Systematics of Elastic and Inelastic Deuteron Breakup

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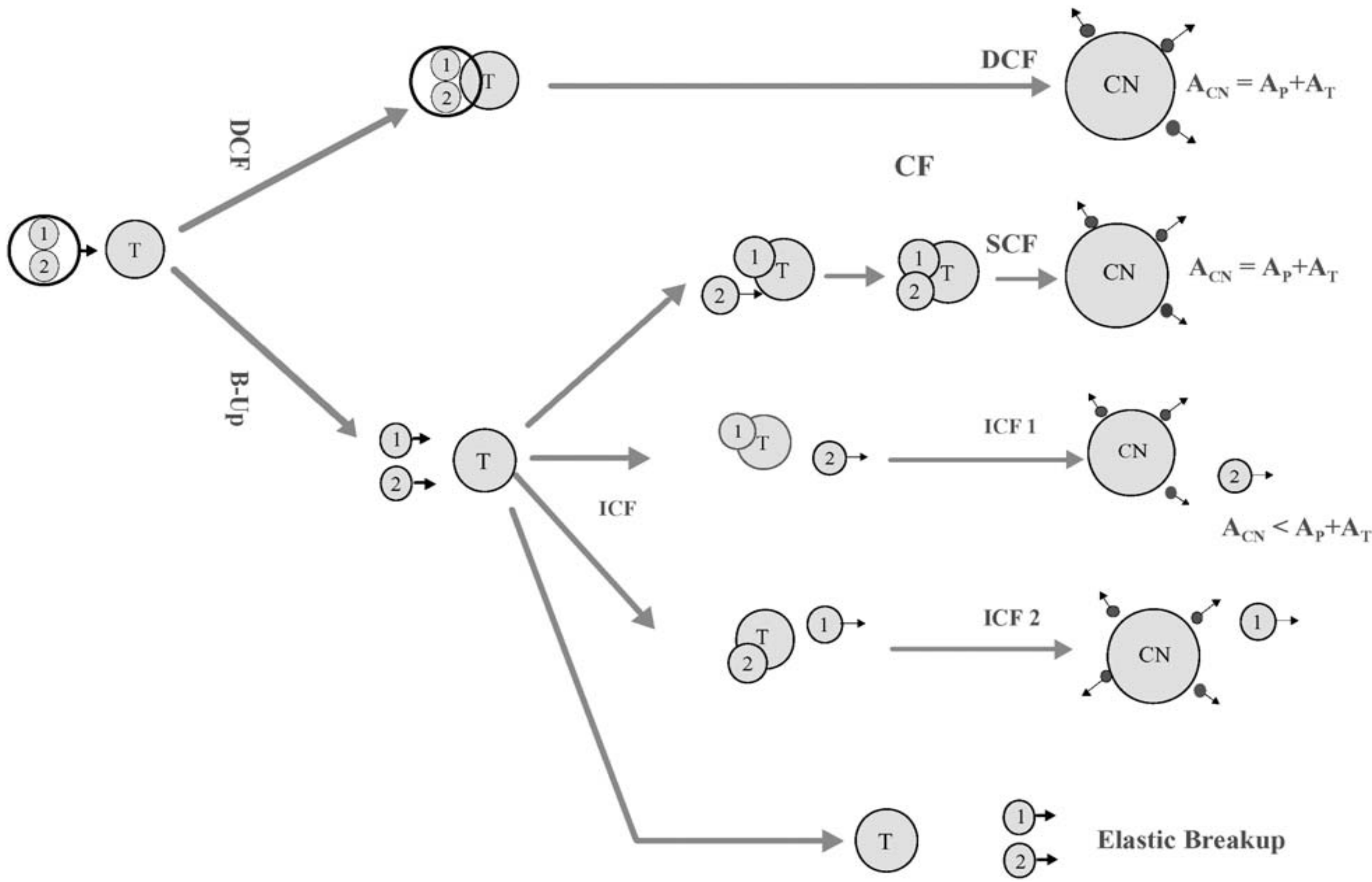
Breakup reactions

