A Comprehensive Comparison of the INCL4-ABLA Spallation Model with Experimental Data.

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Abstract : In order to improve the predictive power of codes used to design ADS or spallation neutron source, a new intra-nuclear cascade model, INCL4, has been developed recently which, coupled to the evaporation-fission model ABLA of GSI, gives very encouraging results. These models have been already implemented into LAHET3 and delivered to the MCNPX and GEANT4 developers. In this contribution, a summary of comparisons of the model with a wide set of experimental data covering various decay channels (neutrons, light charged particles and residues production) for different energies and systems will be shown. An emphasis will be put on recent confrontations with experimental results concerning isotope production excitation functions and composite particle emission. Improvements of the model still under progress will also be discussed.

I. INTRODUCTION

The potential use of spallation in various applications has reinforced the need for a good modelisation of this broad range of nuclear phenomena. On the one hand, a comprehensive and coordinated experimental program is active in various countries to cover more specifically the new domain of interest. On the other hand, models are improved to become as predictive as possible, and are compared to an increasing number of data. A large part of this work is done in the framework of HINDAS.

Spallation is currently described by a brief time phase of intra-nuclear cascades governed by nucleon-nucleon collisions, and leading to a distribution of hot nuclei after ejection of a few energetic particles. The second longer phase is the decay by evaporation with a possible competition with fission (and Fermi breakup, and pre-equilibrium…).

The need for a spallation model can be understood at two levels. It provides first a comprehensive link between various types of data generally obtained with thin targets (production of light particles, production of residual nuclei, incident energy and target mass dependence…), and consequently it should avoid phenomenological parameters. It is also needed for design and optimization of practical spallation targets, which are thick. In that case, the transport of particles is essential as well as the energy dependence of the model. It is also important to know which precision can be expected from the calculation in the various sectors of observables.

We will report here on improvements brought to the Intra-Nuclear-Cascade-Liege[1] model leading to the version called INCL4.

Here, for comparison with data, this code has been coupled with the fission-evaporation code ABLA [2] developed at GSI, but it can also be coupled with other de-excitation descriptions like DRESNER, GEM, SMM… and this is useful to disentangle the part coming specifically from the cascade.

For transport of particles in thick targets, the code has been recently included in LAHET3 and HERMES. Inclusion in MCNPX and GEANT4 is in progress.

II. PRESENT STATUS OF INCL4

Based on a realistic parameterization of the nucleon-nucleon interaction (elastic and inelastic channels) in the ~20 MeV to ~2 GeV range, the model uses Monte-Carlo techniques and a semi-classical multiple scattering of particles moving freely in an average nuclear potential. Main quantum effects taken into account are the Pauli blocking, the transmission at the surface of the nucleus and the Δ_{33} resonance.

Main improvements leading to the version 4 of INCL are the realistic shape of the potential (Saxon-Wood for A larger than 19, and Modified Harmonic Oscillator or Gaussian below, which parameters are taken from charge densities measured by electron-scattering), a long range correlation due to a dynamical minimal energy of the nucleus, a calculation of the intrinsic spin of the remnant nucleus (the nucleus produced by the cascade step), further improvements in the pion sector and the possibility to treat light composite projectiles (up to the ^{4}He). The detailed description and an extensive comparison with data have been recently published [1].

Due to the surface diffuseness, the stopping time of the cascade is now a simple and stable parameter, which has been adjusted from the cascade physics itself (time evolution of the nucleus excitation and of the mean energy of emitted particles).

This leads to a parameter free code in the 200 MeV - 2 GeV range with its own absolute normalization (the computed total reaction cross section is right). The neutron and proton energy spectra are well reproduced for a set of target nuclei and incident energies (Fig 1, Fig 2 and [1]). We remind that above ~20 MeV these spectra are entirely fed by the cascade. Below, the evaporation step, correctly fed by the cascade gives also convincing results (Fig 1). For nucleon production, local disagreements on the experimental spectra are of the order of 20% but frequently smaller.

