Compound nuclear reaction mechanisms of light composite particles

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with lots of help from

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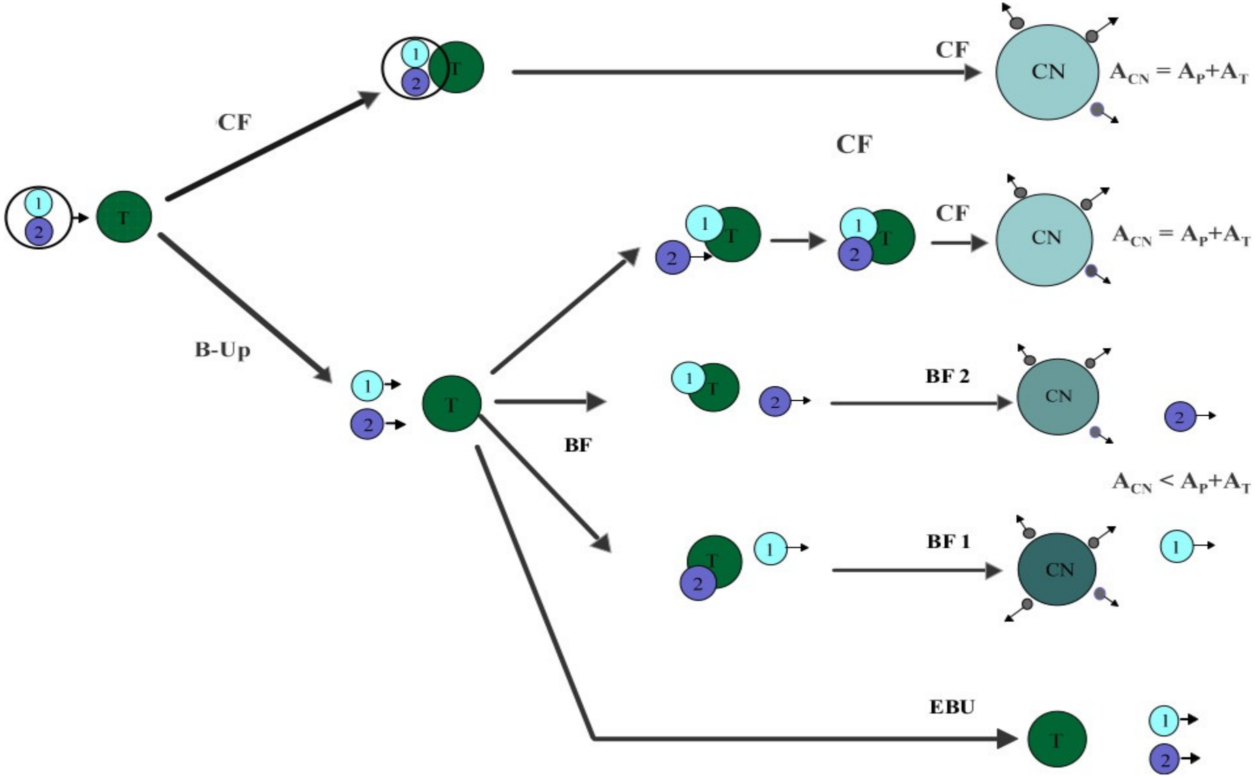
Breakup and stripping reactions

$$\sigma_{reac} = \sigma_{bu} + \sigma_{bf,n} + \sigma_{bf,p} + \sigma_{cf}$$



L.F. Canto, P.R.S. Gomes, R. Donangelo, M.S. Hussein, Phys. Rep. **424** (2006) 1.

The IAV formalism

The inclusive proton breakup cross section

$$\frac{d^2\sigma}{d\Omega_p dE_p} = \frac{d^2\sigma^{EBU}}{d\Omega_p dE_p} + \frac{d^2\sigma^{NEB}}{d\Omega_p dE_p}$$

is the sum of the elastic breakup cross section (EBU),

$$\frac{d^2\sigma^{EBU}}{d\Omega_p dE_p} = \frac{2\pi}{\hbar v_d}\rho_p(E_p)\int \left|T(\vec{k}_p,\vec{k}_n;\vec{k}_d)\right|^2 \delta(E_d+\varepsilon_d-E_p-E_n)d\vec{k}_n$$

defined in terms of the post-form DWBA matrix element,

$$T(\vec{k}_p,\vec{k}_n;\vec{k}_d) = \left\langle \tilde{\chi}_p^{(-)}(\vec{k}_p,\vec{r}_p)\tilde{\chi}_n^{(-)}(\vec{k}_n,\vec{r}_n)\left|v_{np}(\vec{r})\right|\chi_d^{(+)}(\vec{k}_d,\vec{R})\phi_d(\vec{r})\right\rangle$$

The IAV formalism

and the nonelastic breakup cross section (NEB or BF,p),

$$\frac{d^2\sigma^{NEB}}{d\Omega_p dE_p} = -\frac{2}{\hbar v_d}\rho_b(E_B)\left\langle \Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\middle| W_n(\vec{r}_n)\middle|\Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle$$

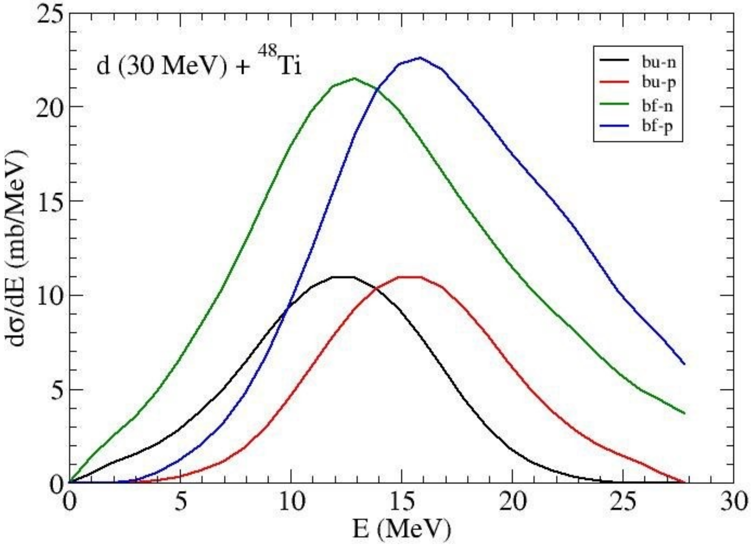
which can be interpreted as the generalized absorption cross section of the breakup neutron,

$$\left|\Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle = \left(\tilde{\chi}_p^{(-)}(\vec{k}_p,\vec{r}_p)G_n^{(+)}(\vec{r}_n,\vec{r}_n^{\,\prime})\,|v_{pn}(\vec{r})|\,\chi_d^{(+)}(\vec{k}_d,\vec{R})\phi_d(\vec{r})\right\rangle$$

The theory is old. Systematic calculations are more recent.

