
Recent developments in the nonelastic reaction code BRIEFF deuteron induced reaction and emission

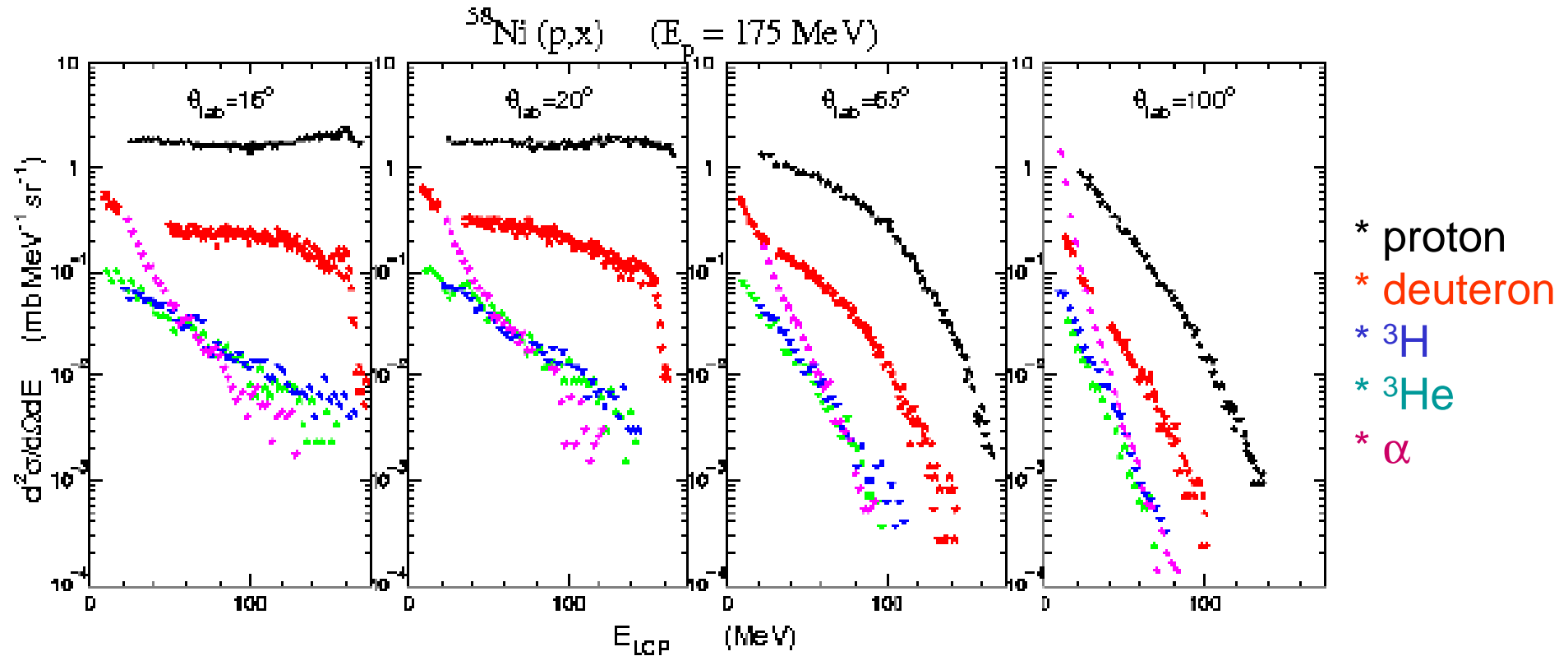
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LCP production in nucleon induced reaction



Data : (p,xLCP) B. Piskor-Ignatowicz et al., EXFOR D058003
(p,xp) v. Richter et al., Phys.Rev. C46, 1030 (1992)



Model Description

- **Fast stage of reaction is based on the Intra-nuclear Cascade (BRIC code)** (H. Duarte, PRC 75, 024611)
 - Incident particles : p,n, $\pi^{+,-,0}$
 - Particles are points in phase space {r,p}
 - Nucleus described by realistic density distribution and smooth potential :
 $V(r) = V_N(r) + V_C(r)$
 - Time-dependent approach ($t < 200$ fm/c)
 - Equations of motion of quasi-free hadrons ($E - m > -V$):
$$\frac{d\vec{r}}{dt} = \vec{p} / E \quad \frac{d\vec{p}}{dt} = -\vec{\nabla}V$$
 - NN in-medium cross sections (of Li and Machleidt) used in collision term
 - **Improvement at low incident energy : $E_{\text{threshold}} \sim \text{Max}(V(r))$**
Coulomb barrier (H. Duarte, proceed. of Nuclear Data Conf. ND2007)