Concerning residue production, close to the target mass, where the cascade dominantly influence the final result, cross sections are correctly reproduced (Fig 3). The fission products (around A equal 80) are also well predicted by the evaporation fission code ABLA, and this means that the excitation energy and the spin of the remnant nucleus should be rather correct. However light evaporation nuclei are systematically underestimated (Fig 3). This could be due to a lack of high excitation energy in the cascade stage or to a missing mechanism for these small cross sections. This part of the calculation is also strongly dependent of the evaporation model. Note that the isotopic cross sections [1] [7-8] are also rather precisely reproduced, both for evaporation and fission residues, and this is a success of the ABLA code.

Another weakness of the cascade is the overestimation of the pion production (factor around 1.6) although reduced compared with previous versions of INCL. It should be mentioned however that there is rather few reliable and extensive inclusive pion spectra in the domain of interest.

The incident energy dependence of the code can be tested on excitation functions as measured for example by M. Gloris et al. [9] by activation of natural lead samples and γ decay identification and counting. Proper corrections to the calculation are done, and the result on a set of nuclei (Fig 4) having very different evolution with energy, is rather convincing. The kick observed at 100 MeV is due to a too crude implementation of a forced absorption in the code below this energy.

III. LIGHT COMPOSITE EMISSION

The good success of the cascade observed for the production of nucleons could be misleading due to the fact that the model does not consider the emission of high energy composite light particles experimentally observed. To have a more realistic approach, we have implemented the production of d, t, ^{3}He and ^{4}He in INCL4. We have followed the idea tested by A. Letourneau et al. [10] with a previous version of INCL without surface diffuseness of the target nucleus. The idea is that when a nucleon fulfills the conditions to escape the nucleus, it can clusterize with neighboring nucleons at the surface if they are found in an appropriate phase space. This makes sense since inside the nucleus, formation and destruction of composites should occur.

To preserve long tails of r and p space cluster densities, the closeness criteria is given on the product of distances in geometrical and momentum space (actually smaller than 387 fm.MeV/c in our case). The delicate technical point was to ensure the formation in the diffuse surface, which leads to a second empirical parameter.

A priority to the heaviest cluster is also necessary otherwise for example the ^{4}He production almost vanishes to the benefit of two deuterons. It is gratifying that with these simple ingredients, and without adjustments pertaining to the specific nature of the composites, the gross feature of cross sections as a function of angle and of energy comes right (Fig 5) on the NESSI data from the reaction p+Au at 2.5 GeV [10]. Note that the evaporation code ABLA produces only ^{4}He, resulting in a lack of other composites at low energy. At a much smaller incident energy, we have the same rough success (Fig 6 for n+Bi at 540 MeV from [11]).

This shows that the model is a good starting point, independently of the incident energy, and that we can rather safely discuss several consequences of our account for a reasonable cluster production. First, our production of cascade p and n is reduced (20% and 15% respectively), mainly in the range 15 MeV to 140 MeV. Clearly, the calculated proton production of the NESSI experiment is now obviously too small, but it was already like so before including the production of composites, and it could be a consequence of the incident energy (2.5 GeV) which is at the limit of the model. At 540 MeV, the picture is not the same, and the proton production is certainly not underestimated. If we compute again the neutron production from a lead target at 1.2 GeV, as mentioned above, there are small reduction of the cross section in the range 15 MeV-150 MeV. Agreement with data is slightly worse than it was for angles below 40°, but it is slightly better for larger angles. It results actually to a net neutron production of 2.69 (multiplicity of neutrons above 20 MeV per interaction) which agrees perfectly with experiment (2.7 ± 0.3 from [3]) and which is an improvement compared to the calculation without clusters (3.17). As expected, accounting for a reasonable light composite production reduces the multiplicity of cascade neutrons by ~15% and the protons by ~20%. The multiplicity of evaporated neutrons or protons remains stable within ~1%. In the overall, including all nucleons (free or in a cluster), this cluster mechanism increases the cascade neutron multiplicity by ~10% and the proton one by ~15%. It is due to the fact that a fast nucleon escaping from the surface can drag away other nucleons which otherwise would have remained inside the nucleus. And this explains why the calculation without composites is not so much affected by this missing mechanism.

If we consider cross sections of residual nuclei after evaporation, a calculation including clusters goes also in the right direction since it leaves in the target nucleus the binding energy of the emitted cluster, resulting in slightly larger excitation energy of the remnant. As mentioned above, this slightly improves the predicted cross sections, (actually ~20% increase of the cross sections around A=160 for p+Pb at 1 GeV, Fig 3).

