# Dependence and Influence of Projectile Energy and Target Mass on the Production of Light Charged Particles and Intermediate Mass Fragments in Proton Induced Reactions

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Calculations were performed for proton induced spallation reactions over a wide range of atomic masses on the targets: $^{12}$C, $^{27}$Al, $^{nat}$Ni, $^{108}$Ag and $^{197}$Au using an Intra-nuclear Cascade Model (INCL4.6) with coalescence which includes the emission of protons, light clusters (d$-^4$He), and intermediate mass fragments (up to A=8) formed by the nucleons during the first stage of the reaction. The emission of particles from excited cascade residua are described using three different theoretical models SMM, ABLA07, and GEMINI++. A comparison of calculations with experimental double differential cross$-$sections $d^2\sigma/d\Omega dE$ for light charged particles and selected intermediate mass fragments was studied at proton beam energies from 1.2$-$2.5 GeV. Systematic deviations of the simulated cross sections from the experimental data were found for both light charged particles and intermediate mass fragments.

## I. INTRODUCTION

During the past years, a major effort has been undertaken for the validation and development of high energy codes [1]. The products produced in proton induced reactions play an important role in estimating the performance of particle transport codes used to design accelerator application facilities like accelerator based nuclear waste transmutation or spallation neutron sources. This task requires a thorough study over a wide range of nuclear systems and reaction observables. One important observable is to measure the production cross sections of various ejectiles and their angular distributions. It is also of equal importance to investigate the influence of varying target mass and projectile energy on the experimentally measured differential cross sections and the predictive capabilities of the model calculations. An experiment was performed in the framework of the PISA [2] collaboration at COSY in Juelich, to measure the production cross section of light charged particles ( LCP ), intermediate mass fragments ( IMF ) and their angular distributions for various nuclear systems, see Table I.

To draw some conclusions on the performance of models, a comparison of calculations with a selected set of data needs to be performed. In the present work, a study is shown for two targets; $^{27}$Al and $^{197}$Au, at selected incident proton beam energies; 1.2 and 2.5 GeV, respectively. The intranuclear cascade stage, where pre-equilibrium particle emission takes place mainly via single/multi step direct processes was evaluated by INCL4.6 [3] with the possibility of surface coalescence. At the end of cascade, residua is supposed to be left in an equilibrium state characterized by its mass, charge and excitation energy is described by three different evaporation/fission/fragmentation models SMM [4], ABLA07 [5] and Gemini++ [6].

TABLE I. Nuclear systems studied by the PISA collaboration.

| Targets | Proton Energy (GeV) | | | |
|---|---|---|---|---|
| $^{12}$C | 2.5 | 1.9 | 1.2 | |
| $^{27}$Al | 2.5 | 1.9 | 1.2 | |
| Ni | 2.5 | 1.9 | 1.2 | 0.175 |
| $^{108}$Ag | 2.5 | 1.9 | 1.2 | |
| $^{197}$Au | 2.5 | 1.9 | 1.2 | |

