Nonelastic nuclear reactions induced by light ions with the BRIEFF code

H. Duarte
CEA/DAM/DIF, F-91297, Arpajon Cedex, France

Abstract
The intranuclear cascade (INC) code BRIC has been extended to compute nonelastic reactions induced by light ions on target nuclei. In our approach the nucleons of the incident light ion move freely inside the mean potential of the ion in its center-of-mass frame while the center-of-mass of the ion obeys to equations of motion dependant on the mean nuclear+Coulomb potential of the target nucleus. After transformation of the positions and momenta of the nucleons of the ion into the target nucleus frame, the collision term between the nucleons of the target and of the ion is computed taking into account the partial or total breakup of the ion. For reactions induced by low binding energy systems like deuteron, the Coulomb breakup of the ion at the surface of the target nucleus is an important feature. Preliminary results of nucleon production in light ion induced reactions are presented and discussed.

1 Introduction

The Monte-Carlo code BRIEFF [1] computes nonelastic nuclear reactions induced by nucleons and pinos on nuclei at intermediate energy up to several GeV. It is based on two stages: the intranuclear cascade (INC) and the de-excitation of the compound nucleus formed at the end of the INC. Our intranuclear cascade code BRIC [2] has recently been extended down to low intermediate energy, the threshold energy of incident proton and a few MeV for incident neutrons. Those developments were done to improve the energy-angle distribution of preequilibrium emitted neutrons and protons and also to allow the calculation of cross sections of compound nucleus formation, both in nucleon-induced reaction at low intermediate energy [1]. In the evaporation model the cross sections of compound nucleus formation σ_{cn} appear in the calculation of probabilities of nucleons and light nuclei emission and of their energy distribution. We were interested to use these cross sections rather than the reaction cross sections in our evaporation code since the excitation energy of compound nuclei produced at the end of the INC stage can reach several hundreds of MeV in high energy spallation reaction. Moreover the calculation of these cross sections by the INC code strengthens the link between the INC and the de-excitation stage. In our INC code these cross sections σ_{cn} are defined as the fraction of events without emission of particles before the time cut of INC stage, among all nonelastic events that contribute to the reaction cross section. 200 fm/c is now our default INC time cut to insure that the preequilibrium stage implicitly included in BRIC is fulfilled even at low intermediate energy as was discussed in [2]. In Ref. [1], the cross sections σ_{cn} were computed for neutron and proton induced reaction on 2000 target nuclei and are now completed for other 1400 heavier target nuclei. For the moment the cross sections σ_{cn} for light ions d, t, ^{3}He and α-particles are deduced from the relation

$$\sigma_{cn}^{(LI)}(e^{(LI)} - e_{thresh}^{(LI)}) = \sigma_{cn}^{(p)}(e^{(p)} - e_{thresh}^{(p)}) \frac{\sigma_R^{(p)}(e^{(p)} - e_{thresh}^{(p)})}{\sigma_R^{(LI)}(e^{(LI)} - e_{thresh}^{(LI)})} \tag{1}$$

where $\sigma_R^{(LI/p)}$, $e^{(LI/p)}$ and $e_{thresh}^{(LI/p)}$ are the reaction cross sections and the incident energies of light ion and proton and their threshold energies, respectively. In order to build a new database of σ_{cn} for reactions induced by light ions we started to extend our INC to compute such reactions. The emission of light clusters in nucleon induced reaction, that is still lacking in the BRIC code but is scheduled in the near future, should share some common pieces of physics with this extension.

In this paper we describe the new development of the BRIC code about nonelastic reactions induced by light ions and present some preliminary results.

2 Description of the BRIC development

Besides the phase-space coordinates of the nucleons of the target nucleus, the phase-space coordinates of the incident ion and those of the nucleons of the ion are now used in the BRIC code.