M. Ichimura, N. Austern, and C. M. Vincent, Phys. Rev. C 32, 431 (1985).
N. Austern, Y. Iseri, M. Kamimura, M. Kawai, G. Rawitscher, M. Yahiro, Phys. Rep. 154, 125 (1987).
Jin Lei and A. M. Moro, Phys. Rev. C 92, 044616 (2015).
B. V. Carlson, R. Capote, M. Sin, Few-Body Syst. 57, 307 (2016).
G. Potel et al, Eur. Phys. J. A 53, 178 (2017).
F. Torabi and B. V. Carlson, J. Phys. G 50, 045107 (2023).

Spectra



$$E_{n,peak} \approx \frac{1}{2}\left(E_d - \frac{Ze^2}{R_{bu}} - \varepsilon_d\right)$$

$$E_{p,peak} \approx \frac{1}{2}\left(E_d + \frac{Ze^2}{R_{bu}} - \varepsilon_d\right)$$

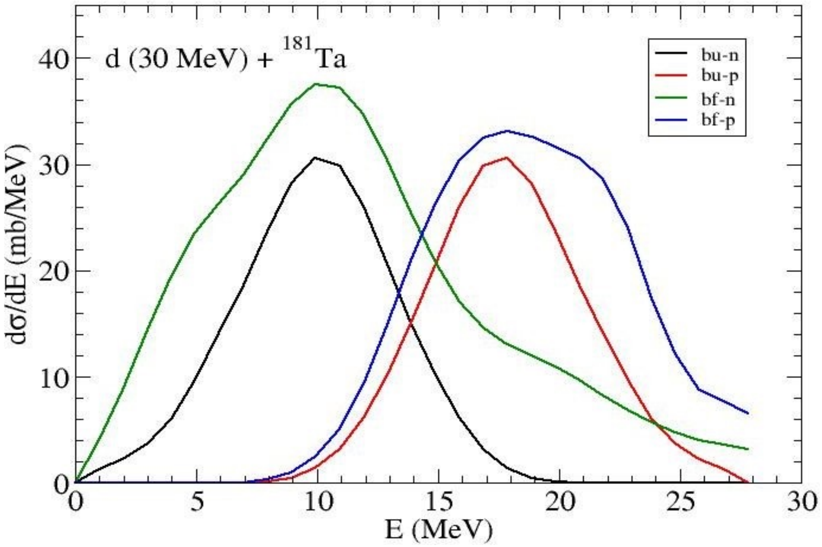
$$R_{int} \approx 1.25(A^{1/3} + 2^{1/3})\ \mathrm{fm}$$

Ti:

$$R_{bu} \approx 10.6\ \mathrm{fm} \quad R_{int} \approx 6.0\ \mathrm{fm}$$

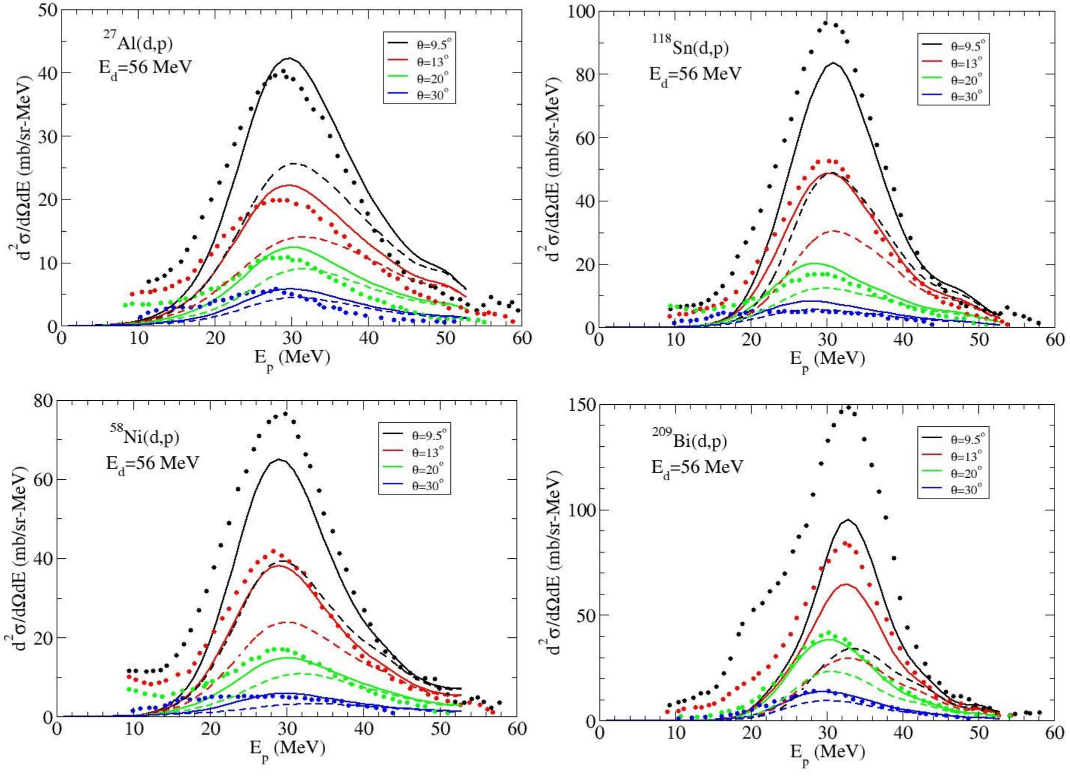
Ta:

$$R_{bu} \approx 14.6\ \mathrm{fm} \quad R_{int} \approx 8.6\ \mathrm{fm}$$



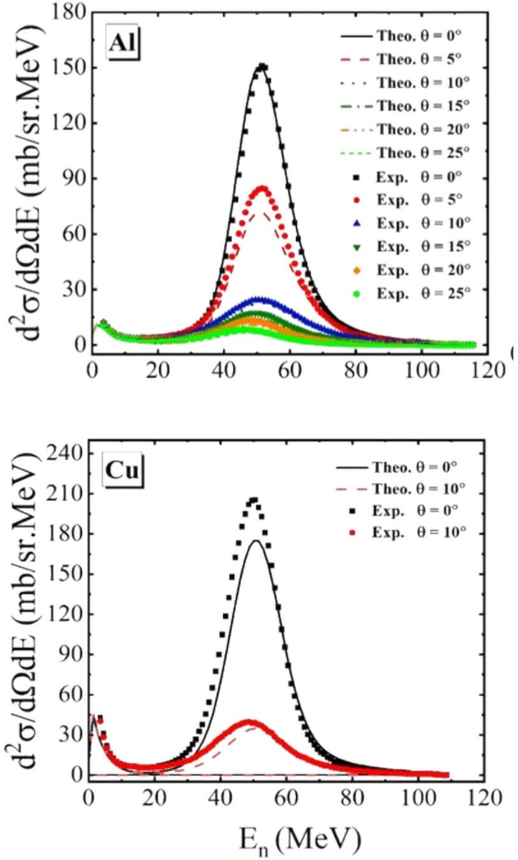
Inclusive double differential cross sections