IV. CONCLUSIONS

We have obtained a realistic model for the intra-nuclear cascade stage of the spallation. This code (INCL4) gives in association with the evaporation-fission code (ABLA) a reasonable account of spallation observables for protons projectiles in the ~150MeV to ~2 GeV range on nuclei heavier than, say aluminum. Technically the code also works for lighter targets and light composite projectiles but has not yet been extensively tested in this sector.

The code is parameter free, and in that sense is really predictive. It gives the full correlation between emitted particles, including their dynamics. We can expect overall accuracies of 15%-20%, but for some peculiar observables (especially for the production of residual evaporative nuclei far from the target mass) it can be (locally) wrong by large factors. The code can be used directly for thin targets and is or will be soon available in several transport codes (LAHET, MCNPX, HERMES, GEANT4).

This success proves that the semi-classical multiple scattering works satisfactorily well in a rather broad range of incident energies and target masses. Of course, collective effects like giant resonances, elastic scattering or specific nuclear states of residual nuclei are out of its scope.

In a recent development, we have included the production of light composites formed on the nuclear surface. This works surprisingly well to predict the ratio and the order of magnitude of the various species of composites on the scarce existing data. However, some phenomenology is here included which should be controlled and constrained by more data. But we can already conclude that this will not spoil the quality of the code on neutron and residues production, and on the contrary has a good chance to improve it.

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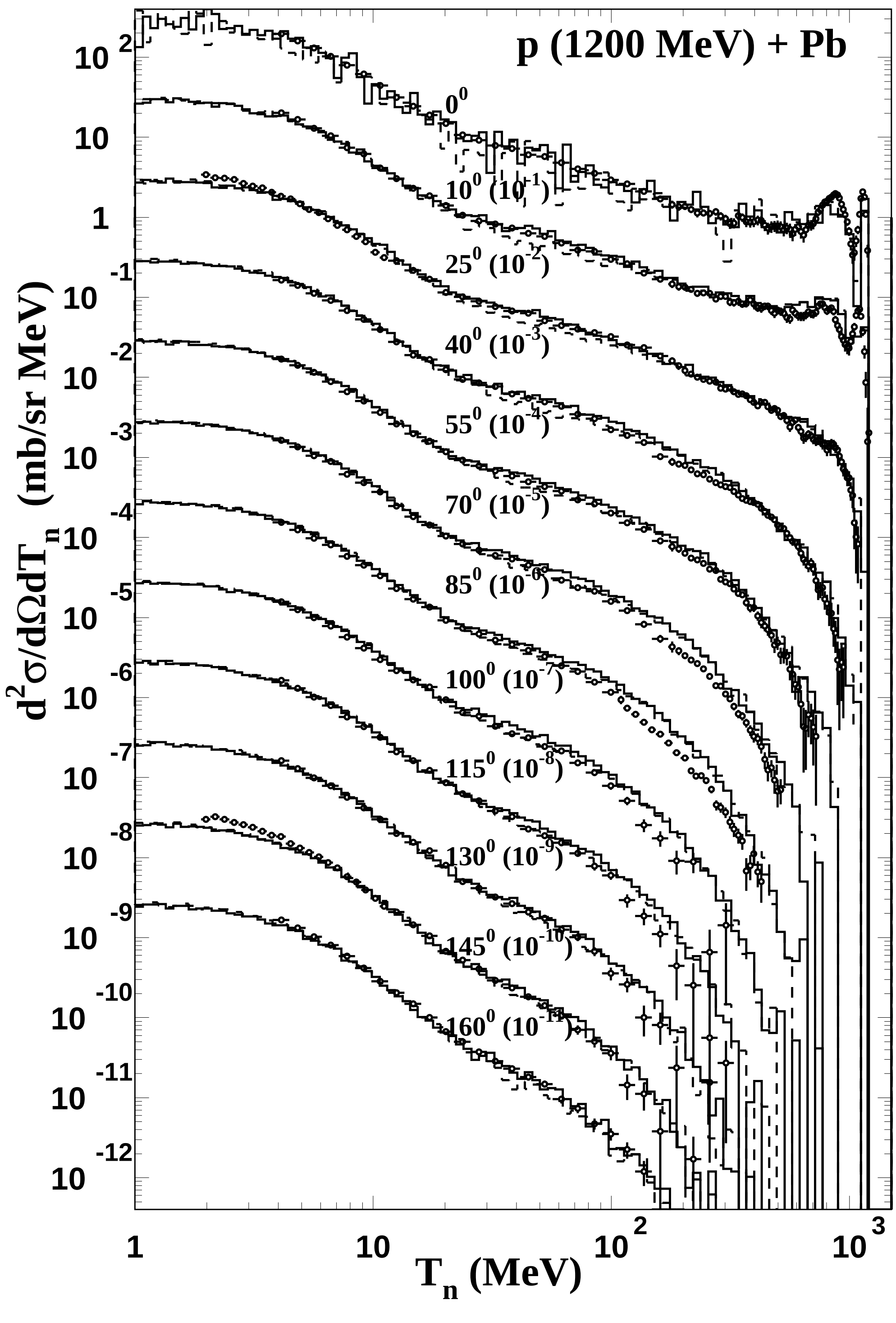