A limit of the BRIEFF

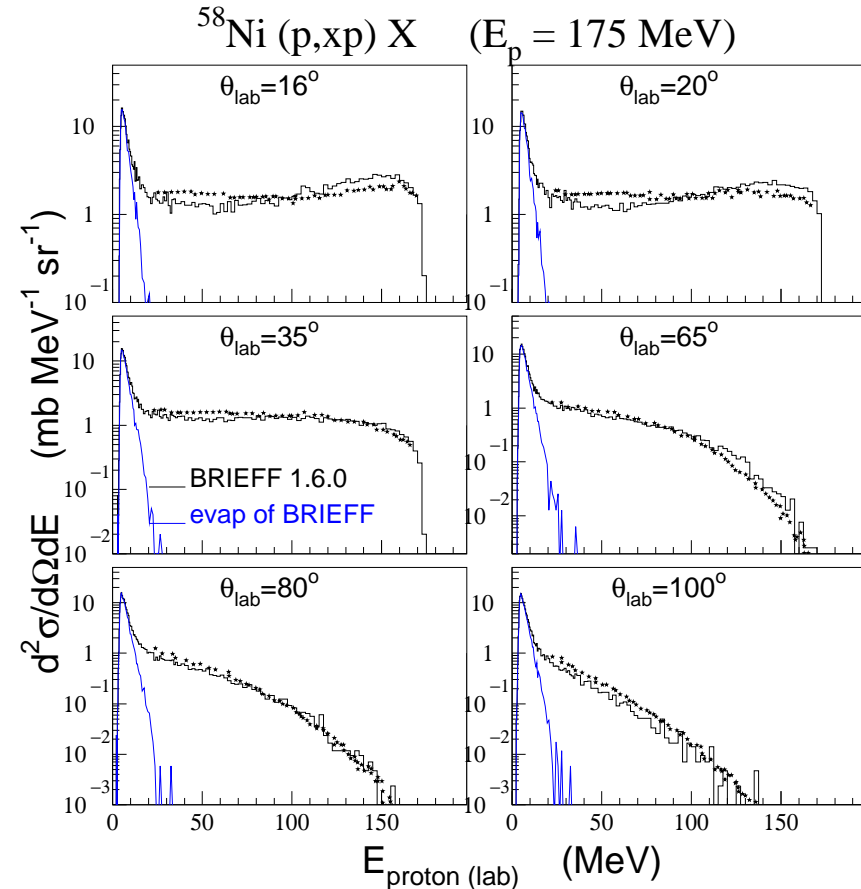
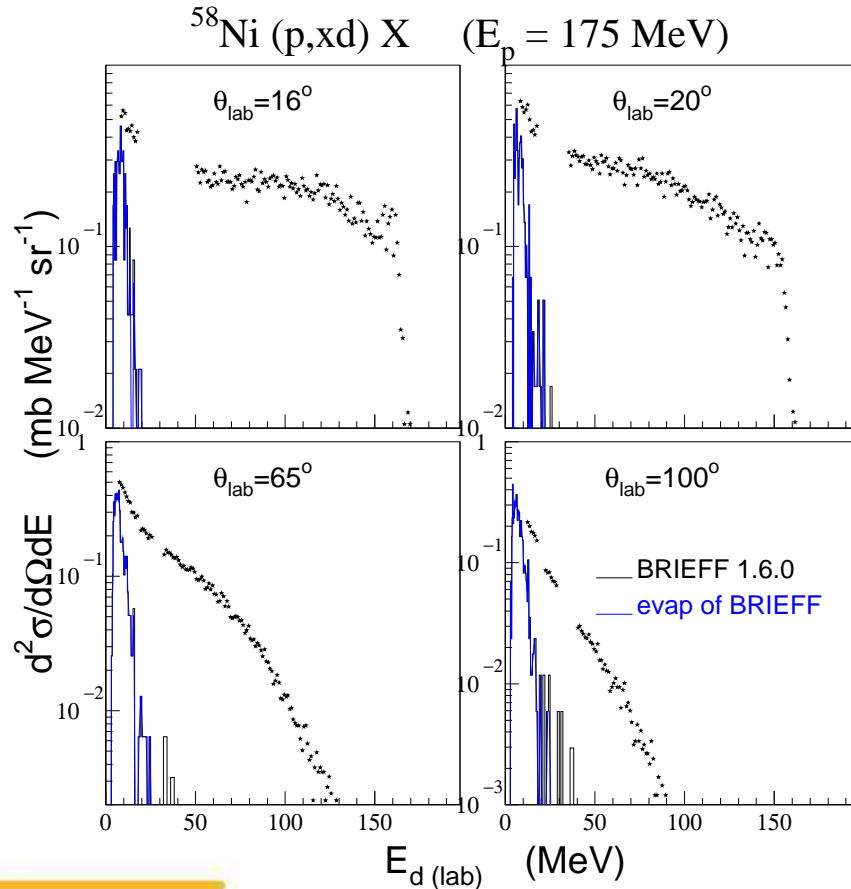
- Emission of p,n,d,t,³He and α -particle in the evaporation of BRIEFF

But

- No emission of light-mass ions (d,t,³He, α -particle ...) in INC stage (BRIC)



(p,xd) and (p,xp) $d^2\sigma/dE d\Omega$ 175 MeV BRIEFF 1.6



Data : (p,xd) B. Piskor-Ignatowicz et al., EXFOR D058003
(p,xp) v. Richter et al., Phys.Rev. C46, 1030 (1992)



⇒ Emission of high-energy light-mass ions (d,t, ^3He , α -particle ...) in INC stage (BRIC) is required

- high-energy deuterons are the most produced light-mass ions (with α -particles in some reactions)
- deuteron has a low binding energy. Then it certainly does not come from knock-out process (while high-energy α -particles can come from this process).

⇒ 1st : study of deuteron induced reactions to include deuteron breakup (and to include the “cluster”-type in BRIC).

⇒ 2nd : definition of deuteron formation in nucleon-induced reaction taking into account deuteron breakup.



Reactions induced by deuteron (1/2)

- Position and momentum of proton and neutron of incident deuteron inside its c.m. frame :

- r^* : nucleon position in the c.m. of deuteron

density distribution from the Hulthén wave function

$$\Phi_H(r^*) \propto [\exp(-\alpha.r^*) - \exp(-\beta.r^*)]/r^* \quad \text{with } \beta = 7.\alpha$$

- $V^*(r^*)$: potential of Malfliet - Tjon (Nucl Phys A 127, 161)

for proton and neutron in c.m. frame of deuteron

$$V^*(r^*) = \lambda_A \exp(-\mu_A.r^*)/r^* - \lambda_B \exp(-\mu_B.r^*)/r^*$$

$$E^* = \sqrt{p^{*2}(r^*) + m_{eff}^2(r^*)} = m_N + e_{bind}/2 \quad \text{with } \sum \vec{p}^* = \vec{0}$$

$$m_{eff}(r^*) = m_N + V^*(r^*)$$



Reactions induced by deuteron (2/2)