56 MeV (d,p)



N. Matsuoka, Nucl. Phys. A 345, 1 (1980).

102 MeV (d,n)



S. Araki, Methods Phys. Res. A, 842, 62, (2017).

EMPIRE3 reaction code

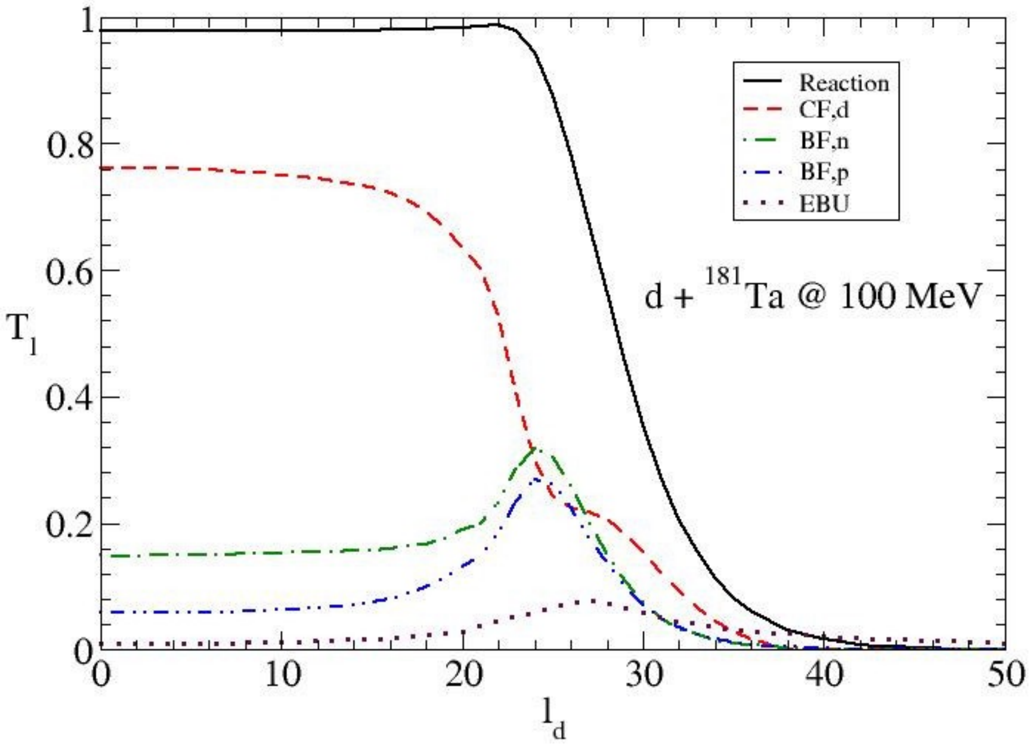
- Calculates pre-equilibrium and equilibrium emission from the compound nucleus
- Takes into account emission of γ, n, p, d, t, ^{3}He and α

- The IAV formalism is integrated into the code
- Deuteron-induced reactions form three compound nuclei

$$\begin{aligned} d + (Z, A) &\rightarrow (Z+1, A+2)^* \\ &\rightarrow (Z+1, A+1)^* + n \\ &\rightarrow (Z, A+1)^* \quad + p \end{aligned}$$

M. Herman et al., Nucl. Data Sheets 108, 2655 (2007).

$$\sigma_x = \frac{\pi}{k_d^2} \sum_l (2l+1)\, T_{l,x}$$



The (d,2n) reaction

Complete fusion

$$d + (Z,A) \rightarrow (Z+1,A+2)^* \\ \rightarrow (Z+1,A)+2n$$

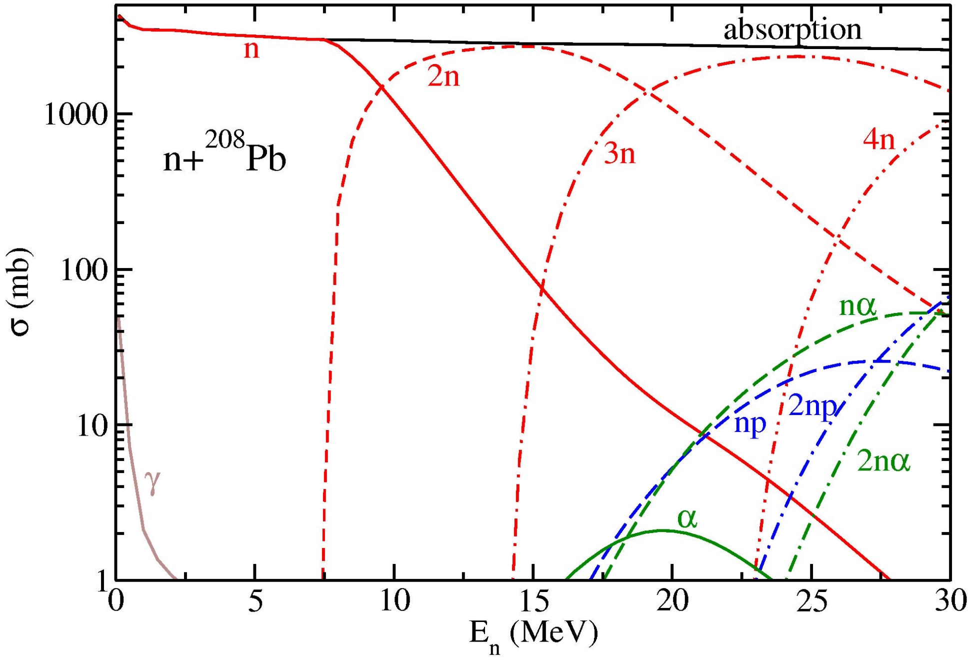
Breakup-fusion

$$d + (Z,A) \rightarrow (Z+1,A+1)^* + n \\ \rightarrow (Z+1,A)+2n$$

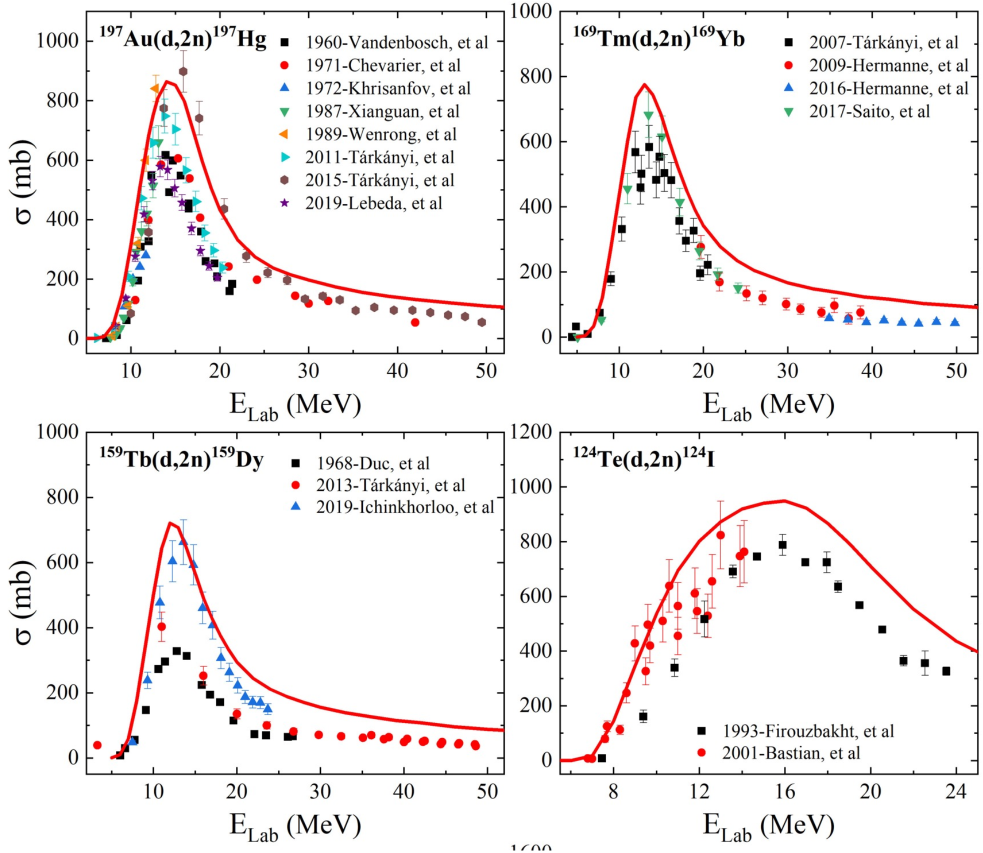
- The NEB cross section can include inelastic breakup as well as breakup fusion
- How important is the inelastic breakup (IBU)?