$\vec{P_G}(t)$, $E_G(t)$ and $\vec{R_G}(t)$ are the momentum and the energy of the incident ion and the position of its center of mass at time t in the laboratory frame, respectively. These phase-space coordinates obey to the equations of motion

$$\frac{d\vec{R_G}}{dt} = \frac{\vec{P_G}}{E_G} \tag{2}$$

$$\frac{d\vec{P_G}}{dt} = -\vec{\nabla} V_G \tag{3}$$

where V_G is the potential seen by the ion along its trajectory. We assume that the mean nuclear+Coulomb potential of the target nucleus on the ion is defined by

$$V_G(R_G) = Z_{ion} V_p(R_G) + (A_{ion} - Z_{ion}) V_n(R_G) \tag{4}$$

by analogy with optical potential. In Eq. 4, V_p and V_n are the potentials seen by an incident proton and neutron, respectively. They are the potentials that were previously defined in BRIC [1]. As the ion goes through the target nucleus, other quantities like the relativistic factor $\gamma_G(t) = E_G(t)/M_{ion}$ evolve with the time t in the laboratory frame.

At initialization, the position of the center-of-mass of the ion has a random impact parameter in comparison to the z-axis defined by the momentum direction. The deflection due to Coulomb+nuclear potential V_G is then computed up to the position $|\vec{R_G}(t_{ini})| = R_{limit} + R_{ion}$ where R_{limit} and R_{ion} are the maximal radius of the target nucleus and of the light ion, respectively. t_{ini} is then arbitrarly set to 0 and the phase-space coordinates are updated at each time step dt_{step} [2].

The nucleons of the incident ion, Z_{ion} protons and $A_{ion} - Z_{ion}$ neutrons, are inside the spherical potential $V^*(r^*)$ that describes the own mean field of the ion. The position r_i^* of its i-th nucleon is relative to the ion center-of-mass position in its center-of-mass frame. In this frame, the position $\vec{r_i^*}$ and momentum $\vec{p_i^*}$ of each nucleon i of the ion are updated according to the following equations of motion

$$\frac{d\vec{r_i^*}}{dt^*} = \frac{p_i^*}{E^*} \tag{5}$$

$$\frac{d\vec{p_i^*}}{dt^*} = -\vec{\nabla}_i V^* \tag{6}$$

where t^* is the proper time in the ion's center-of-mass frame. t^* is defined with the relativistic factor γ_G by: $t^* = t/\gamma_G(t)$. E_i^* is the relativistic energy of the i-th nucleon defined with the effective mass $m_i^* = m_{free} + V^*(r_i^*)$: $E_i^* = ((p_i^*)^2 + (m_i^*)^2)^{1/2}$. The condition on the momenta $\sum_i \vec{p_i^*} = \vec{0}$ is required to insure the momentum conservation when breakup occurs. The position and momentum are then transformed into the laboratory frame with the right lorentz boost of the ion to get the position $\vec{r_i}$ and the momentum $\vec{p_i}$ in the laboratory frame.

The times and positions of the collisions between the nucleons N_{targ} of the target nucleus and the nucleons N_{ion} of the light ion are then searched as in the previous version of BRIC [2]. A $N_{ion} - N_{targ}$ collision is allowed if the energies of the two nucleons in the laboratory frame after the collision are compatible with the Pauli exclusion principle in the target nucleus as it was done before, but also if the energy of nucleon N_{ion} after collision is greater than m_{free}.