Fig. 1. Neutron production double differential cross sections from proton on lead at 1.2 GeV. Data from [3)] are the points, INCL4+ABLA calculations are histograms without (continuous lines) and with (dashed lines) emission of light clusters in the cascade. Cross sections are properly normalized for the smallest angle; for the others they are divided by successive powers of ten as indicated.

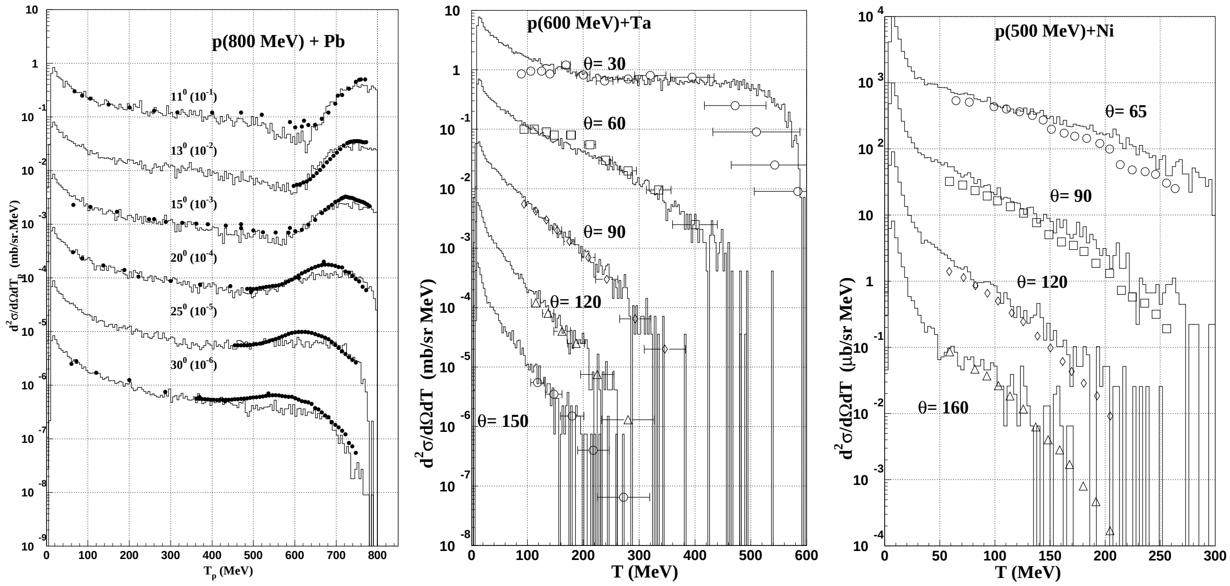

Fig. 2. Proton production double differential cross sections from various systems: p+Pb at 800 MeV (data points from [4]), p+Ta at 600 MeV (data points from [5]), and p+Ni at 500 MeV (data points from [6]). The histograms are the INCL4+ABLA calculations. Data are displayed with the same convention as in Fig 1.