- Look at heavy nuclei, where charged particle emission is suppressed.

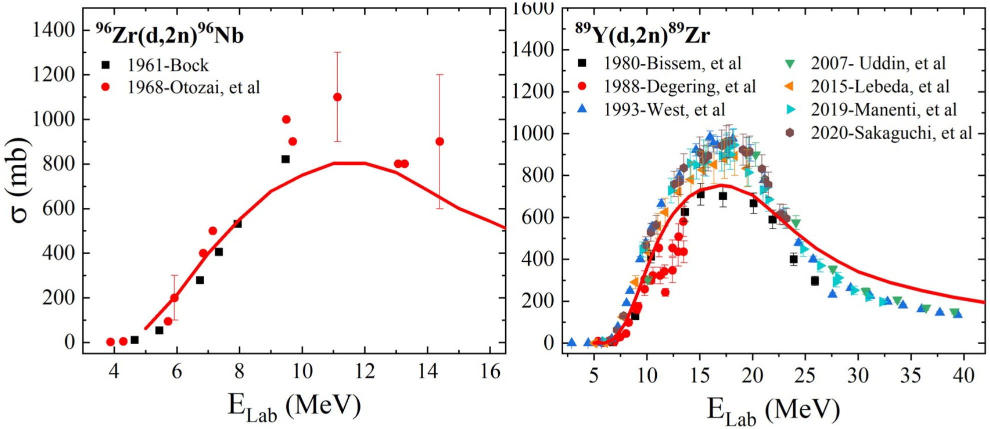
- Only neutrons are emitted.



(d,2n) activation cross sections



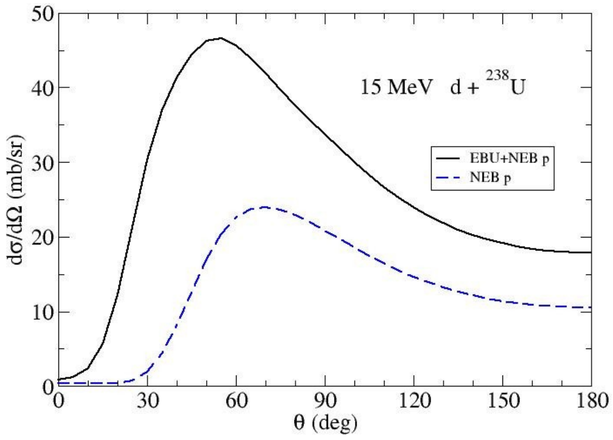
β_2	DD-ME2	FRDM	Sk-HFB	Exptl
^{89}Y	0.000	0.035	0.000	-
^{96}Zr	0.254	0.217	-0.220	0.080
^{124}Te	0.217	0.208	0.260	0.183
^{159}Tb	0.322	0.271	0.350	-
^{168}Tm	0.346	0.295	0.360	-
^{197}Au	-0.131	-0.130	-0.140	-
^{238}U	0.276	0.215	0.270	0.278

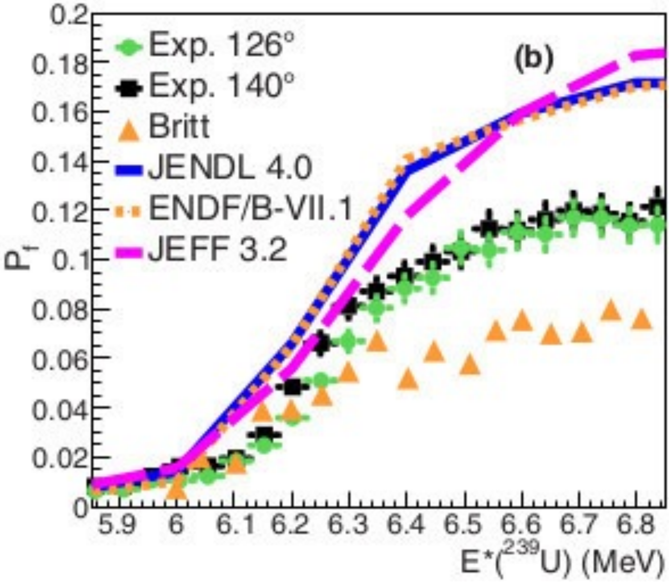


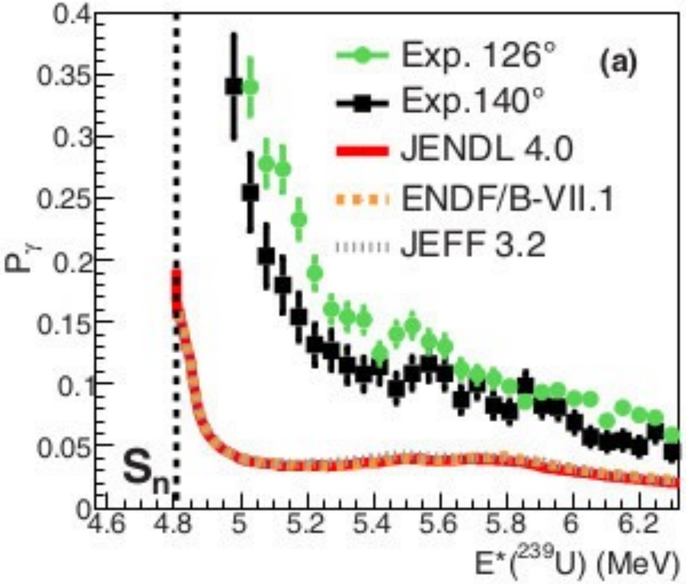
Experimental data taken from the EXFOR library.