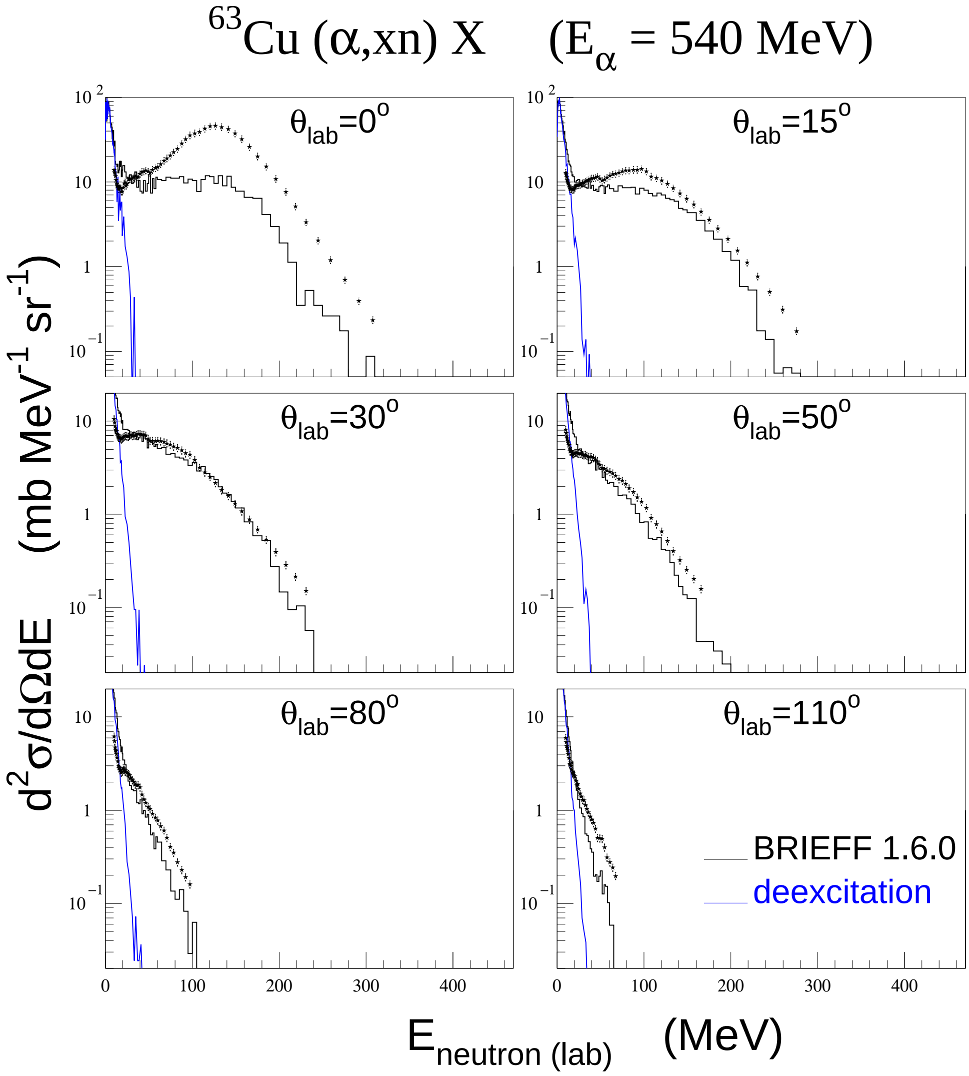

Fig. 1: Double differential cross sections of neutron production for $\alpha+^{63}$Cu reaction at 540 MeV. Black histograms are the results of the full calculation of BRIEFF and includes deexcitation component (blue lines). Black symbols are the data of H. Sato *et al.* [6].

After an allowed collision the nucleon of type N (N=n or p), from the target or from the ion, becomes a quasi-free hadron in the target nucleus if its new kinetic energy is greater than $-V_N - e_{bind}$ where e_{bind} is the binding energy of the target nucleus. The mass, charge and energy-momentum of the remaining ion are deduced from the conservation laws. The partial or total breakup of the ion is then explicitly taken into account.

During the development of the extension of our INC code, we noticed that the results of the neutron and proton production were largely underestimated in deuteron induced reaction in comparaison to available experimental data [3]- [5]. We then decided to include the Coulomb breakup of the deuteron at the surface of the target nucleus. Two conditions are required to induce the Coulomb breakup of the deuteron into a quasi-free proton-neutron pair in the laboratory frame. The first condition is applied on the difference of the potentials seen by the proton and neutron of the deuteron: $|V_p(R_G) - V_n(R_G)| > e_{brkup}$ where e_{brkup} is a free parameter. The second condition concerns the total energy of the proton-neutron pair: $E_{ion} + V_G(R_G) - (E_p + E_n) - B_d > m_p + m_n$. Here E_p, E_n are the energies of the binded proton and neutron of the deuteron (before breakup) in the laboratory frame while B_d, m_p and

