decided to remove this deficiency. This raises some problem linked to the fact that, contrarily to nucleons, pions are not really good quasi-particle excitations of the nucleus, and therefore their potential energy is not simply related to the real part of the pion–nucleus potential. We were then forced to adopt a purely phenomenological pion potential and try to determine it by comparing with pion production and absorption data. Roughly speaking this potential has a constant value and extends a little bit farther than the half-density radius. The amplitude of the nuclear part has the following isospin structure

$$V_N = V_N^0 + V_N^1 \tau \xi, \tag{3}$$

where τ is third isospin component of the pion and where $\xi = (N - Z)/A$ is the asymmetry parameter of the target. Numerically, $V_N^0 \approx -30$ MeV and $V_N^1 \approx -70$ MeV. Of course, a Coulomb part is added. A fairly good agreement is now obtained for pion production in p-induced reactions (which was overestimated in the standard version), but also for pion absorption and proton production in pion-induced reactions (Aoust and Cugnon, 2006). We just show here the results for pion production in Fig. 3. One can see that the production cross-section is well-described by our modified version, except perhaps for production of positive pions by a heavy target.

Let us mention that we are currently introducing in our model the multiple production of pions in nucleon-nucleon inelastic collisions, basically by a slightly modified uniform phase space model. This is a crucial step to have the correct inelasticity below 10 GeV. Above this energy, the main issue is the proper introduction of subnucleon degrees of freedom.

3.3. Low energy behaviour

It is generally stated that the INC model is valid when the interaction process reduces to a sequence of collisions, well-separated in space–time, which requires

$$\lambda_B \ll v t_{coll} \leqslant d, \tag{4}$$

where λ_B is the deBroglie wavelength, v the relative velocity, t_{coll} is the collision time and d is the average distance between neighbouring nucleons. This condition expresses both that the incident nucleon can "resolve" individual target nucleons and that a collision is "over" before another one takes place. Hence it is often considered that the validity of the INC model breaks down below ~200 MeV, since this condition is (marginally) satisfied at this energy. This statement has been occasionally challenged in the past. A thorough study was realized recently by Cugnon and Henrotte (2003), who showed that INCL can reproduce nucleon double differential cross-sections satisfactorily down to ~50 MeV, provided the total reaction cross-section is renormalized to the experimental one. This work does not propose any explanation of this paradoxical result. One indeed may expect that quantum motion effects manifest themselves at low energy. A possible explanation may arise from the cancellation of quantum interferences in many collision processes (Cugnon, 2000; Iljinov et al., 1994). What matters then is the energy and particle flows which are driven by the probability of binary collisions. Recently, we showed that INCL4 can also predict reaction cross-sections at low energy (down to 20 MeV) when the Pauli blocking is slightly corrected and when the proper phase space distribution in the nuclear surface is taken into account (Boudard et al., 2006). These modifications do not significantly alter the predictions at high energy.

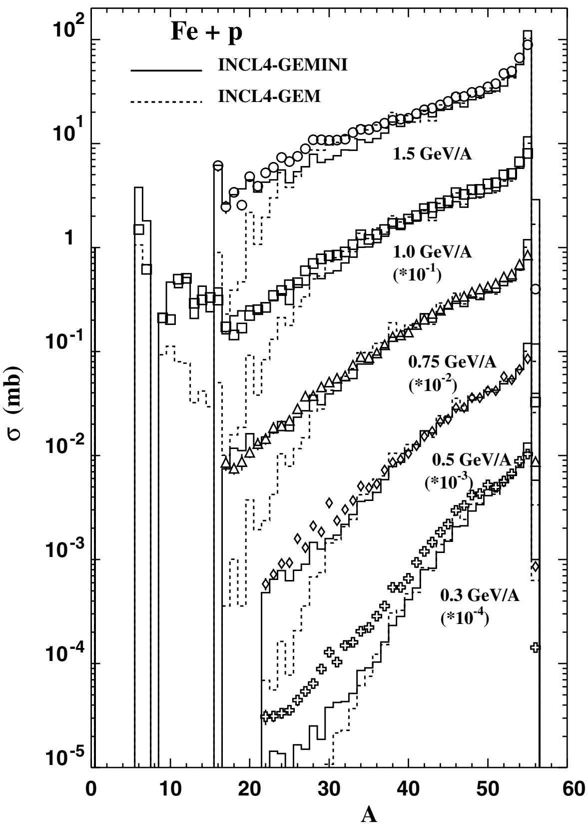

Fig. 4. Residue mass production cross-section in $p + {}^{56}$Fe reactions at various incident energies. Experimental data (symbols) are from Villagrasa (2005). Histograms represent the predictions of standard INCL4 (Boudard et al., 2002), coupled to two de-excitation codes, GEMINI (full lines) or GEM (dotted lines).