## II. COMPARISON OF MODEL CALCULATIONS AND EXPERIMENTAL DATA

A comparison between theoretical model predictions and experimental data for LCP and a selected set of IMF is shown in Fig. 1 and Fig. 2, respectively. The default values of the models parameters were used for all the codes. In addition, the coalescence condition was kept always 'ON' in the INCL4.6 code which allows the emission of composite particles. One can expect a contribution to the production cross section of IMF also from
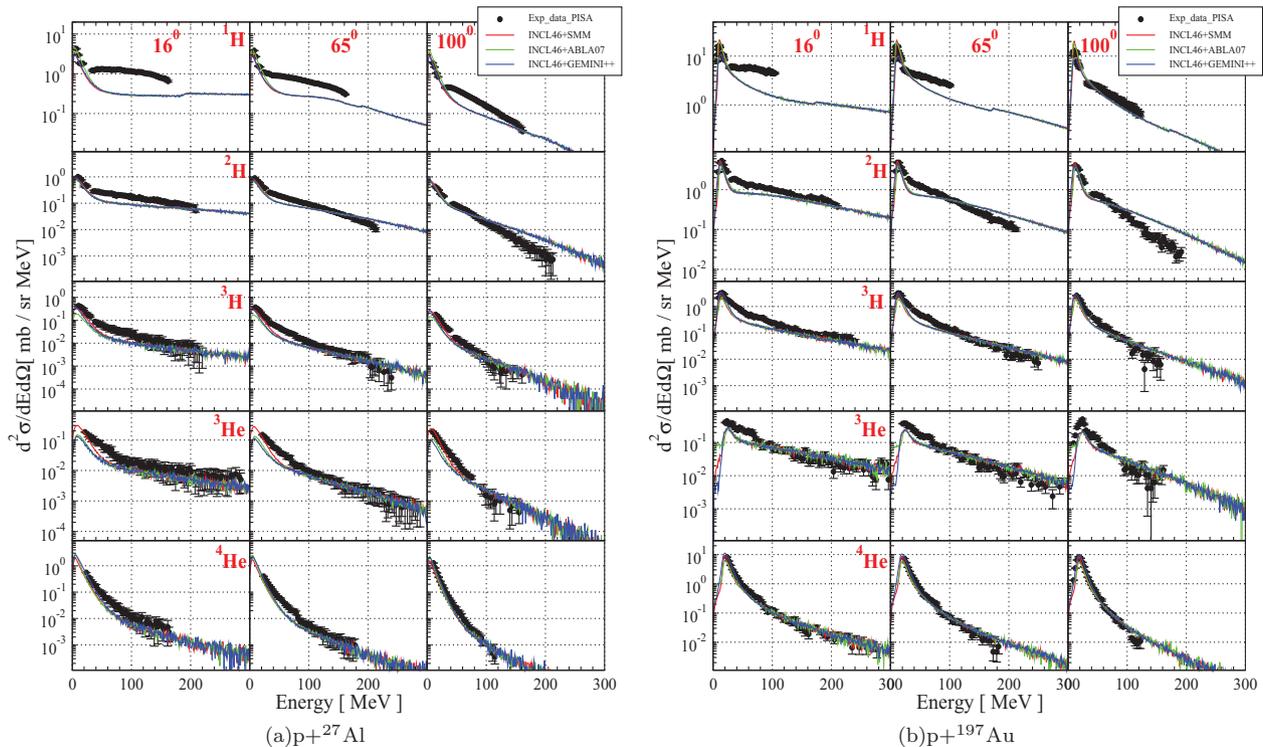
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FIG. 1. Comparison of theoretical models prediction and experimental data of LCP for p+$^{27}$Al at 1.2 GeV and p+$^{197}$Au at 2.5GeV. Black full circles represent the experimental data, red lines are for INCL46+SMM, green lines for INCL46+ABLA07 and blue lines for INCL46+GEMINI++. Different angles and ejectile names are indicated on the graphs.

the first stage of the reaction.

We present in Fig. 1 the double differential cross sections of LCP for the p+$^{27}$Al [7] at 1.2 GeV and p+$^{179}$Au at 2.5 GeV [8] in three angles 16°, 65° and 100° with respect to the beam direction. Model predictions for the shape and magnitude of $^{3}$H, $^{3}$He and $^{4}$He spectra are in reasonable agreement for both targets and energies, only lacking noticeably in the energy range between 30 to 100 MeV. The agreement improves for the higher angles. This clearly indicates the angular dependence in the production of outgoing ejectiles. The agreement between the data and model results deteriorates for the lightest ejectiles. The slope of $^{2}$H spectra is increasing rapidly as a function of angle in the data compared with the calculations. For $^{1}$H, the model seems far from an agreement to reproduce the experimental data at energies greater than 40 MeV, especially in the forward angles. Low energy range of spectra, supposed to be completely dominated and described by evaporation codes is successfully reproduced by all models.

Fig. 2 shows the results for the same targets and energies as Fig. 1, but for IMF. The spectra of $^{6}$He is in better agreement with the calculations performed with INCL4.6+SMM. On the another hand, GEMINI++ underestimates the production of $^{6}$He isotopes for both Al as well as Au targets. Similarly, systematic deviations between the experimental data and the model predictions

for other IMFs are shown. For the Au target there is a significant difference in predictions for low energy spectra by GEMINI++ in comparison to other codes. However, due to the unavailability of experimental data in that region, it is difficult to judge the better choice among all the models. For the Li isotopes, the data is available for low energies and allows to perform comparison with model predictions. For $^{6}$Li and $^{7}$Li both INCL46+SMM and ABLA07 seems equally good to reproduce experimental data, but ABLA07 is not found to predict low energy region for $^{8}$Li. A study of these deviations emerges an impression that INCL46 coupled with SMM remains consistent to describe better the experimental data in comparison to other combinations of codes, where INCL4.6 always describe first stage.