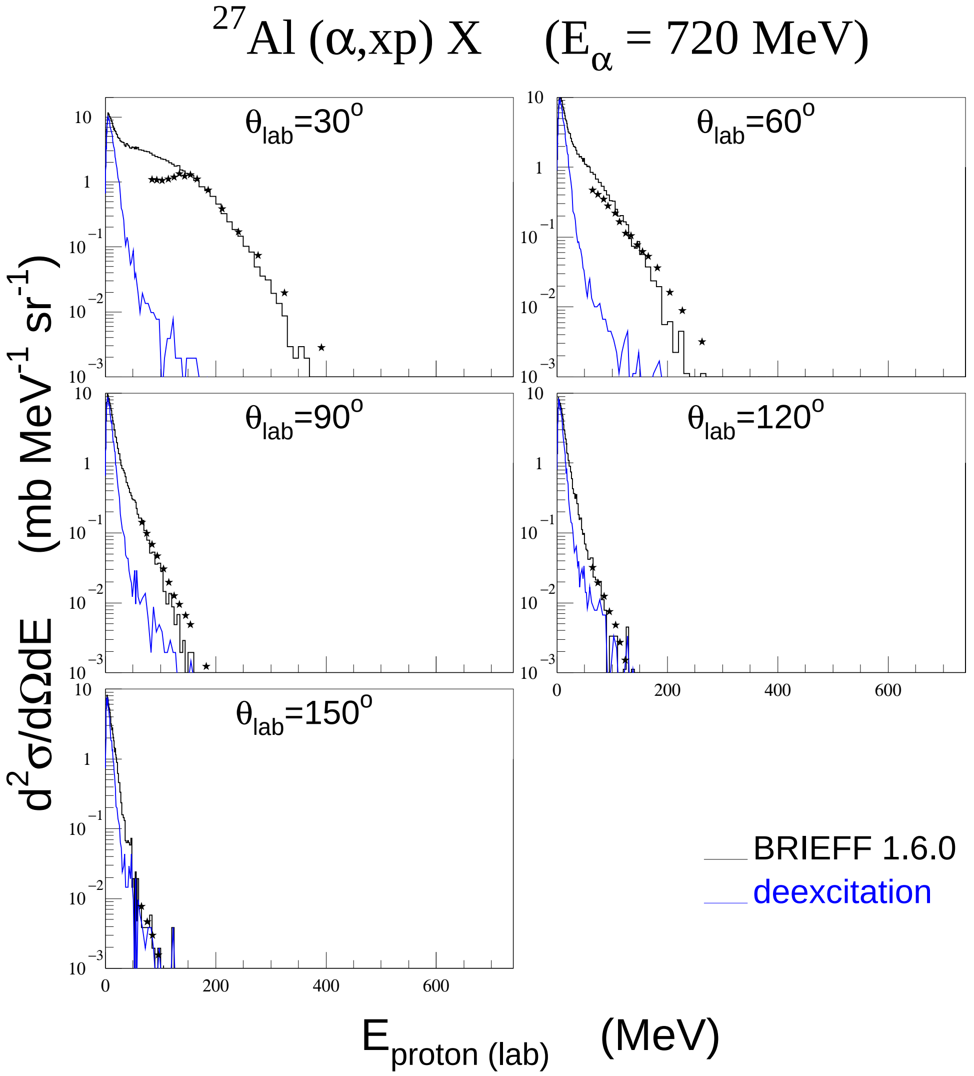

Fig. 2: Double differential cross sections of proton production for $\alpha + {}^{27}$Al reaction at 720 MeV. Black histograms are the results of the full calculation of BRIEFF and includes deexcitation component (blue lines). Black symbols are the data of K.R. Cordell *et al.* [7].

m_n are the binding energy of the deuteron and the free masses of proton and neutron, respectively. The value $e_{brkup} = 11.5$ MeV is currently the best value we obtained.

3 Results of $d^2\sigma/d\Omega dE$ calculations

The results of double differential cross section of nucleon production provide informations on the dynamics of the reaction that should be described by the fast stage of the reaction, the INC stage. For α-particle induced reactions, the production of neutrons at very forward angles at 540 MeV is systematically underestimated by the code (Fig. 1 and other reactions at the same energy) while neutron and proton production are rather well reproduced at intermediate angles at 540 and 720 MeV (figures 1 and 2). The large peak of neutron at 0^o around 135 MeV (540/4 MeV) comes certainly from the stripping of one neutron of the incident α-particle and from the head-on collision on a neutron of the target nucleus. For the moment we have not found the reason of such discrepancy.