3.4. De-excitation model for "light" nuclei

Most of the observables are testing the INC and the associated de-excitation models in a combined manner. Some of them are testing the INC only, such as the reaction cross-section and the nucleon spectra above 20 MeV. Some others are testing predominantly the de-excitation model, although the influence of the INC stage is never absent. An example of such observables is given by the production of deep spallation products (corresponding to a large mass loss), presumably produced at the end of a long chain of evaporation steps. This is of course mainly sensitive to the details of the evaporation model, albeit the excitation energy prior to evaporation is provided by the INC. In Fig. 4, we give the experimental residue production cross-sections in $p + {}^{56}$Fe reactions, along with calculations using INCL4 coupled to two different de-excitation models, GEM (Furihata, 2000; Furihata and Nakamura, 2002) and GEMINI (Charity et al., 1988). The latter model is a singular one as it is the only one which can accomodate emission of particles of any charge larger than $Z = 2$ by the so-called transition state model (Bohr and Wheeler, 1939; Swiatecki, 1983). No other evaporation model (including ABLA) seems to be able to reproduce light residue (A < 30) cross-sections. In a system such as $p + {}^{56}$Fe, the excitation of energy per particle is higher than in a heavier system at the same incident energy and can reach ~3 MeV per nucleon. It is then perhaps not surprising that the de-excitation does not proceed as with lower excitation energy. An alternative explanation of the data of Fig. 4 may correspond to the onset of multifragmentation. Further work is needed to clarify this point.

Data of Fig. 4 are also important for study of the interaction of cosmic rays. From the energy deposit point of view, ^{56}Fe nuclei are a very important component (Durante and Kronenberg, 2005). They improve and enlarge sizably the data of previous measurements (Webber et al., 1998a,b). We also compared these data with the Silberberg and Tsao (1990) formula. Surprisingly enough, this formula gives good results down to $A = 20$, almost as good as the

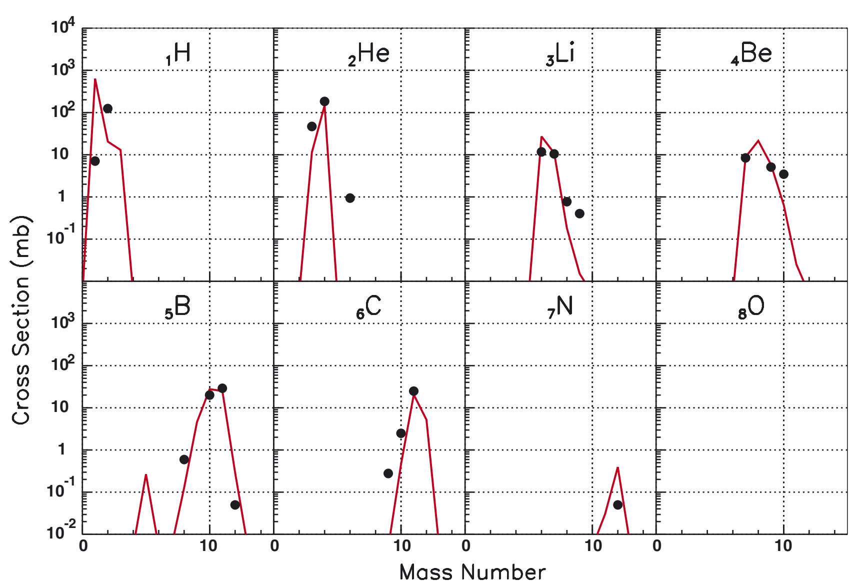

Fig. 5. Isotope production cross-sections in $p + {}^{12}$C reactions at 1 GeV. Experimental data from Lindstrom et al. (1975) and Olson et al. (1983) (symbols) are compared with the predictions of the standard INCL4 + ABLA model (lines).

INCL4+GEMINI calculations, and in any way much better than the systematics of Sümmerer et al. (1990).

3.5. Other current developments of INCL4

We just want to mention here two other potential applications of the INCL4 model related to astrophysics and radioprotection from high energy particles. The first one is the development of a model for antinucleus–nucleus collisions, which are then described as sequences of antinucleon-nucleon and pion–(anti)nucleon collisions. This may be helpful in view of the search of possible antinuclei in cosmic rays, since it can give an idea of the shape of the events generated by the interaction of an antinucleus with a nucleus of the atmosphere. The second one is the improvement and the possible specialization of our model for p-induced reactions on light nuclei. Fig. 5 gives our present results for p-induced reactions on ^{12}C, a nucleus of primary importance in radioprotection and protontherapy. As a first attempt, these results are rather satisfactory. However, significant discrepancies occur for hydrogen and ^{10}Be isotopes. We plan to investigate the reliability of the target momentum distribution and the possible introduction of alpha-cluster degrees of freedom for this kind of light nuclei.

4. Conclusion

We have briefly presented here the INCL4 version of the Liège intranuclear cascade model, which has been shown to be quite successful for the description of nucleon-induced spallation reactions in the 200 MeV to 2 GeV range, without parameter fitting. However, this version presents still some shortcomings, that need to be removed in order to have sufficient predictive power for the design of ADS. We have investigated several possible improvements that are reported on in this paper. These improvements deal with the introduction of light charged cluster production in the cascade stage (through a dynamical coalescence model), the improvement of the pion dynamics (by introducing a proper pion potential well and by allowing multiple pion production in elementary nucleon-nucleon collisions, a necessary condition for the extension to higher incident energy, up to 10 GeV), the improvement of the model below 200 MeV (by refining the implementation of the Pauli blocking and the phase space distribution in the nuclear surface) and the de-excitation model for the production of deep spallation products.

The model has been particularly tested on data relevant to transmutation of nuclear wastes. In particular emphasis has been put on heavy target nuclei, which are typical in ADS's. Nevertheless, the model presents good potentialities for applications which are specific to space research (essentially radioprotection in space missions) and radiotherapy, for which the energy range of interest is similar to the one of ADS's. However, in those cases, a more detailed description of the target nucleus is probably needed.

Acknowledgements

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