Exclusive (d,pg) and (d,pf)

$$P_x = \frac{N\,(x \text{ and } p)}{N\,(p)\,\varepsilon\,(x)}$$



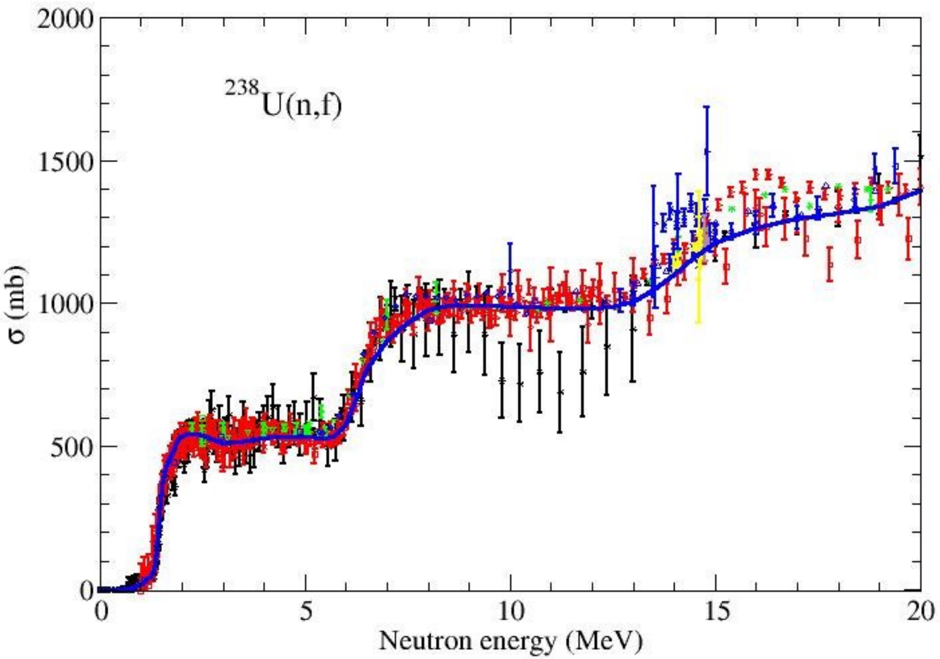




15 MeV - Q. Ducasse et al., Phys. Rev. C 94, 024614 (2016).
18 MeV - H.C. Britt and J.D. Cramer, Phys. Rev. C 2, 1758 (1970).

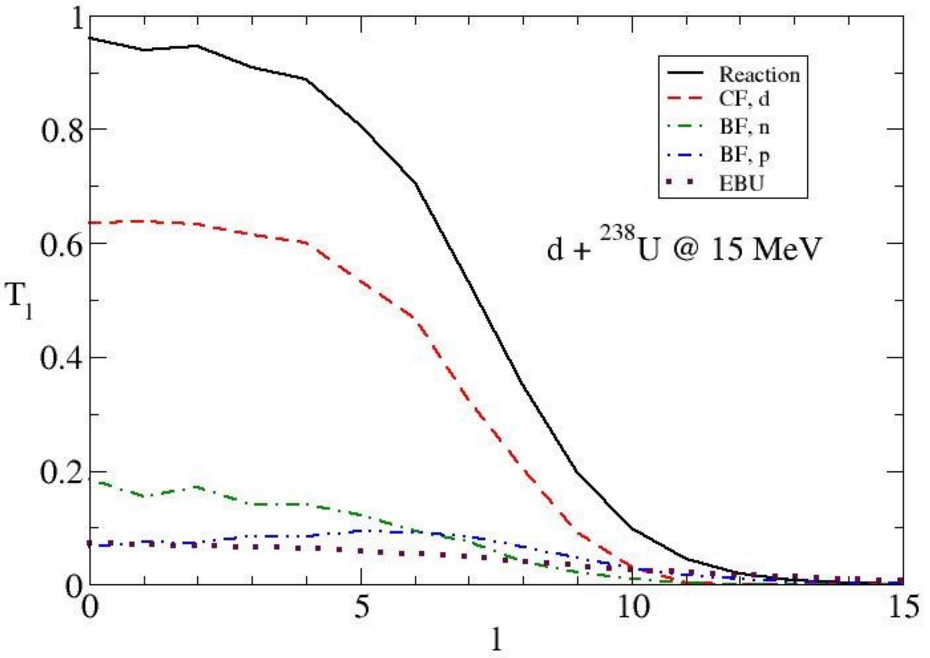
The (n,f) cross section

The fission barriers and densities of the CIELO evaluation were used to calculate the ^{238}U fission cross section.



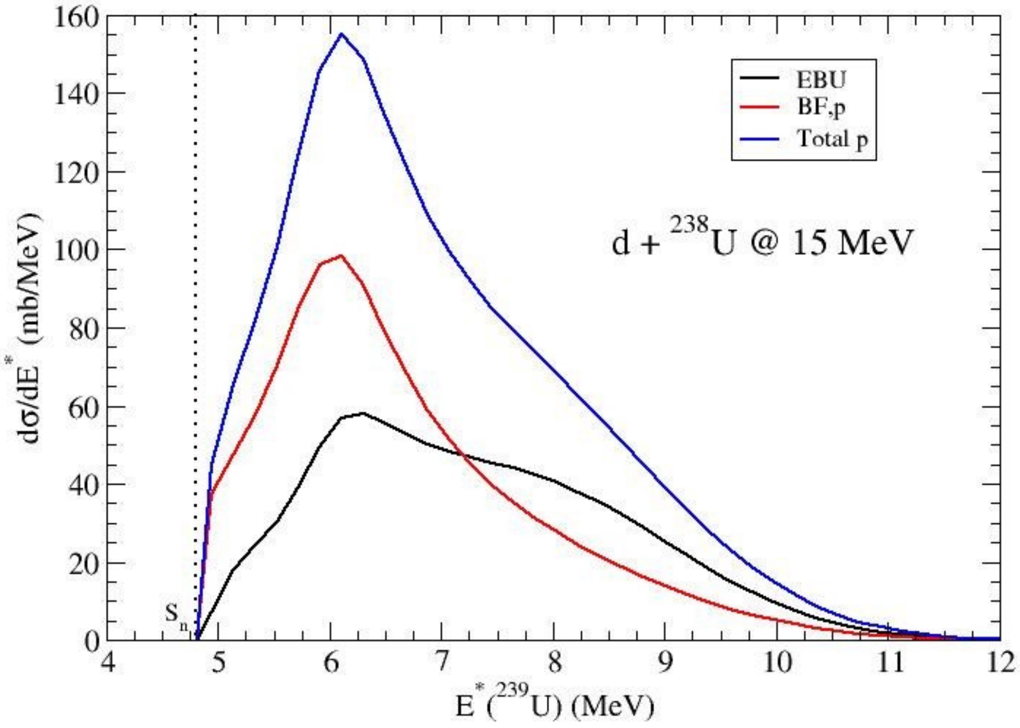
R. Capote et al., NDS 148, 254 (2018).

The ^{238}U CN (BF,p) cross section corresponds to about 10% of the total CN cross section at E = 15 MeV.