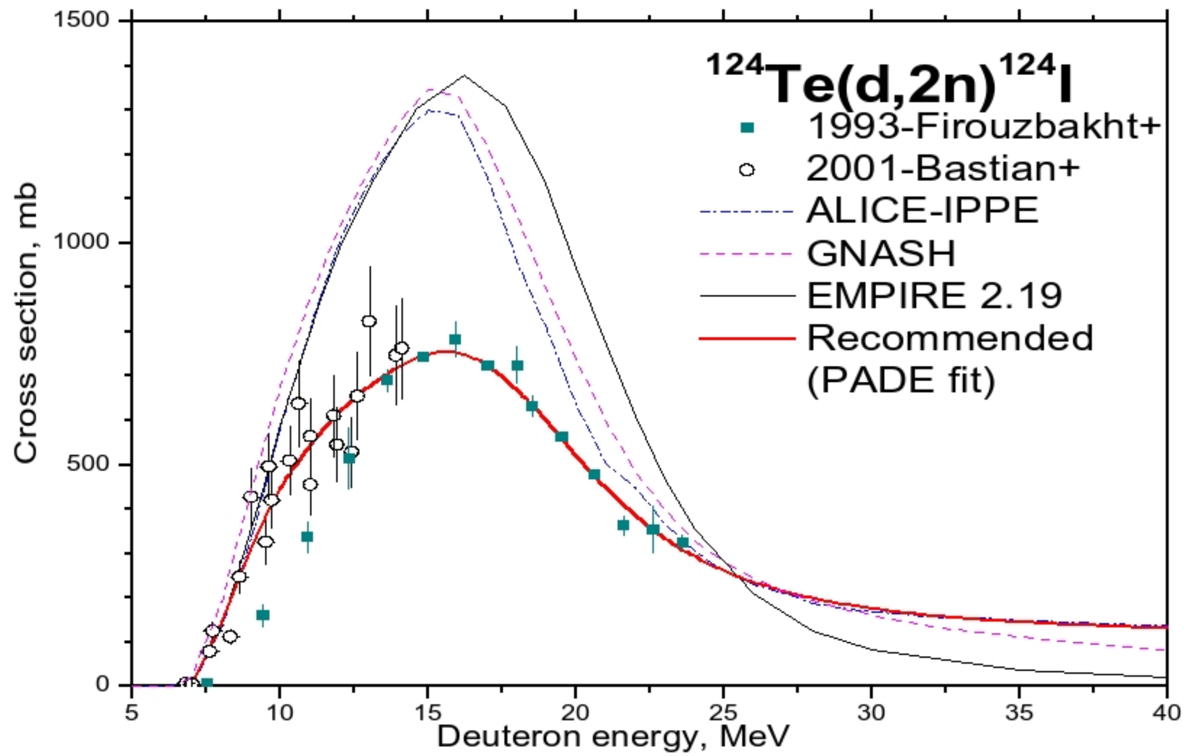
$$\sigma_{reac} = \sigma_{bu} + \sigma_{bf,n} + \sigma_{bf,p} + \sigma_{cf}$$



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

Compound nucleus formation

CN formation is overpredicted when a deuteron optical model is used to calculate absorption.



$$\sigma_{abs} = \sigma_{bf,n} + \sigma_{cf}$$

R. Capote et al., ND2007 Proceedings, (2007) 167.

Formalism – Elastic Breakup

The differential breakup cross section

$$\frac{d^6\sigma^{bu}}{dk_p^3 dk_n^3} = \frac{2\pi}{\hbar v_d}\frac{1}{(2\pi)^6}\left|T(\vec{k}_p,\vec{k}_n;\vec{k}_d)\right|^2 \delta(E_p+E_n-E_d-\varepsilon_d)$$

in the post form of the DWBA approximation is

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

We use the zero-range approximation to the amplitude

$$T(\vec{k}_p,\vec{k}_n;\vec{k}_d) \to D_0\left\langle \tilde{\psi}_p^{(-)}(\vec{k}_p,a\vec{R})\tilde{\psi}_n^{(-)}(\vec{k}_n,\vec{R})\,\middle|\,\psi_d^{(+)}(\vec{k}_d,\vec{R})\right\rangle$$

taking

$v_{np}(\vec{r})\phi_d(\vec{r}) \approx D_0\delta(\vec{r})$ with $D_0 = -125\ \mathrm{MeV\,fm}^{3/2}$

Formalism – Breakup-fusion (Inelastic breakup)

Introduce the target ground state and neutron+target states to write an inclusive differential proton cross section

$$\frac{d^3\sigma}{dk_p^3} = \frac{2\pi}{\hbar v_d}\frac{1}{(2\pi)^3}\sum_c \left|\left\langle \tilde{\psi}_p^{(-)}\psi_{nA}^c \left| v_{pn} \right| \psi_d^{(+)}\phi_d \Phi_A \right\rangle\right|^2 \delta(E_d + \varepsilon_d - E_p - E_{nA}^c)$$

Rewrite this as

$$\frac{d^3\sigma}{dk_p^3} = -\frac{2}{\hbar v_d}\frac{1}{(2\pi)^3}\mathrm{Im}\sum_c \left\langle \psi_d^{(+)}\phi_d \Phi_A \left| v_{pn} \right| \tilde{\psi}_p^{(-)}\psi_{nA}^c \right\rangle \left(E_d^+ + \varepsilon_d - E_p - E_{nA}^c\right)^{-1} \left\langle \tilde{\psi}_p^{(-)}\psi_{nA}^c \left| v_{pn} \right| \psi_d^{(+)}\phi_d \Phi_A \right\rangle$$

and associate the Φ_A expectation of the sum over states with an optical propagator

$$\frac{d^3\sigma}{dk_p^3} = -\frac{2}{\hbar v_d}\frac{1}{(2\pi)^3}\mathrm{Im}\left\langle \chi_n(\vec{r}_n) \left| G_n^{(+)}(E_d + \varepsilon_d - E_p) \right| \chi_n(\vec{r}_n) \right\rangle$$

with $\chi_n(\vec{r}_n) = \left(\tilde{\psi}_p^{(-)}(\vec{r}_p) \left| v_{pn}(\vec{r}) \right| \psi_d^{(+)}(\vec{R})\phi_d(\vec{r}) \right\rangle$