- Equation of motion of deuteron inside target (lab frame) :

$$\frac{d\vec{R}_G}{dt} = \frac{\vec{P}_G}{E_G} \quad \frac{d\vec{P}_G}{dt} = -\vec{\nabla}_G V_{ion}$$

$$V_{ion}(R_G) = A_{ion} \cdot V_N(R_G) + Z_{ion} \cdot V_C(R_G)$$

\vec{R}_G : position of deuteron center - of - mass in lab frame

- Nucleons of deuteron (N_{ion}) in lab frame :

$$\vec{P}_i = (\vec{p}_i, E_i) : \text{Lorentz transf. } (\vec{p}_i^*, E_i^*) \Rightarrow \sum \vec{p}_i = \vec{P}_G, \quad \sum E_i = E_G$$

$$\left(\vec{r}_i\right) : \text{Lorentz transf. } \left(\vec{r}_i^*\right) \quad (\text{used in the INC collision term})$$



Breakup of deuteron

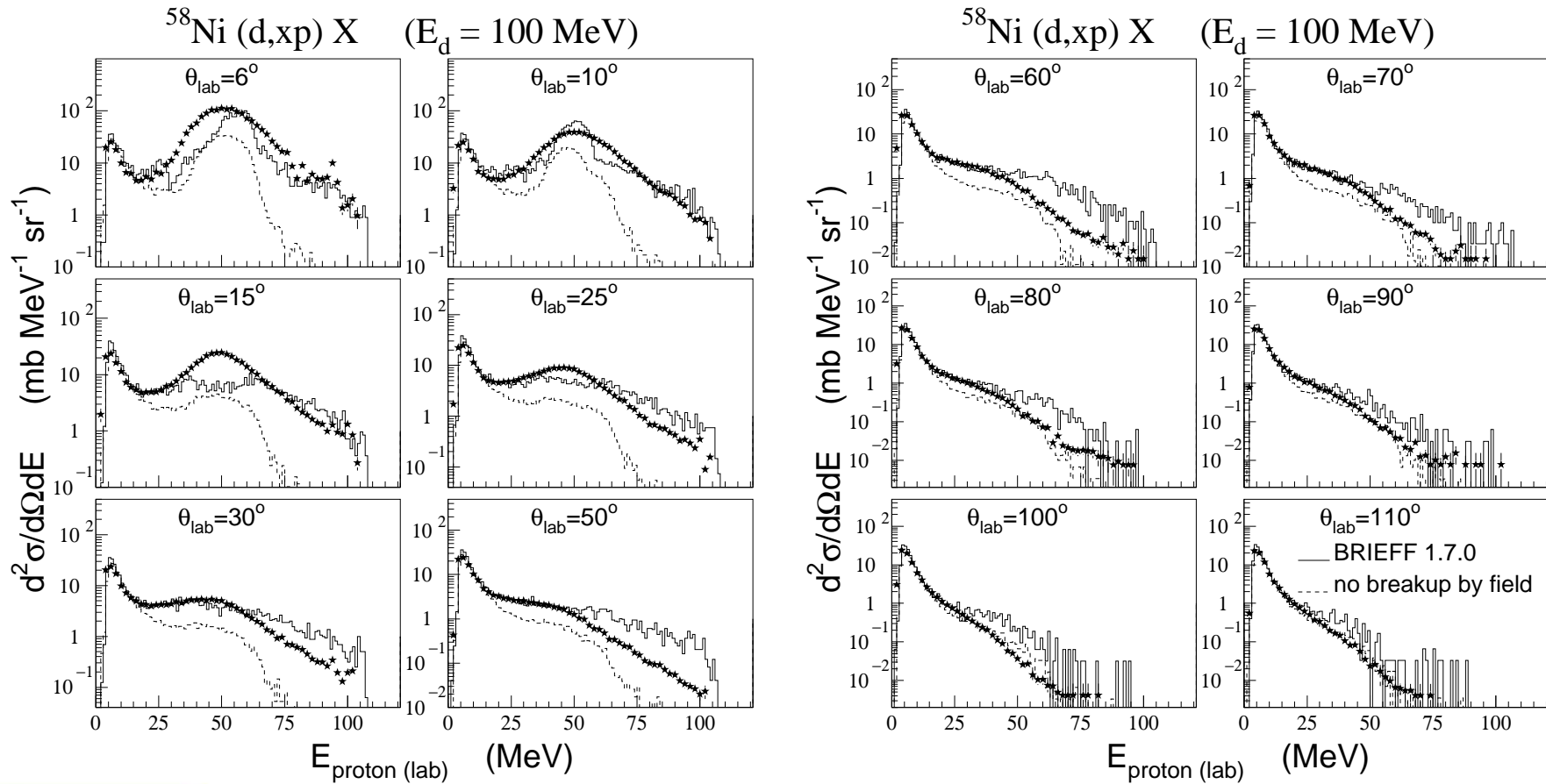
- **by the nuclear+Coulomb field of target nucleus**

$|V(r_n) - V(r_p)| > E_{\text{break}}(A_{\text{targ}})$ where $V(r_n)$ and $V(r_p)$ are the potentials of the target nucleus for the neutron and proton of deuteron in lab. frame ($E_{\text{break}} \approx 4.3 \text{ MeV}$ for $A_{\text{targ}} \approx 60$)

- **or by $N_{i \text{ of deut}} - N_{\text{targ}}$ collision** (INC collision term)
 - allowed if conditions on Pauli blocking are fulfilled in target nuclei and $S = (\tilde{P}_i + \tilde{P}_{\text{targ}})^2 \geq (2.m_N)^2$



(d,xp) $d^2\sigma/dE d\Omega$ 100 MeV



Data : D. Ridikas et al. Phys. Rev. C 63, 014610 (2000)



Deuteron formation

- Inverse process of the deuteron breakup by the nuclear+Coulomb field = quasi-free coalescence process, but it occurs at any time of the INC and at any position of the p-n pair:

$\tilde{P}_i = (\vec{p}_i^*, E_i^*)$: inverse Lorentz transf. (\vec{p}_i, E_i)

with $m_{eff}(r_i^*)$, then that depends on $V_{Malfliet-Tjon}^*(r_i^*)$.

a p - n pair forms a deuteron candidate if

- $|\Delta\vec{P}_{np}^*| < P_{cut}^* = 20 \text{ MeV}/c$ where $\Delta\vec{P}_{np}^* = \vec{p}_n^*(r_n^*) - \vec{p}_p^*(r_p^*)$
- $r_i^* < R_{max}^{(d)} = 6 \text{ fm}$

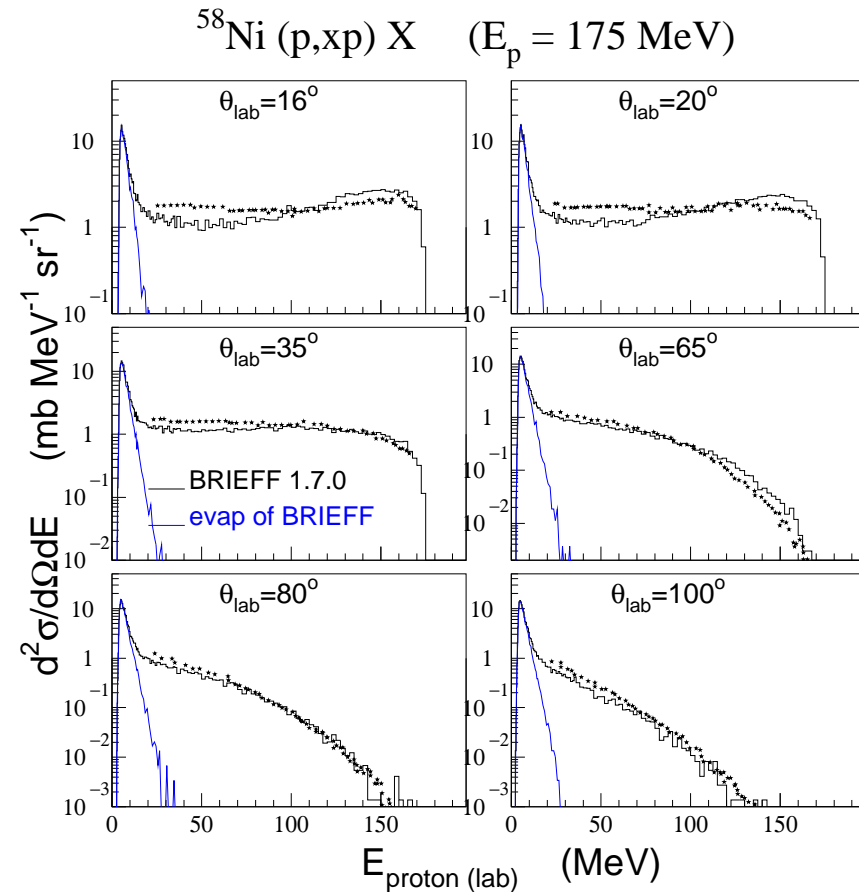
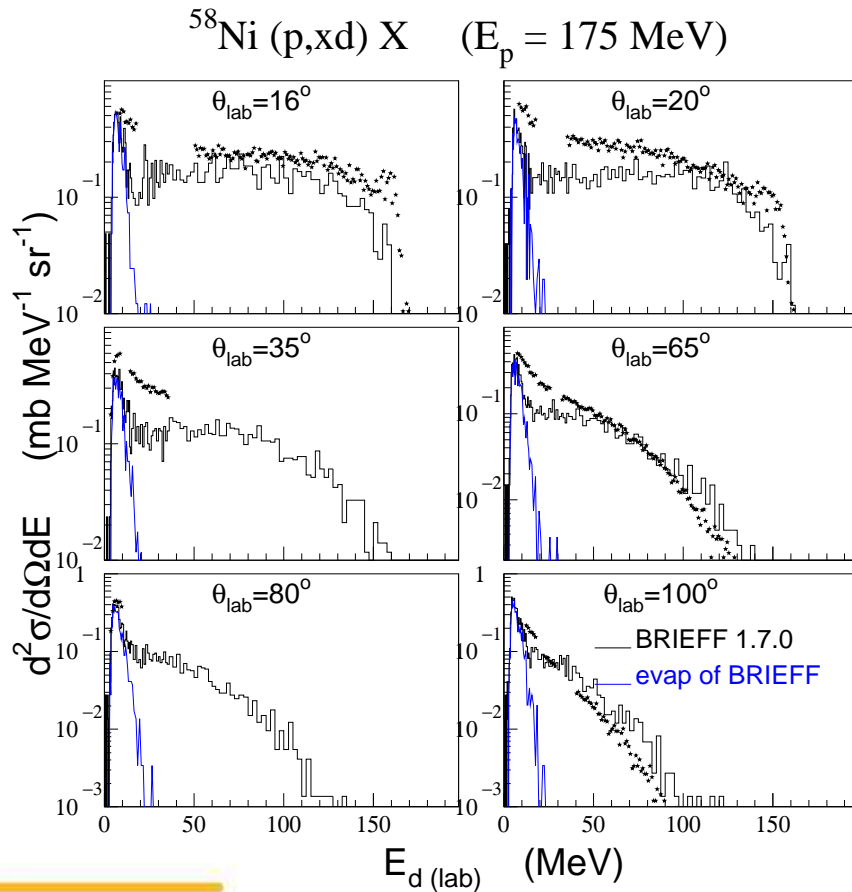


Deuteron emission

- Deuteron center-of-mass follows the equation of motion inside nuclear+Coulomb field ($2*V_N(R_G)+V_C(R_G)$ in lab frame)
- There is a competition between deuteron formation and deuteron breakup (by INC collision and by nuclear+Coulomb field)
 - Successive breakups and formations of the “same” deuteron candidate inside nuclear target
- Deuteron emission is the result of this competition when center-of-mass of the deuteron candidate is far above the radial position of the maximum of the nuclear+Coulomb field.