The proton and neutron productions in deuteron induced reactions are rather difficult to calculate in spite of the free parameter e_{brkup} (figures 4-6). The best value we obtained $e_{brkup} = 11.5$ MeV

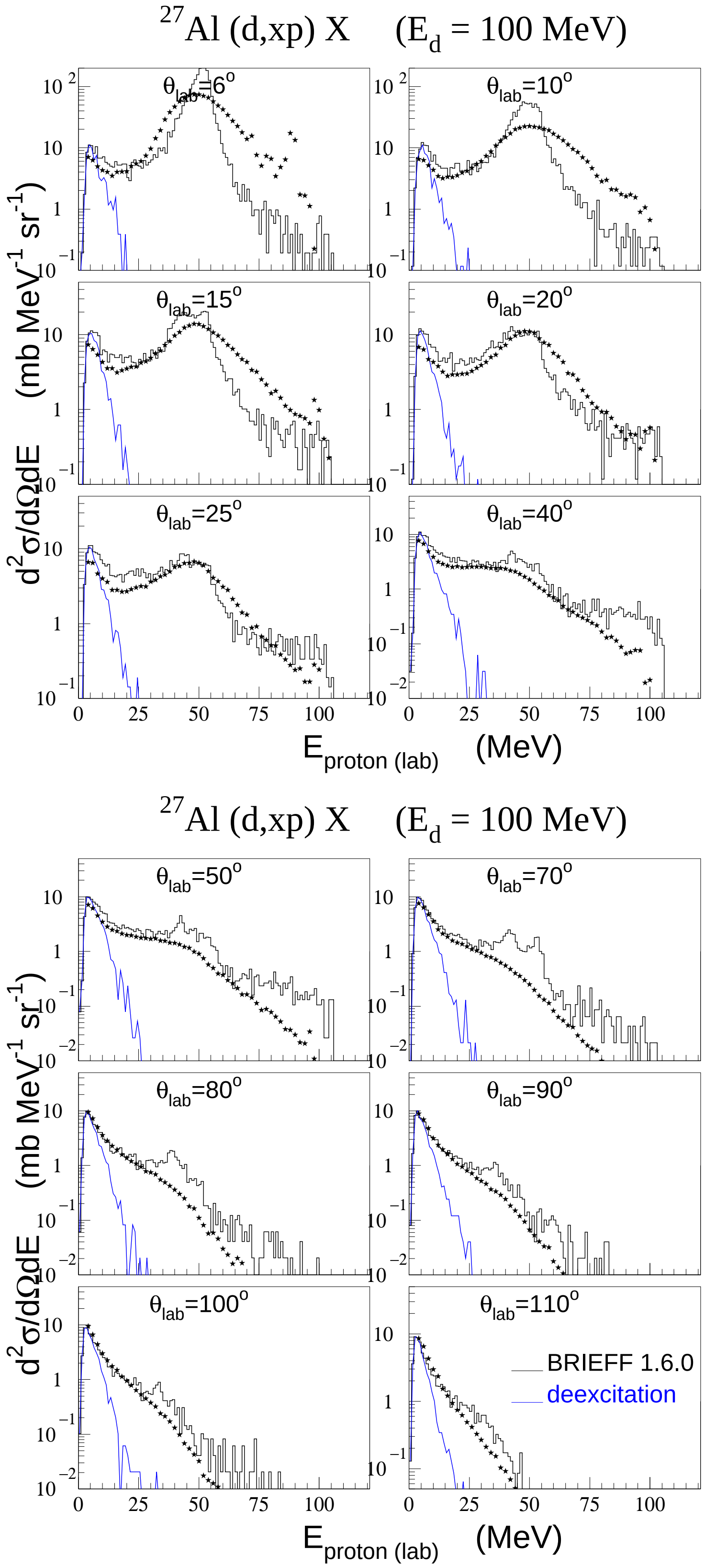

Fig. 3: Double differential cross sections of proton production in $d + {}^{27}$Al reaction at 100 MeV. Black histograms are the results of the full calculation of BRIEFF and includes deexcitation component (blue lines). Black symbols are the data of D. Ridikas *et al.* [3].