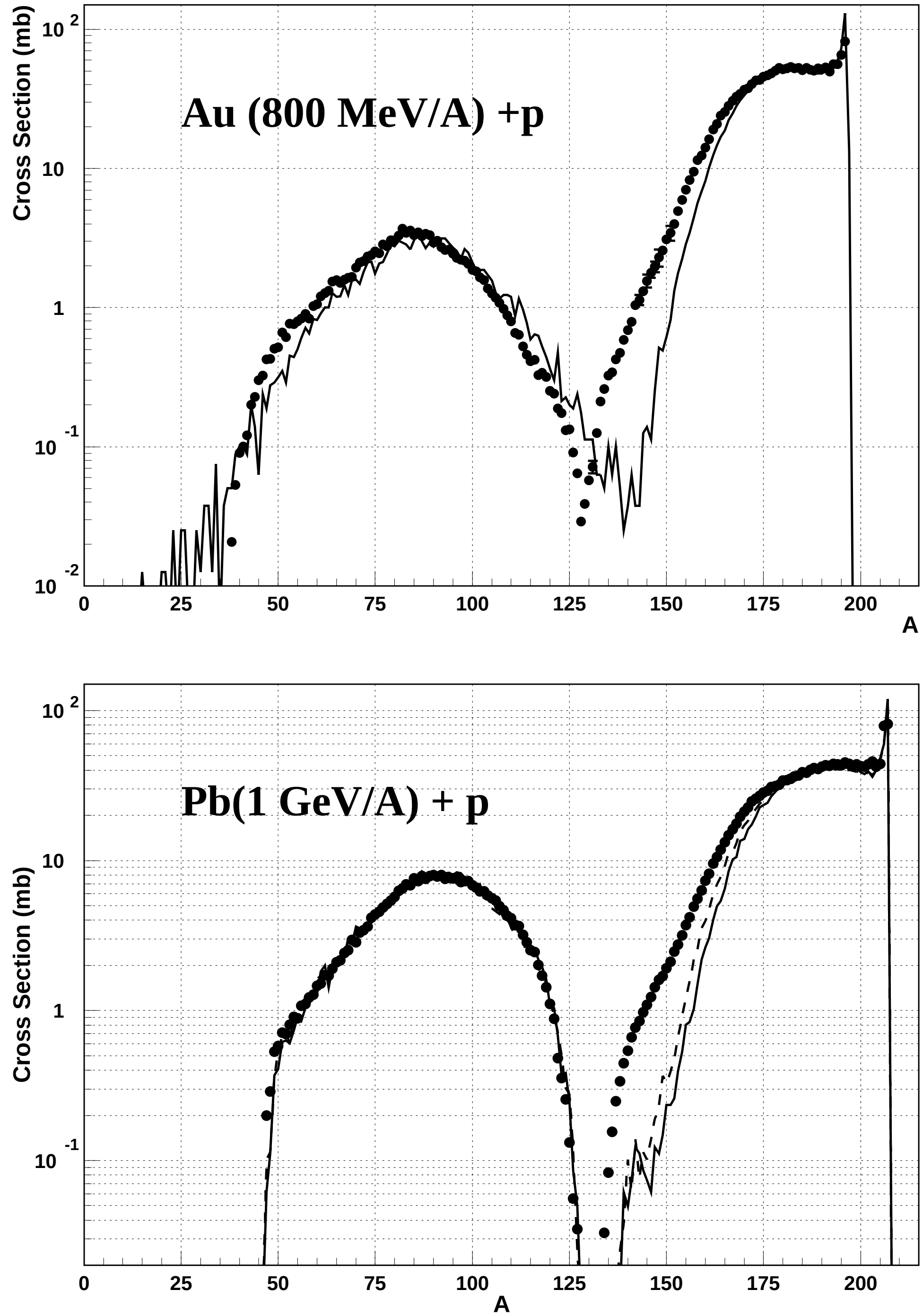

Fig 3: Cross section of spallation residues produced by Au + p at 800 MeV per nucleon (top) [8] and by Pb + p at 1 GeV per nucleon (bottom) [7] as a function of there atomic mass (A). Data points are compared to the INCL4+ABLA calculation without (continuous lines) and with (dashed lines) emission of light clusters in the cascade.