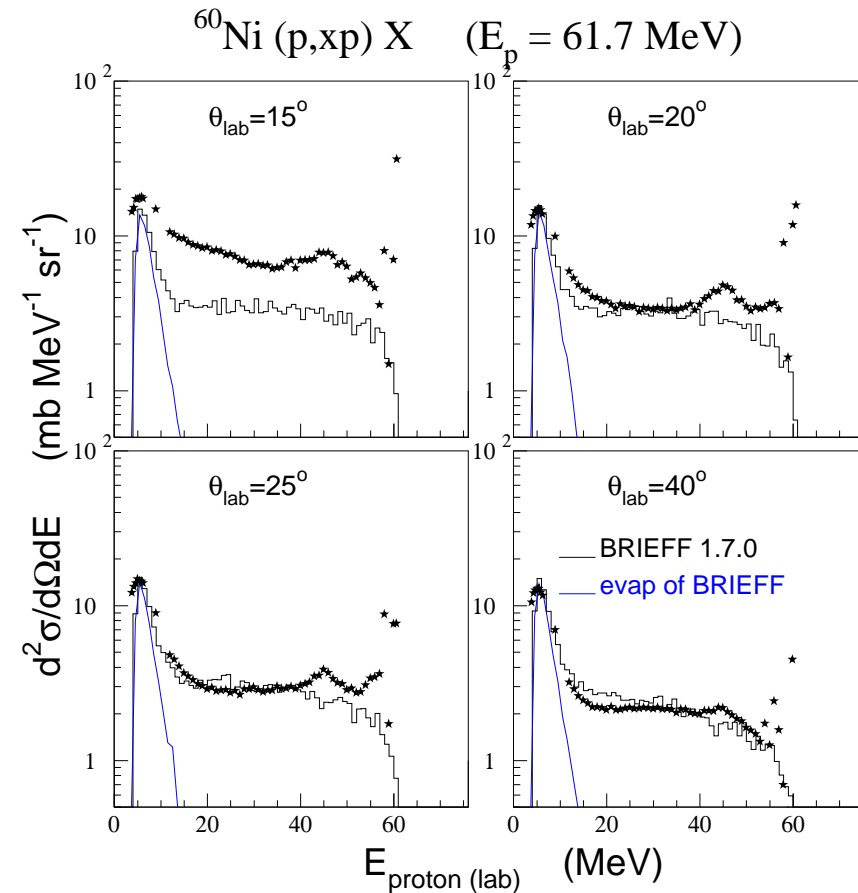
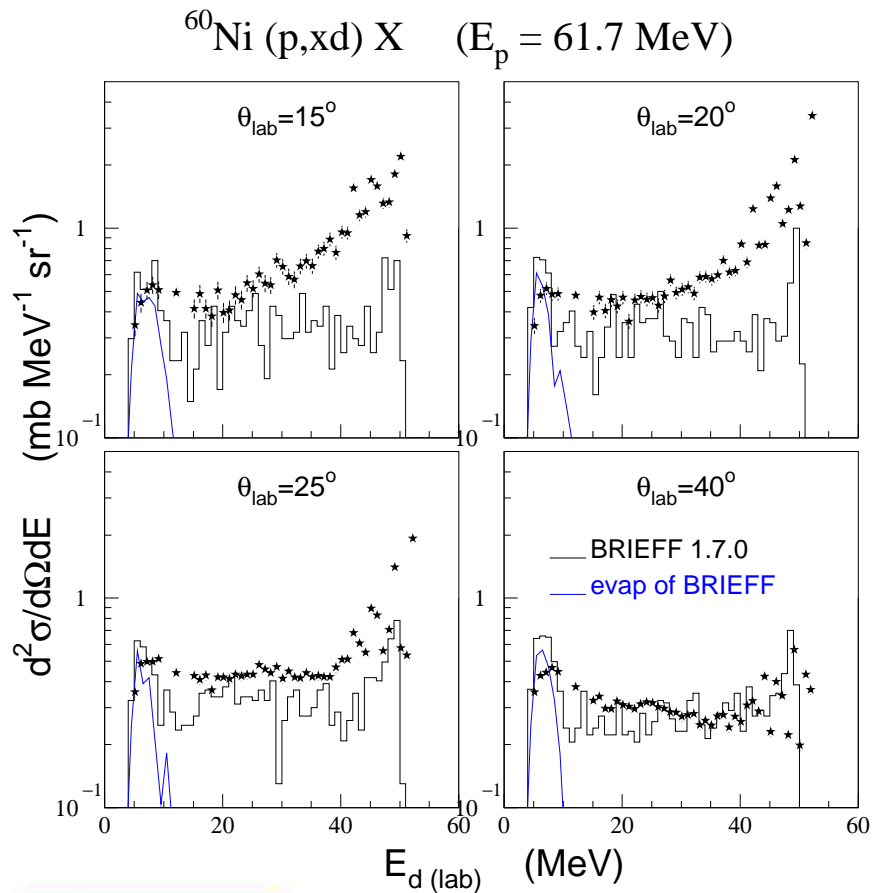
(p,xd) and (p,xp) $d^2\sigma/dE d\Omega$ 175 MeV



Data : (p,xd) B. Piskor-Ignatowicz et al., EXFOR D058003
(p,xp) v. Richter et al., Phys.Rev. C46, 1030 (1992)