## III. SUMMARY

In the present work, calculations were performed for proton induced spallation reactions on Al and Au targets at 1.2 and 2.5 GeV beam energies. In these calculations an Intra-nuclear Cascade Model (INCL4.6) was coupled with three different models describing the deexcitation of the remnants of the intranuclear cascade; SMM, ABLA07 and GEMINI++. The INCL4.6 calculations took into account the coalescence of escaping nucleons
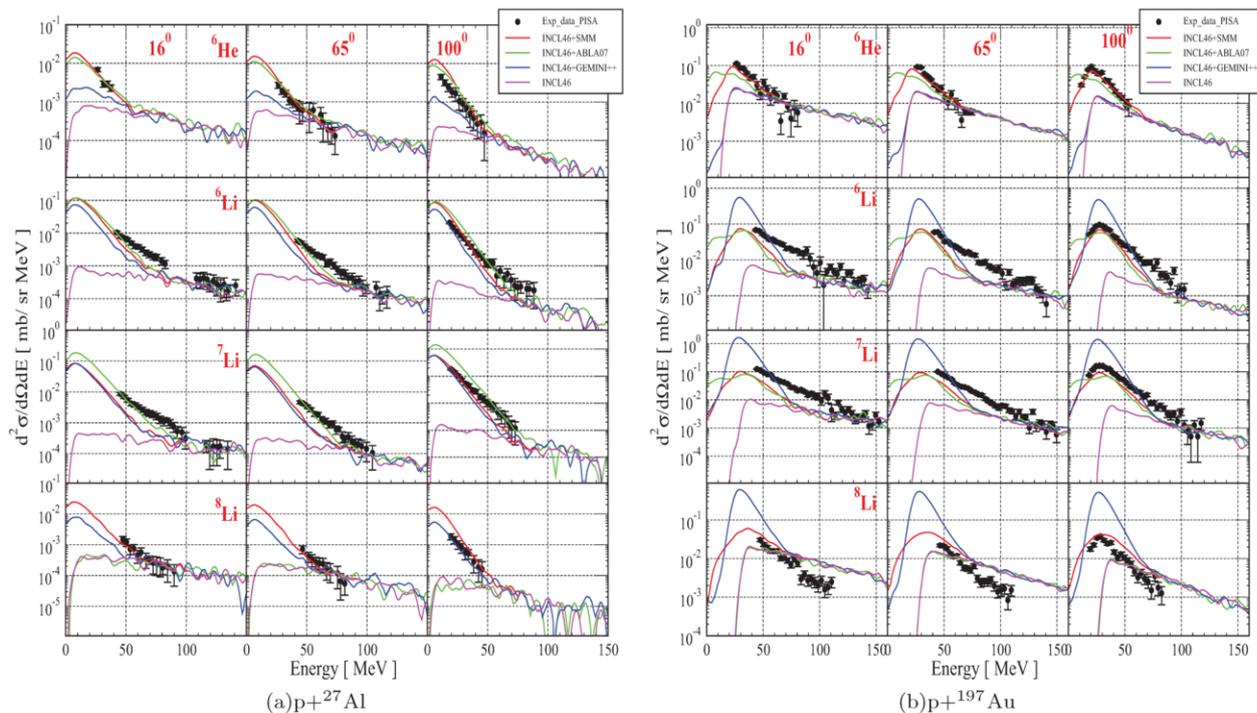
FIG. 2. Comparison of theoretical models predictions and experimental data of IMF for p+$^{27}$Al at 1.2 GeV and p+$^{197}$Au at 2.5 GeV. Black full circles represents the experimental data, red lines are for INCL46+SMM, green lines for INCL46+ABLA07, blue lines for INCL46+GEMINI++ and magenta lines for INCL46 only. Note that all lines overlap with the magenta line for energies larger than $\sim 80$ MeV what indicates dominance of the coalescence contribution to the emission of particles for these energies. Different angles and ejectile names are given on the graphs.

which enabled the emission of protons, light clusters (d−$^4$He), and intermediate mass fragments (up to A=8) formed by the nucleons during the first stage of the reaction. The following conclusions may be stated: The agreement between the experimental double differential cross sections d$^2\sigma$/dΩdE and theoretical predictions for light charged particles improves with increase in angles of observation, target mass and decrease of beam energy. The (dis)agreement between calculations and experimental data for LCP seems to be similar for the beam energy of 1.2 GeV with Al target and the higher energy (2.5 GeV) with Au target. Model's discord, to describe the data of LCP particularly in forward direction and energy range 30-100 MeV, leads to the surmise, that there may

be additional processes which are still missing in theoretical predictions. Selected IMF are better described by the combination of INCL46+SMM code in comparison to INCL46+GEMINI++ and INCL46+ABLA07 in overall prospect.

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