Formalism – Breakup-fusion- II

Using the identity,

$$\mathrm{Im}G_n = \left(1 + G_n^\dagger U_n^\dagger\right) \mathrm{Im}G_0 \left(1 + U_n G_n\right) + G_n^\dagger W_n G_n$$

with U_n the neutron optical potential and W_n its imaginary part, we have

$$\frac{d^3\sigma}{dk_p^3} = \frac{d^3\sigma^{bu}}{dk_p^3} + \frac{d^3\sigma^{bf}}{dk_p^3}$$

where the first term is the breakup contribution

$$\frac{d^3\sigma^{bu}}{dk_p^3} = \frac{2\pi}{\hbar v_d}\frac{1}{(2\pi)^3}\int \frac{d^3k_n}{(2\pi)^3}\left|T(\vec{k}_p,\vec{k}_n;\vec{k}_d)\right|^2 \delta(E_d + \varepsilon_d - E_p - E_n)$$

Formalism – Breakup-fusion - III

The second term is the breakup-fusion contribution

$$\frac{d^3\sigma^{bf}}{dk_p^3} = -\frac{2}{\hbar v_d}\frac{1}{(2\pi)^3}\left\langle \Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\middle| W_n(\vec{r}_n) \middle| \Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle$$

with the neutron wave function

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

We evaluate this in the zero-range approximation

$$\left|\Psi_n(\vec{k}_p,\vec{r}_n;\vec{k}_d)\right\rangle \to D_0\left(\tilde{\psi}_p^{(-)}(\vec{k}_p,a\vec{R})G_n^{(+)}\left(\vec{r}_n,\vec{R}\right)\middle|\,\psi_d^{(+)}(\vec{k}_d,\vec{R})\right\rangle$$

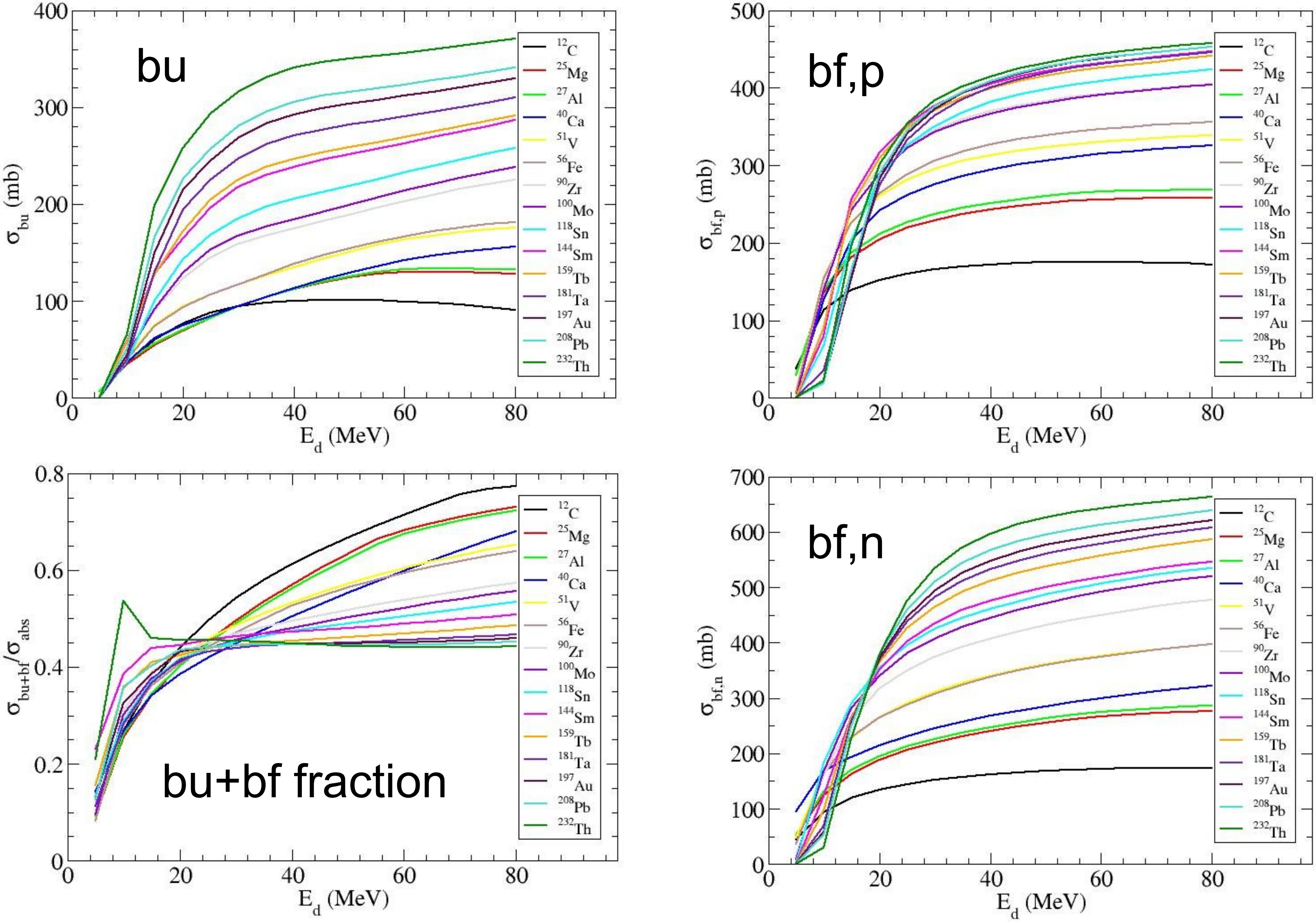
BU: G. Baur, D. Trautmann, Phys. Rep. **25** (1976) 293; G. Baur, F. Rösel, D. Trautmann, R, Shyam, Phys. Rep. **111** (1984) 333.
BF: A. Kasano, M. Ichimura, Phys. Lett. **115B** (1982) 81; N. Austern, Y. Iseri, M. Kamimura, M. Kawai, G. Rawitscher, M. Yahiro, Phys. Rep. **154** (1987) 125.