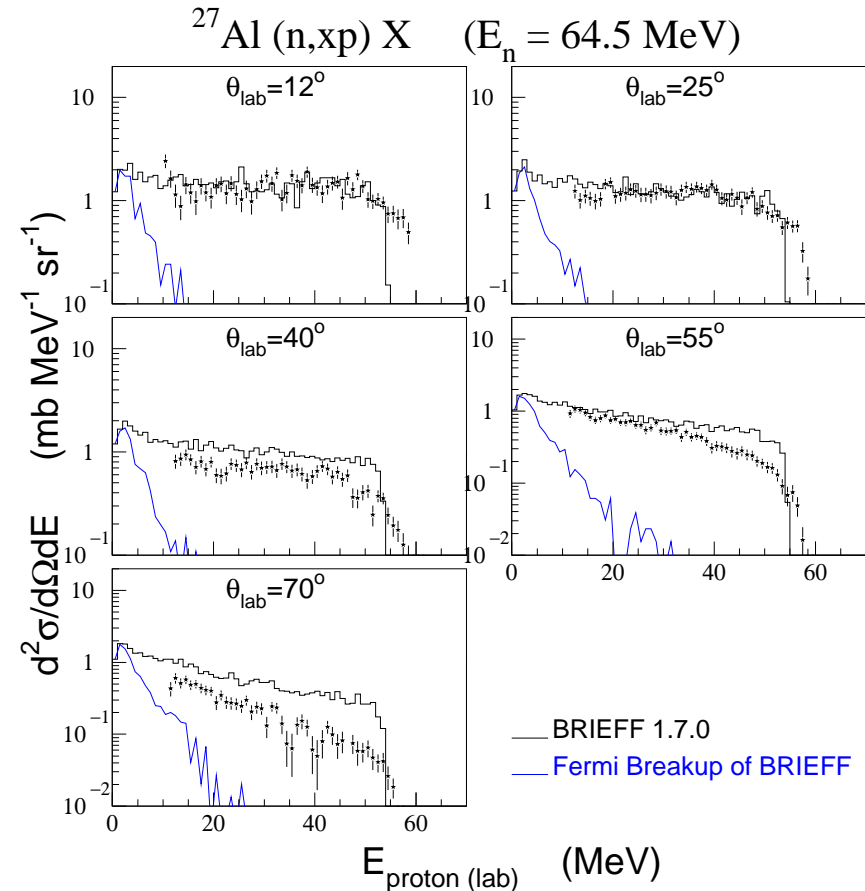
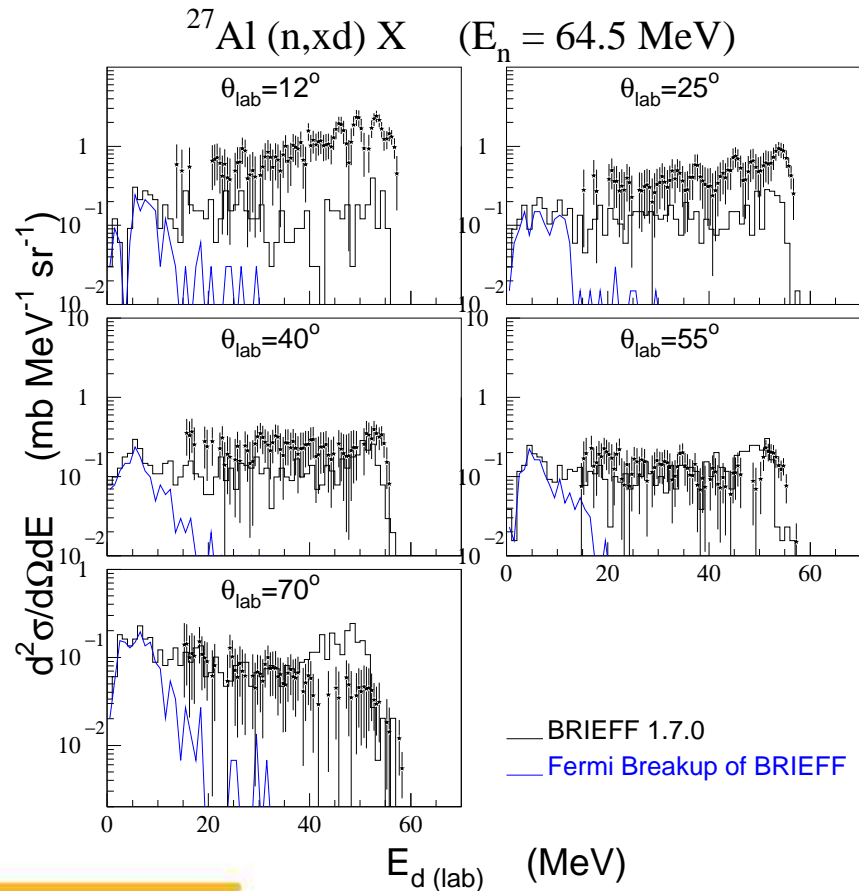
(p,xd) and (p,xp) $d^2\sigma/dE d\Omega$ 61.7 MeV



Data : F.E. Bertrand and R.W. Peele, Phys. Rev. C 8, 1045 (1973)