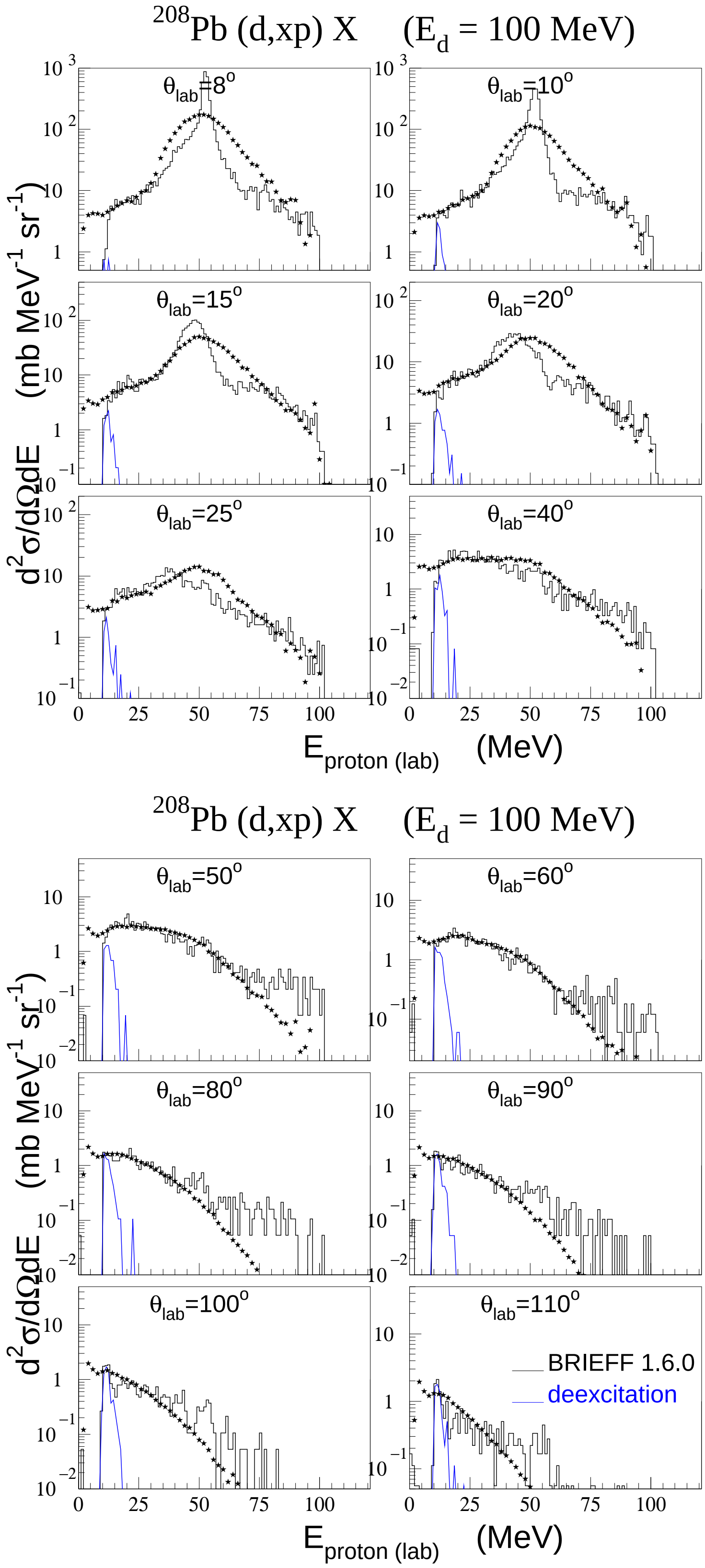

Fig. 4: Double differential cross sections of proton production for $d+{}^{208}$Pb reaction at 100 MeV. Black histograms are the results of the full calculation of BRIEFF and includes deexcitation component (blue lines). Black symbols are the data of D. Ridikas *et al.* [3].