Calculations

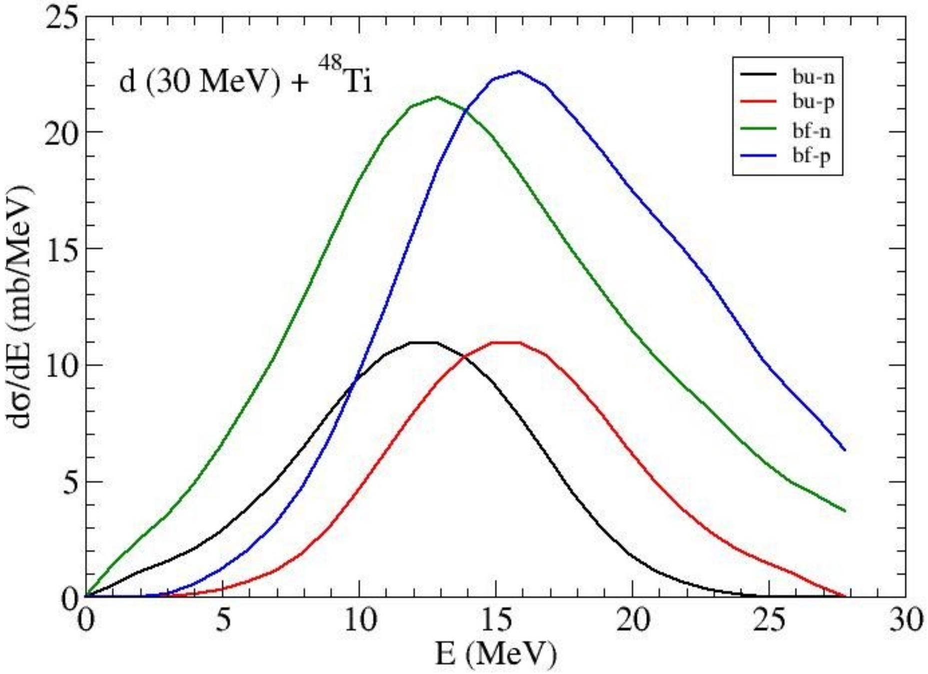
- Partial wave expansion – l_d, l_p, l_n
- Optical potentials:
  n and p : Koning-Delaroche global potentials
  d: Han potential
- Calculations performed on a grid of proton/neutron energies with optical potential parameters corresponding to each energy.
- Vincent-Fortune - complex-plane integration method to speed convergence
- No free parameters included.

A.J. Koning, J.P. Delaroche, Nucl. Phys. A **713** (2003) 231.
Y. Han, Y. Shi, Q. Shen, Phys. Rev. C **74** (2006) 044615.
C.M. Vincent, H.T. Fortune, Phys. Rev. C **2** (1970) 782.