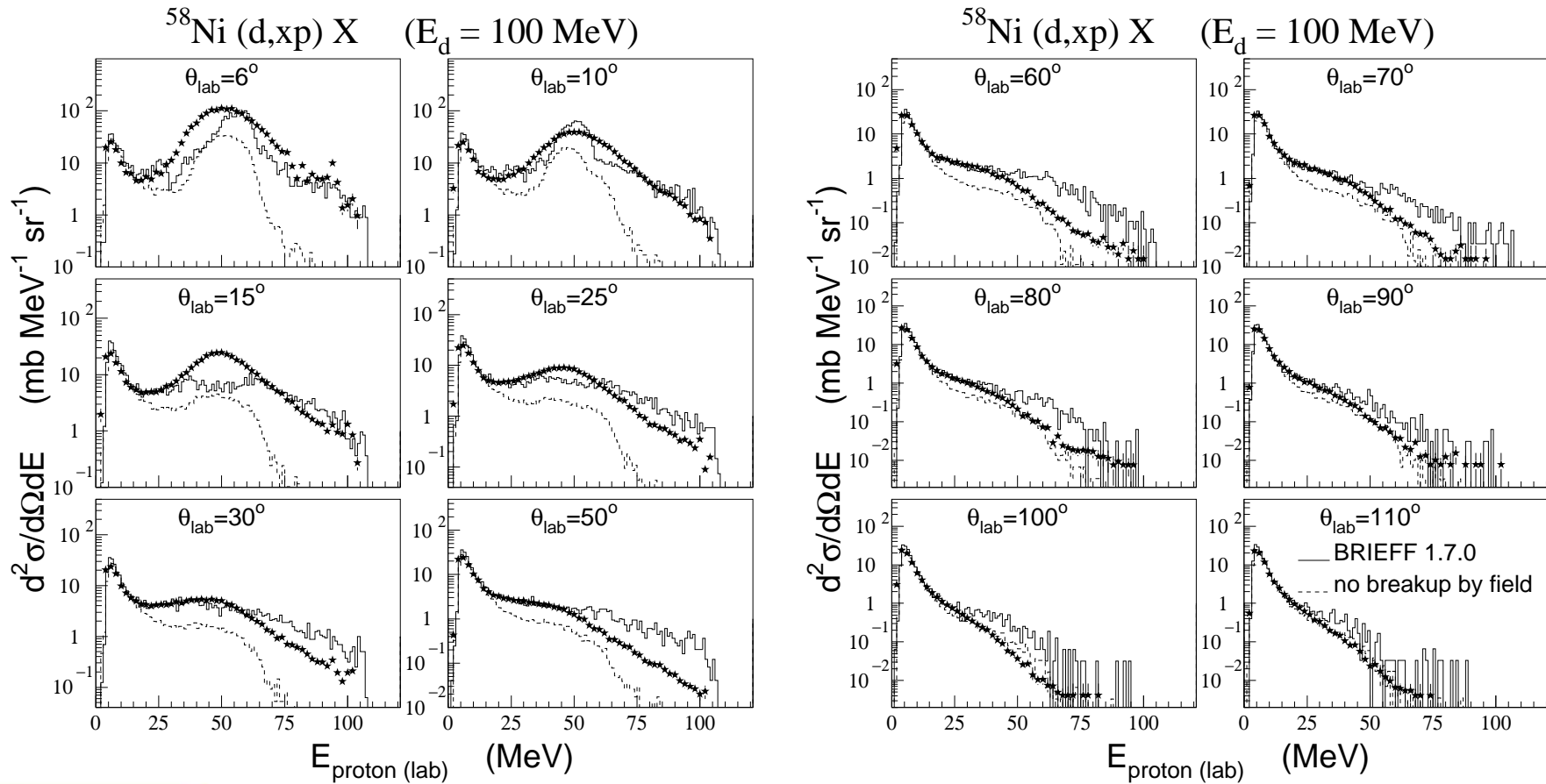
(n,xd) and (n,xp) $d^2\sigma/dE d\Omega$ 64.5 MeV



Data : Y. Nauchi et al., J. Nucl. Sci. Techno. 36, 143 (1999)