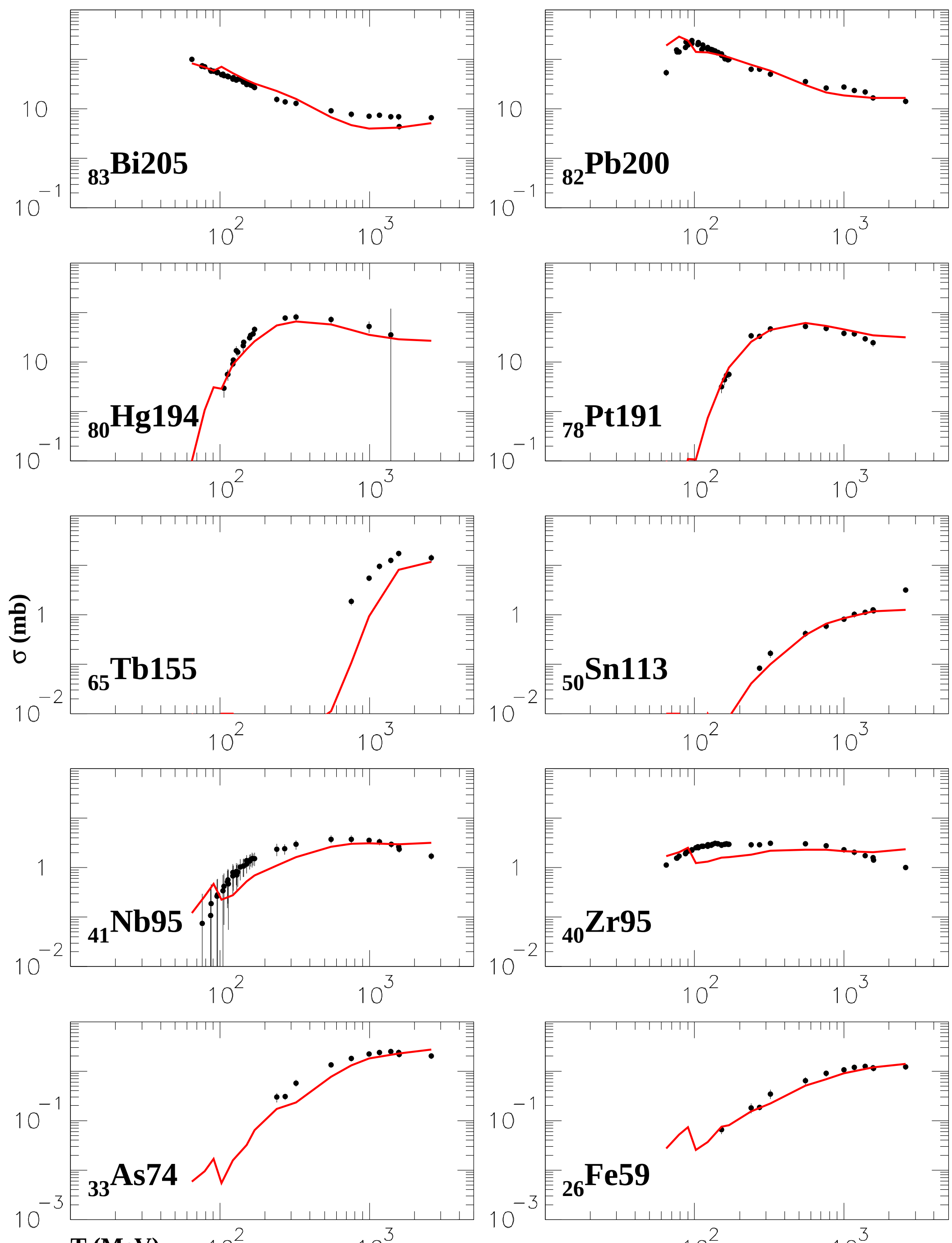

Fig. 4. Cross sections in mb for the production of residual nuclei for the p+Pb system as a function of the proton incident energy in MeV. Data points are from ref [9]). Lines are the INCL4-ABLA results.