Cross sections



Spectra



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

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

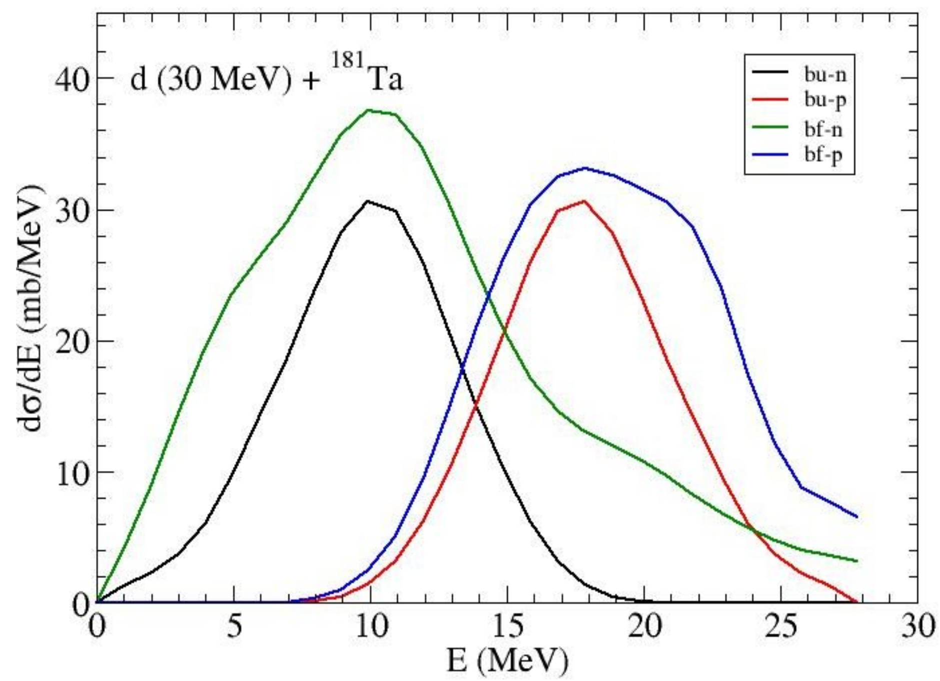
$$R_{int} \approx 1.25(A^{1/3} + 2^{1/3}) \text{ fm}$$

Ti:

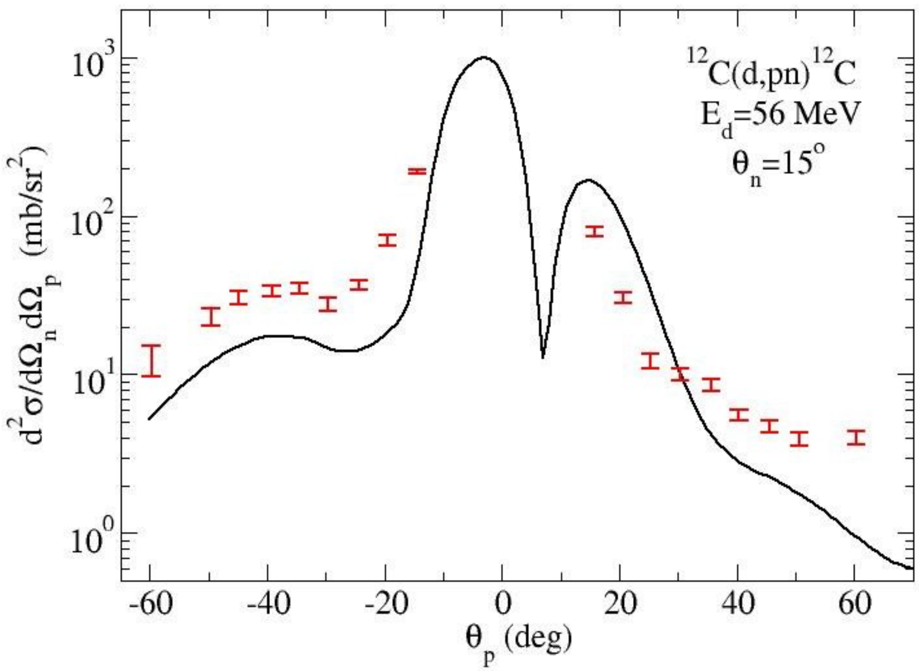
$$R_{bu} \approx 10.6 \text{ fm} \quad R_{int} \approx 6.0 \text{ fm}$$

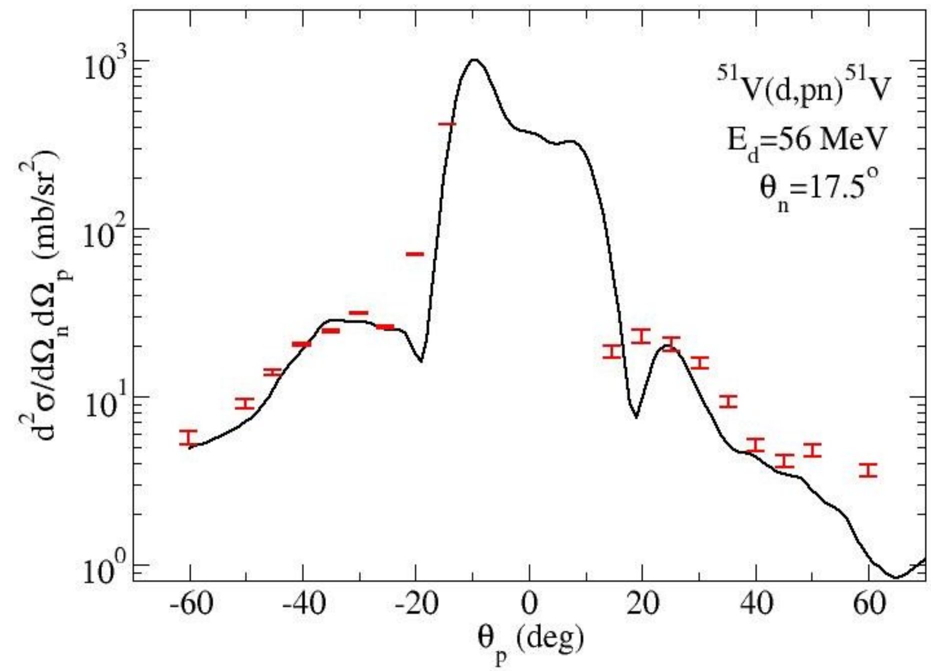
Ta:

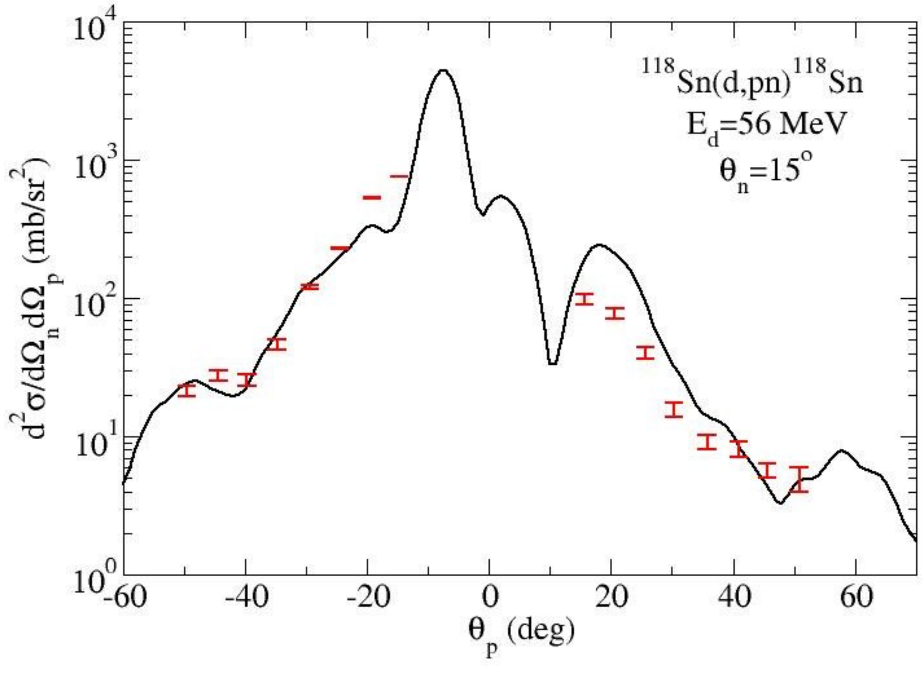
$$R_{bu} \approx 14.6 \text{ fm} \quad R_{int} \approx 8.6 \text{ fm}$$