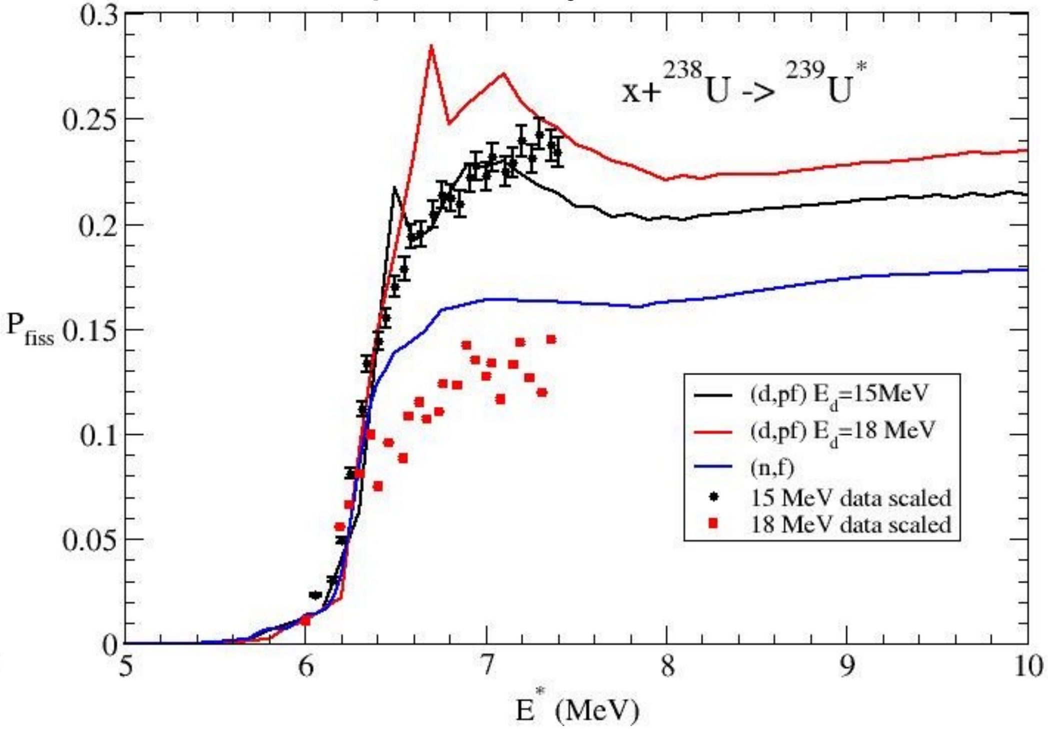


Fission probability

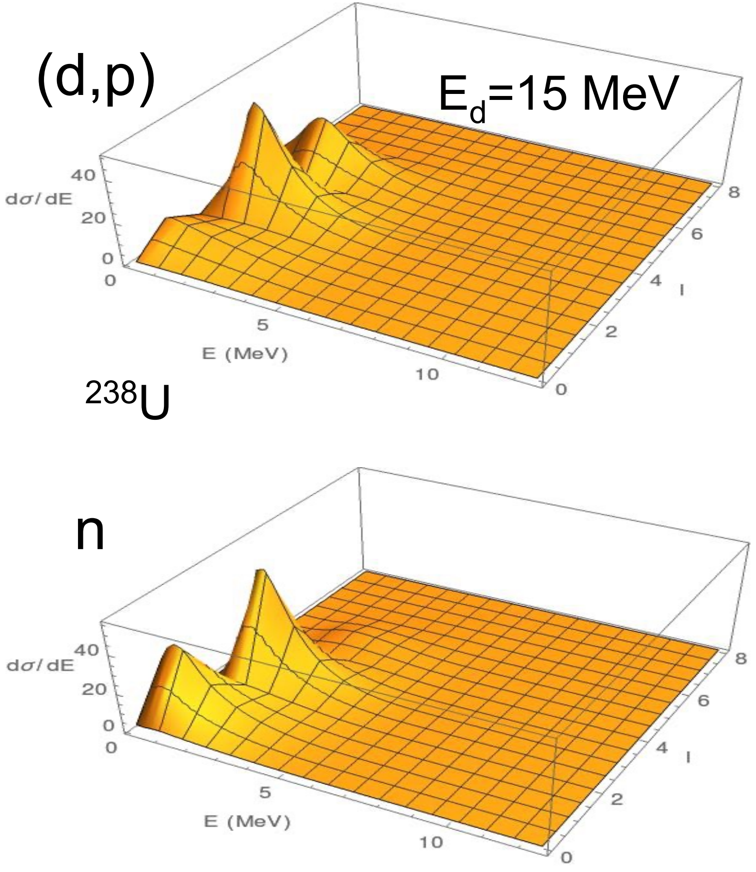
The experimental (d,pf) fission probability includes all protons – both EBU and BF,p ones in the denominator.



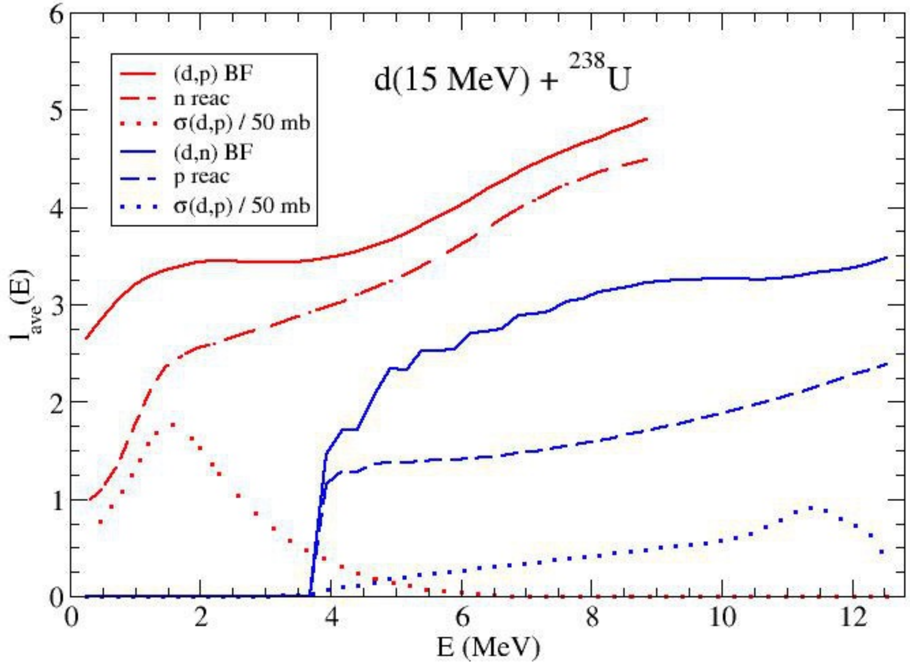
But only BF,p protons contribute to the ^{238}U excitation cross section.
The fission probability must be rescaled.