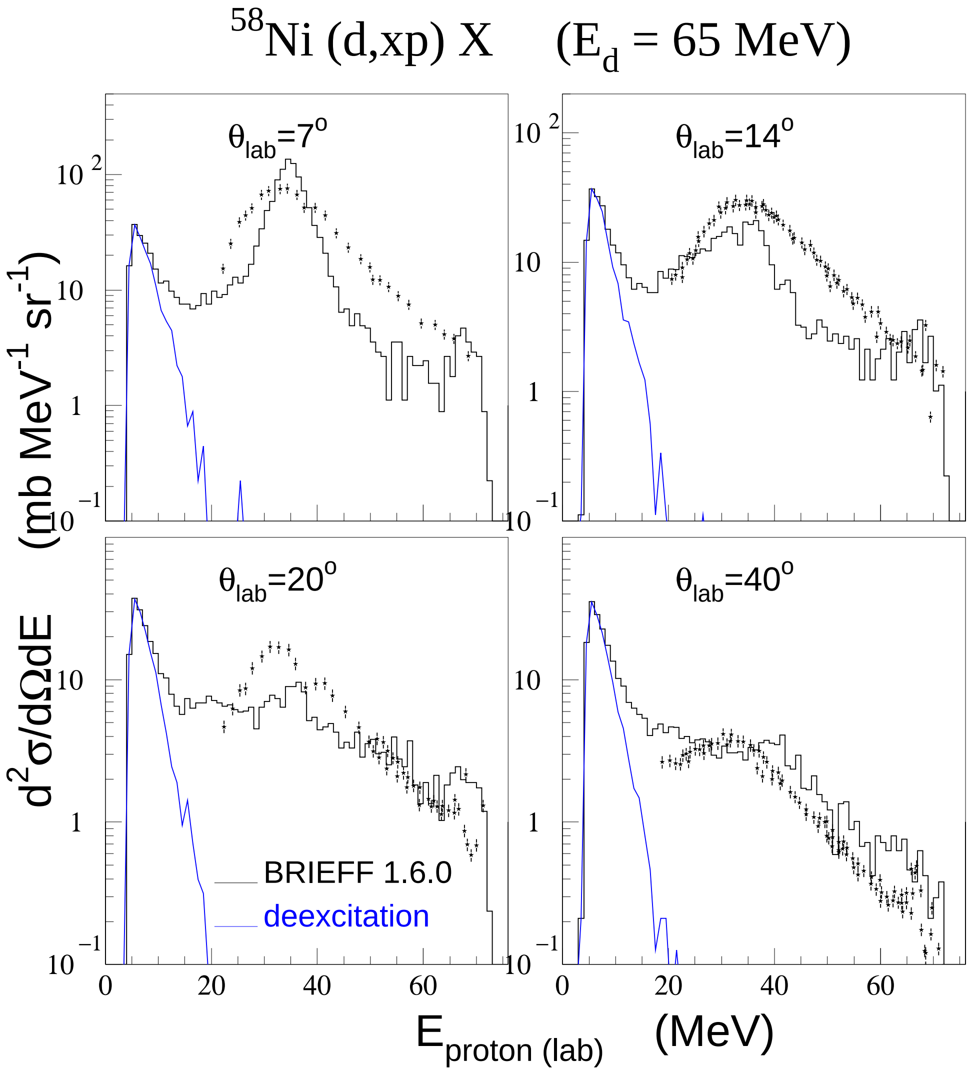

Fig. 5: Double differential cross sections of proton production for $d+{}^{208}$Ni reaction at 65 MeV. Black histograms are the results of the full calculation of BRIEFF and includes deexcitation component (blue lines). Black symbols are the data of N. Matsuoka *et al.* [4].

gives more or less the proton or neutron energy at the maximum of the breakup peak (around $E_d/2$), however the shapes or the amplitude of the peaks, or both, are rather far from the experimental data. Such disagreement could be partly due to a numerical problem: in our INC code the equations of motion of the proton and neutron have to be calculated with enough precision in the center-of-mass frame of the deuteron when it enters and goes through the target nucleus before the Lorentz transformation to the laboratory frame. Another explanation could be the lack of description of the Coulomb breakup in our approach. Seen the bad results of the current Coulomb breakup new developments are needed.

4 Conclusions

The extension of the BRIC code to compute non-elastic reactions induced by light ion has been partly done. Some improvements are still needed to improve the results of particle production. One weak point appears to be the Coulomb breakup of incident deuteron. Nevertheless it provides us the basis to calculate in the near future the cross sections of compound nucleus formation σ_{cn} for light ion induced reaction. Moreover the next main development of the BRIC code, the emission of light clusters (d, t,