Coincidence Angular Distributions - bu





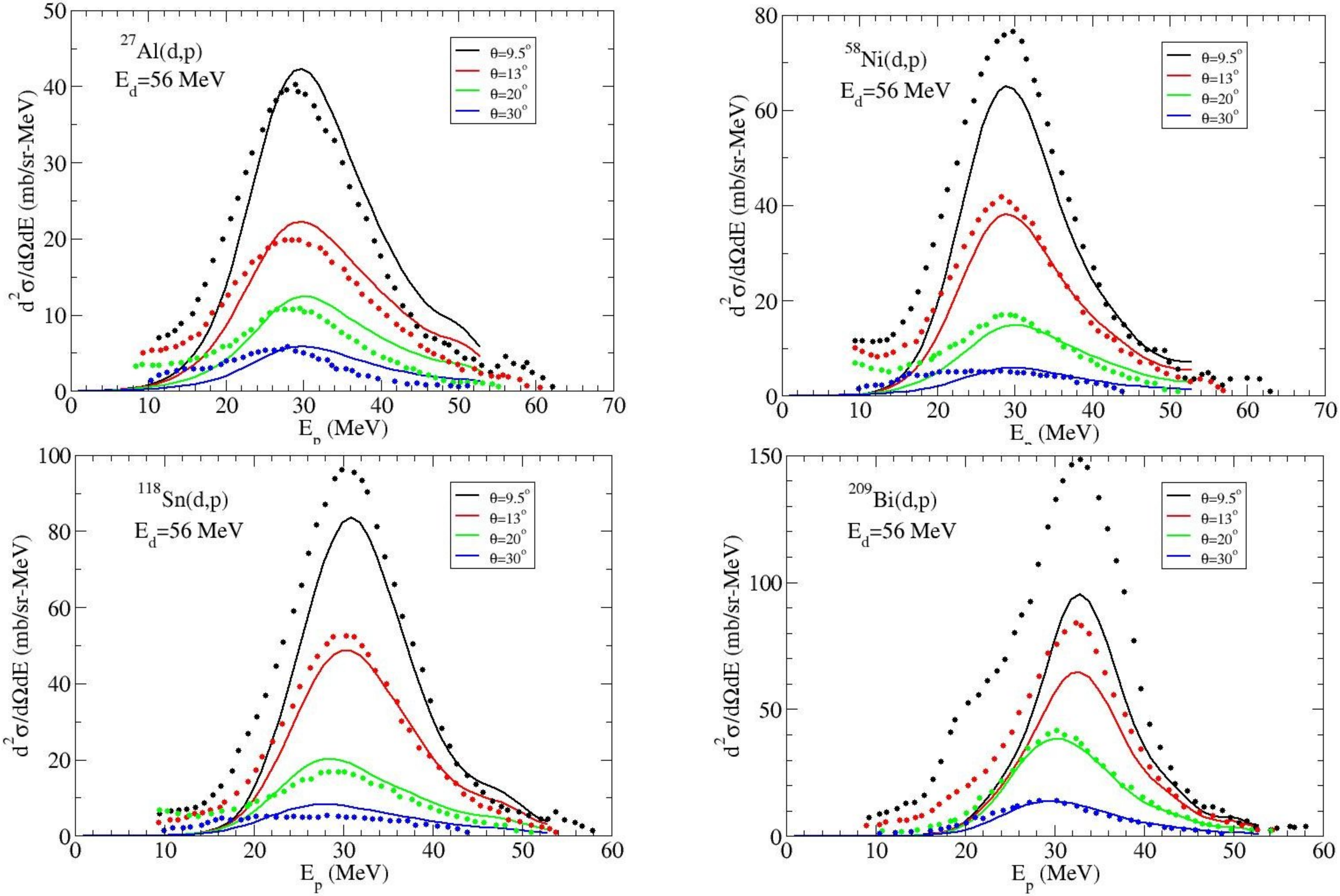


M. Matsuoka et al., Nucl. Phys. **A391** (1982) 357.

Calculations better for heavier nuclei and for non-collinear n and p (no final state interaction)

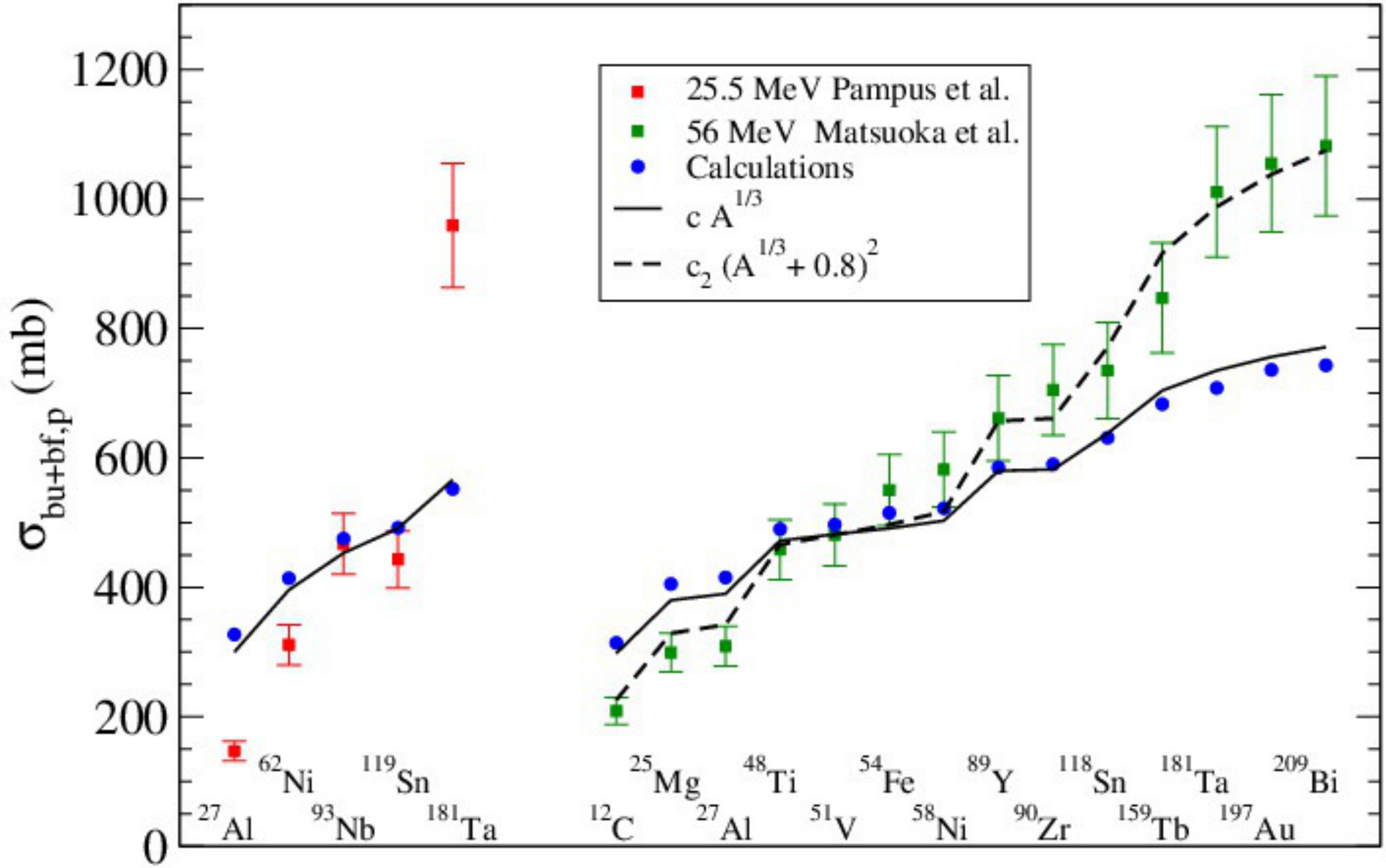
H. Okamura et al., Phys. Lett. B **325** (1994) 308; Phys. Rev. C **58** (1998) 2180.