Angular momentum transfer

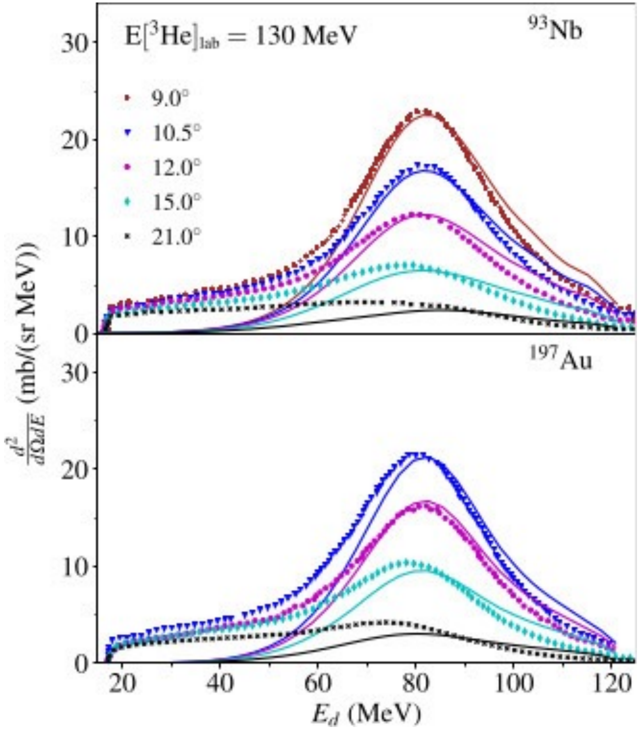


The (d,p) reaction transfers more angular momentum to the compound nucleus than the neutron-induced reaction.

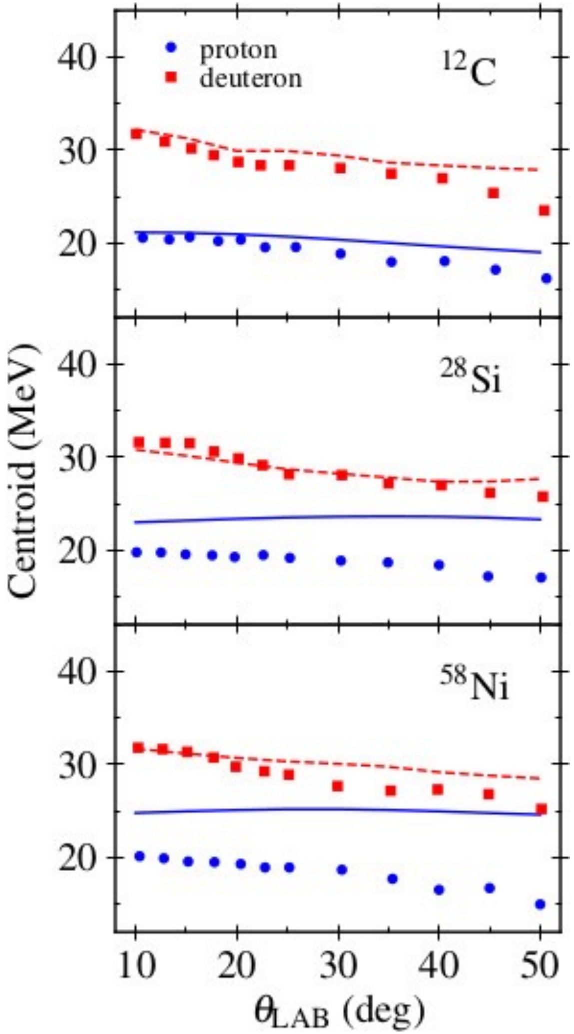


Breakup of ^{3}He

(^{3}He,d)



A. Djaloeis et al., Phys. Rev. C 27, 2389 (1983).



The (^{3}He,d) DDX's can be described reasonably well.

The (^{3}He,p) DDX's cannot.

As well as the

^{3}He → p + d

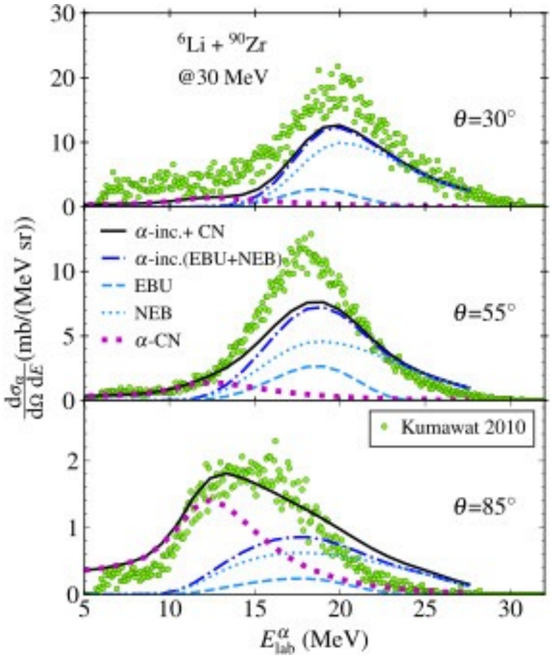
channel, the three-body breakup channel

^{3}He → p + p + n

must also be taken into account.

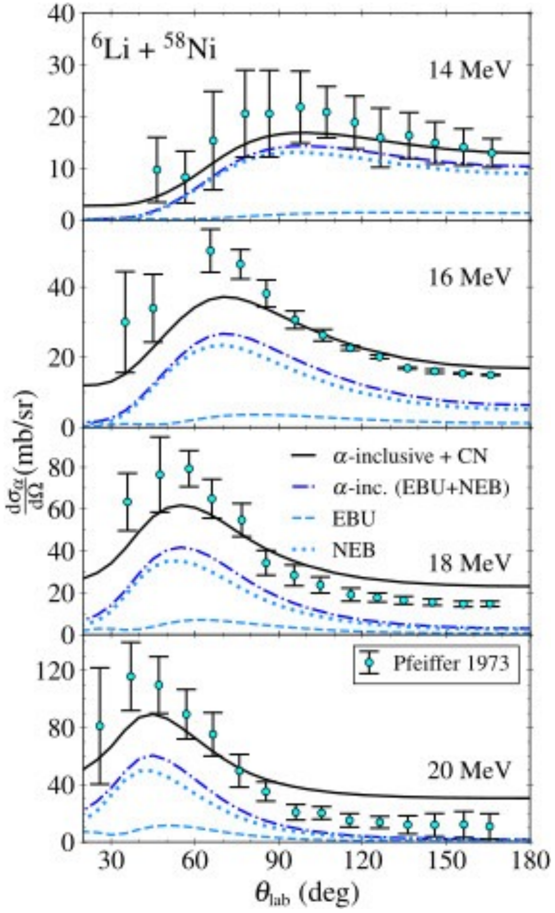
E.V. Chimanski, L.A. Souza and B.V. Carlson, Braz. J. Phys. 51, 323 (2021).