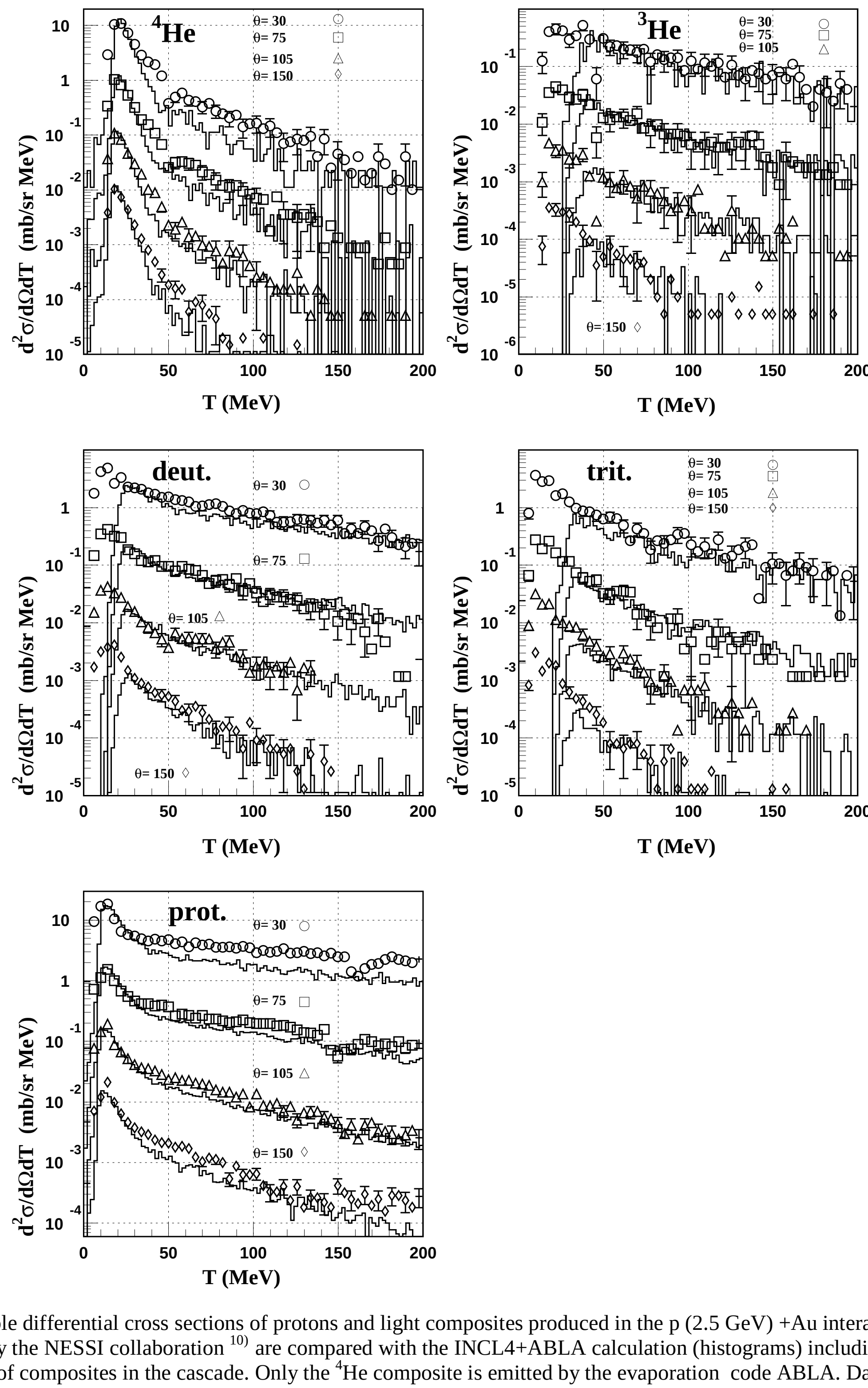

Fig 5: Double differential cross sections of protons and light composites produced in the p (2.5 GeV) +Au interaction and measured by the NESSI collaboration [10] are compared with the INCL4+ABLA calculation (histograms) including the production of composites in the cascade. Only the ^{4}He composite is emitted by the evaporation code ABLA. Data are displayed with the same convention as in Fig 1.