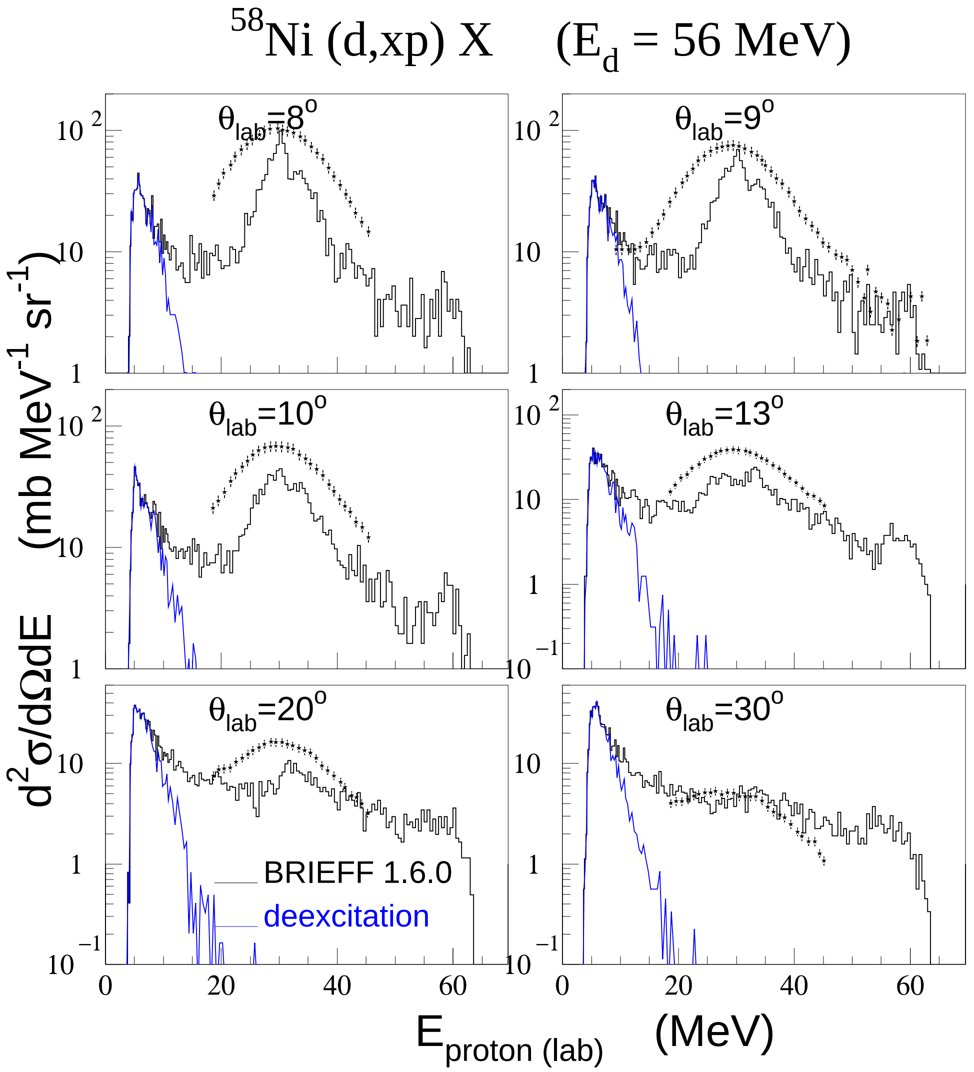

Fig. 6: Same as Fig. 5 for $d + {}^{208}$Ni reaction at 56 MeV. Black symbols are the data of M. Ieiri *et al.* [5].

$\alpha-$particles ...), will certainly share some common pieces of physics of the light ion reaction part.

References

- [1] H. Duarte, "The nonelastic reaction code BRIEFF and its intranuclear cascade BRIC", in Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, ed. O.Bersillon, F.Gunsing, E.Bauge, R.Jacqmin, and S.Leray, EDP Sciences, 2008, pp 1117-1120.
- [2] H. Duarte, Phys. Rev. C 75, 024611 (2007).
- [3] D. Ridikas, W. Mittig, H. Savajols, P. Roussel-Chomaz, S. V. Förtsch, J. J. Lawrie, and G. F. Steyn, Phys. Rev. C 63, 014610 (2000).
- [4] N. Matsuoka *et al*, Nucl. Phys. **A408**, 99 (1983).
- [5] M. Ieiri *et al*, Nucl. Phys. **A504**, 477 (1989).
- [6] H. Sato, T. Kurosawa, H. Iwase, T. Nakamura, Y. Uwamino, and N. Nakao, Phys. Rev. C 64, 034607 (2001).
- [7] K.R. Cordell *et al*, Nucl. Phys. **A362**, 431 (1981).