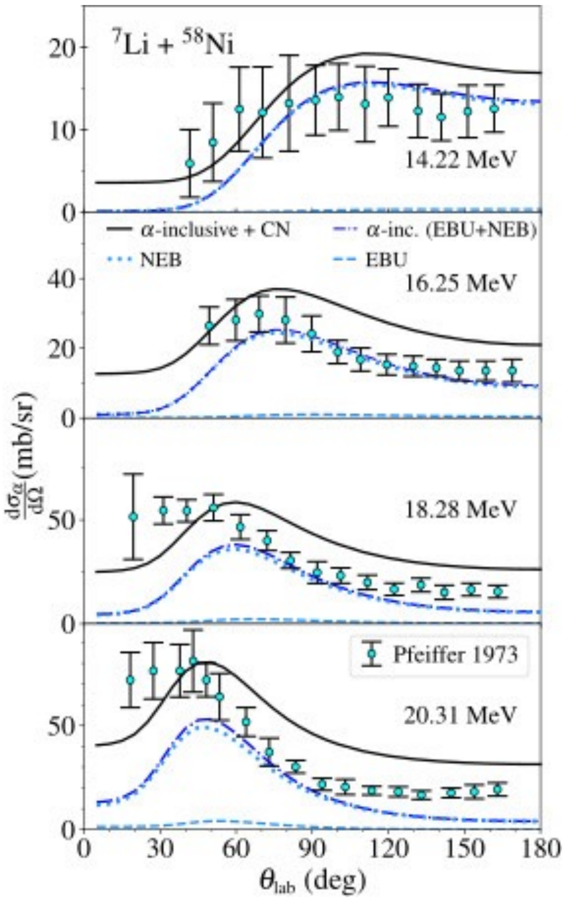
Breakup of ^{6,7}Li
α spectra



Data : H. Kumawat et al., Phys. Rev. C 81, 054601 (2010).

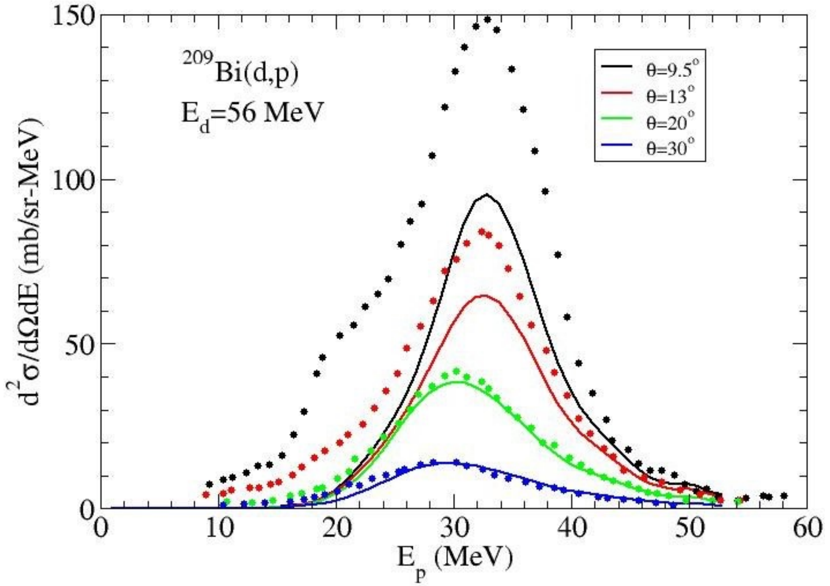
Calculations: L. A. Souza, E. V. Chimanski, B. V. Carlson, Phys. Rev. 104,034623 (2021).





Data : K. Pfeiffer, E. Speth, and K. Bethge, Nucl. Phys. A 206, 545 (1973).

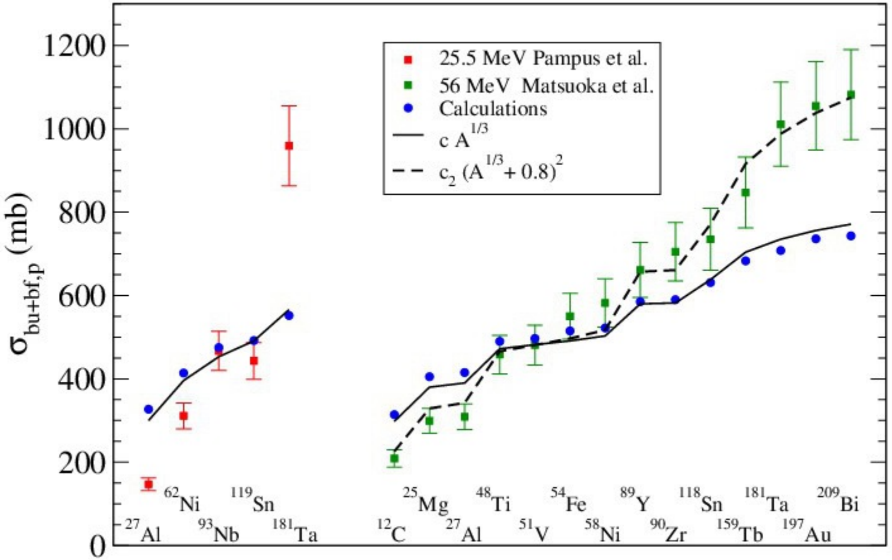
But …



Calculations show discrepancies with data that increase with target charge / mass.
Discrepancies appear in the forward angle diferential cross sections and the integrated inclusive cross sections.

Comparison with analytic expression for elastic Coulomb breakup show that this is not a long-range convergence problem.

Collective nuclear CDCC? Incoherent secondary inelastic collisions?



N. Matsuoka, Nucl. Phys. A 345, 1 (1980).

Summary

- The IAV + CN formalism provides a reasonably good description of inclusive nucleon production in deuteron-induced reactions, as well as inclusive production of tightly-bound fragments in light-ion induced reactions.
- The (d,2n) calculations show no consistent effect of collective inelastic breakup. However, energy shifts in double differential spectra suggest that secondary inelastic collisions are not negligible.
- The (d,pf) reaction illustrates the importance of the additional angular momentum transferred to the compound nucleus when compared to the neutron-induced reaction.
- The model must be extended to three-body fragmentation to describe more complex channels, such as He -> p + p + n or He -> α + n + n.
- More complete calculations (CDCC), as well as systematic calculations, and more experimental data are needed.

Thank you!

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The Coulomb breakup amplitude

The Coulomb breakup amplitude can be expressed as

$$M_C = D_0 \exp[-(\eta_d + \eta_p)/2)]\, \Gamma(1 + i\eta_d)\Gamma(1 + i\eta_p)\, I_C$$

with

$$I_C = -i\frac{d}{d\lambda}\{B(\lambda)\,{}_2F_1(-i\eta_d, -i\eta_p; 1; \zeta(\lambda))\}|_{\lambda=0}$$

where

$$B(\lambda) = B(\vec{k}_d, \vec{k}_p, \vec{k}_n; \lambda) \quad \text{and} \quad \zeta(\lambda) = \zeta(\vec{k}_d, \vec{k}_p, \vec{k}_n; \lambda)$$

With this, we can write the full elastic breakup amplitude as

$$T\left(\vec{k}_p, \vec{k}_n; k_d\hat{z}\right) = M_C + (4\pi)^2 \sum_{l_d l_p l_n} i^{l_d + l_p + l_n} \hat{l}_d \hat{l}_p \hat{l}_n \begin{pmatrix} l_d & l_p & l_n \\ 0 & 0 & 0 \end{pmatrix}$$

$$\times Y_{l_d}^{l_p l_n}\left(\hat{k}_p, \hat{k}_n\right) e^{i\sigma_d} e^{i\sigma_p} \left(T_{l_d l_p l_n} - T^0_{l_d l_p l_n}\right)$$

L. Landau, E. Lifschitz, JETP **18** (1948) 750.
G. Baur, D. Trautmann, Phys. Rep. **25** (1976) 293.