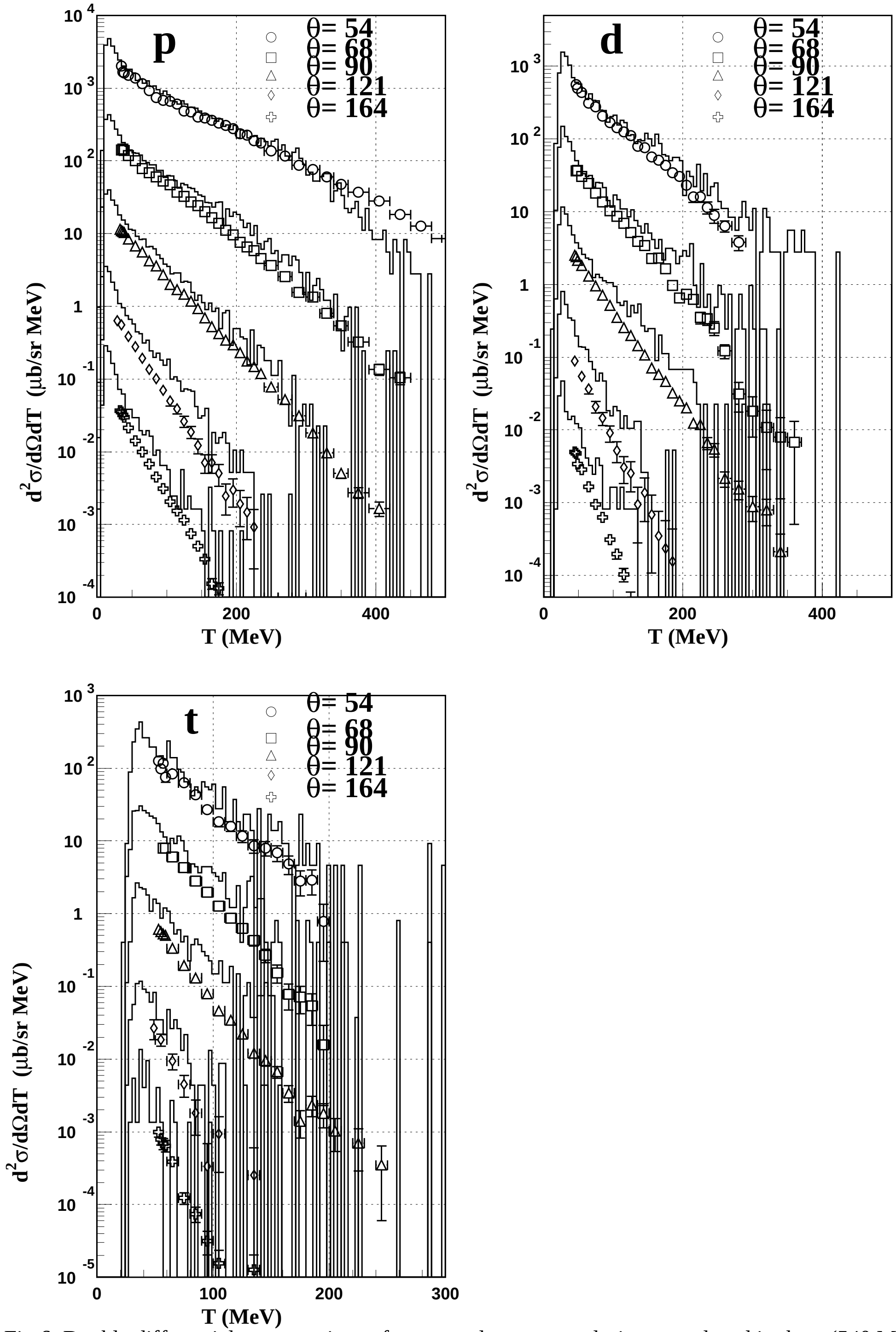

Fig 6: Double differential cross sections of protons, deuterons and tritons produced in the n (540 MeV) +Bi interaction and measured by Franz et al. [11] are compared with the INCL4+ABLA calculation (histograms) including the production of composites in the cascade. Only the ^{4}He composite is emitted by the evaporation code ABLA. Data are displayed with the same convention as in Fig 1.