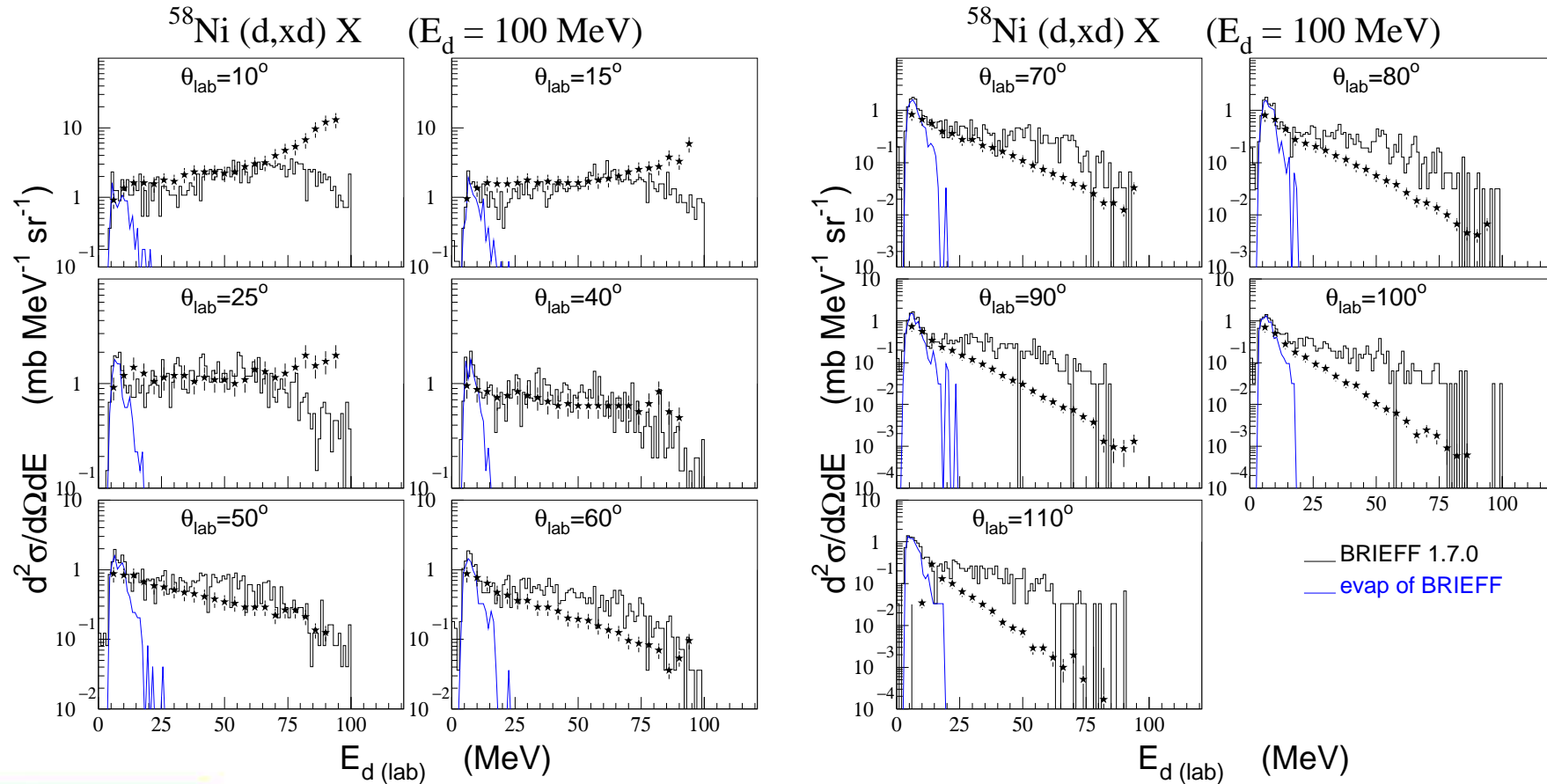
(d,xp) $d^2\sigma/dE d\Omega$ 100 MeV



Data : D. Ridikas et al. Phys. Rev. C 63, 014610 (2000)



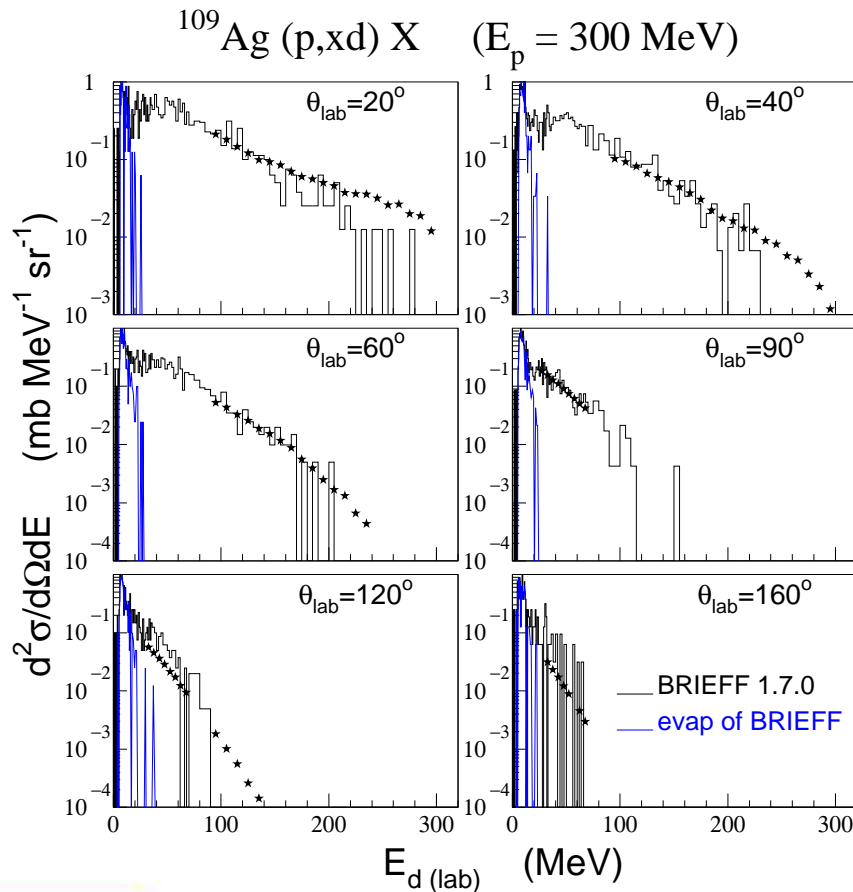
(d,xd) $d^2\sigma/dE d\Omega$ 100 MeV



Data : S.V. Förtsch et al. Proceed ND2001, J.Nucl.Sci.Tech. supp 2, pp 792-794 (2002)



(p,xd) $d^2\sigma/dE d\Omega$ 300 MeV



With formation by quasi-free coalescence only

$N + N \rightarrow d + \pi$ not yet included
in INC collision term since

double counting is possible :

$N_1 + N_2 \rightarrow N_3 + \Delta$

$\Delta \rightarrow N_4 + \pi$

if conditions on N_3 and N_4 fulfilled

$N_3 + N_4 \rightarrow d^{(qf)}$

$\sigma_{\text{prod } d}^{(\text{INC})} = 151 \text{ mb}$ $\sigma_{\text{prod } d}^{(\text{evap})} = 66 \text{ mb}$



Data : R.E.L. Green et al. Phys. Rev. C 35, 1341 (1987)

Summary

- Deuteron induced reactions and deuteron production in N- and d-induced reactions are now taken into account in the Intra Nuclear Cascade BRIC (and the reaction code BRIEFF)
 - Breakup in deuteron induced reaction is very sensitive to nuclear+Coulomb potential and to the (r,p) distribution of its nucleons.
 - (N,xd) and (d,xd') in continuum is the result of the competition between deuteron breakup and deuteron formation (they can occur at any time of the INC and any position of deuteron or p-n pair)



Summary

- Preliminary results of (p,xd) and (d,xd) are promising but need improvements
- Current limits:
 - Cut-off in (r^* , p^*) distribution of nucleon of deuteron in its c.m. ($p^* < 600$ MeV/c, $r^* < 6$ fm)
 - No pickup process (ex: (d,t) ...; it should be partly included in the formation process of other ions)
- However next developments can also change results



Next developments

- Developments to get the emission of other light-mass ions (t, ^3He , α -particle) are under way
 - In an approach consistent with light-mass ion induced reactions (with same in-medium motion, ion breakup by collision and potential, *ion-N and ion-ion in-medium scattering* ...)
- Reactions induced by heavier light ions (Li, Be, B, C...)



Thank you for your attention!