Double Differential Spectra- bu + bf,p



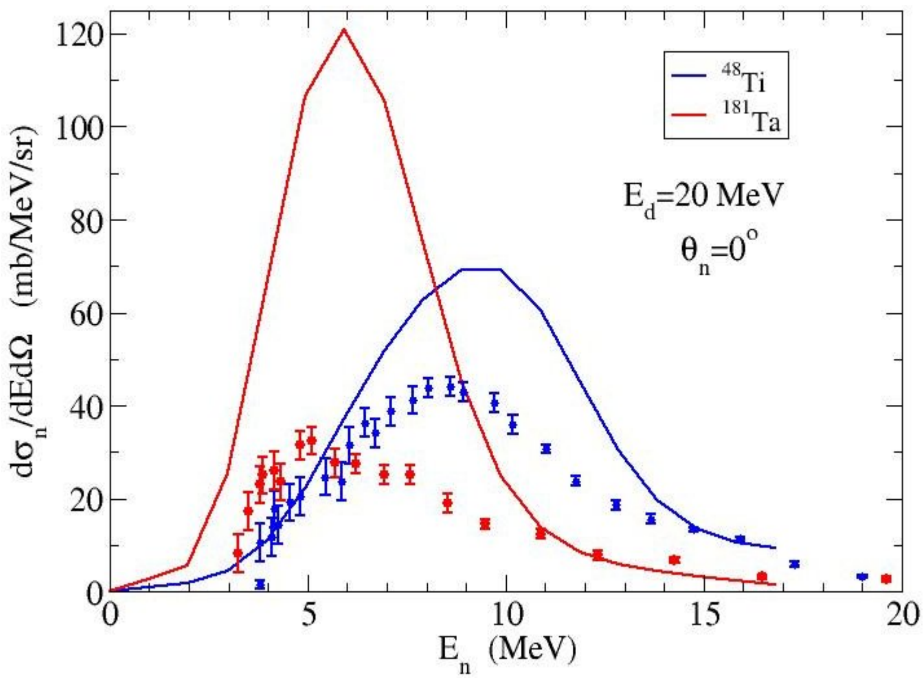
N. Matsuoka et al., Nucl. Phys. **A345** (1980) 1.

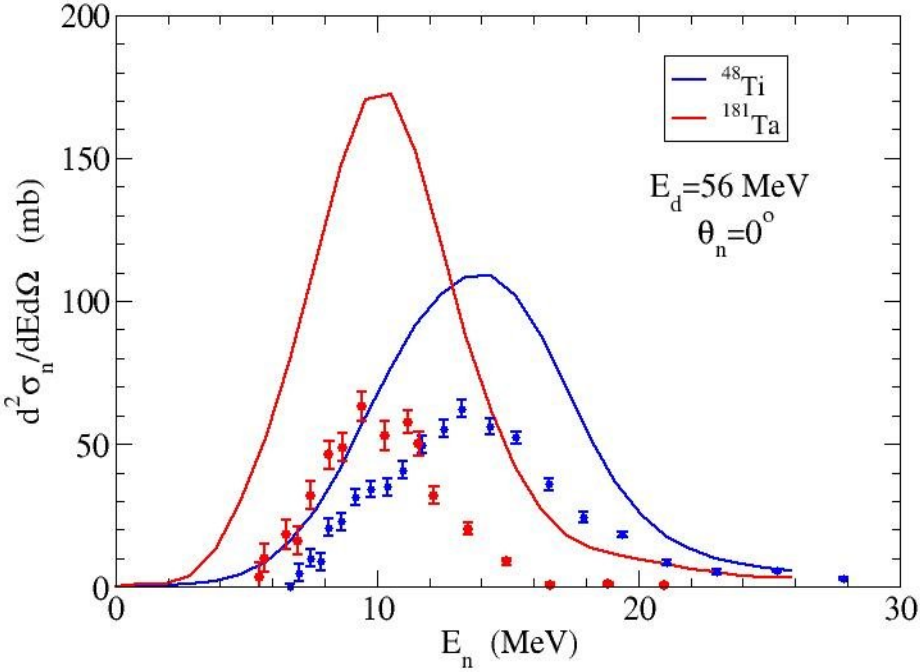
Cross sections – bu + bf,p



J. Pampus et al., Nucl. Phys. **A311** (1978) 141.
M. Matsuoka et al., Nucl. Phys. **A345** (1980) 1.

Double Differential Spectra- bu + bf,n





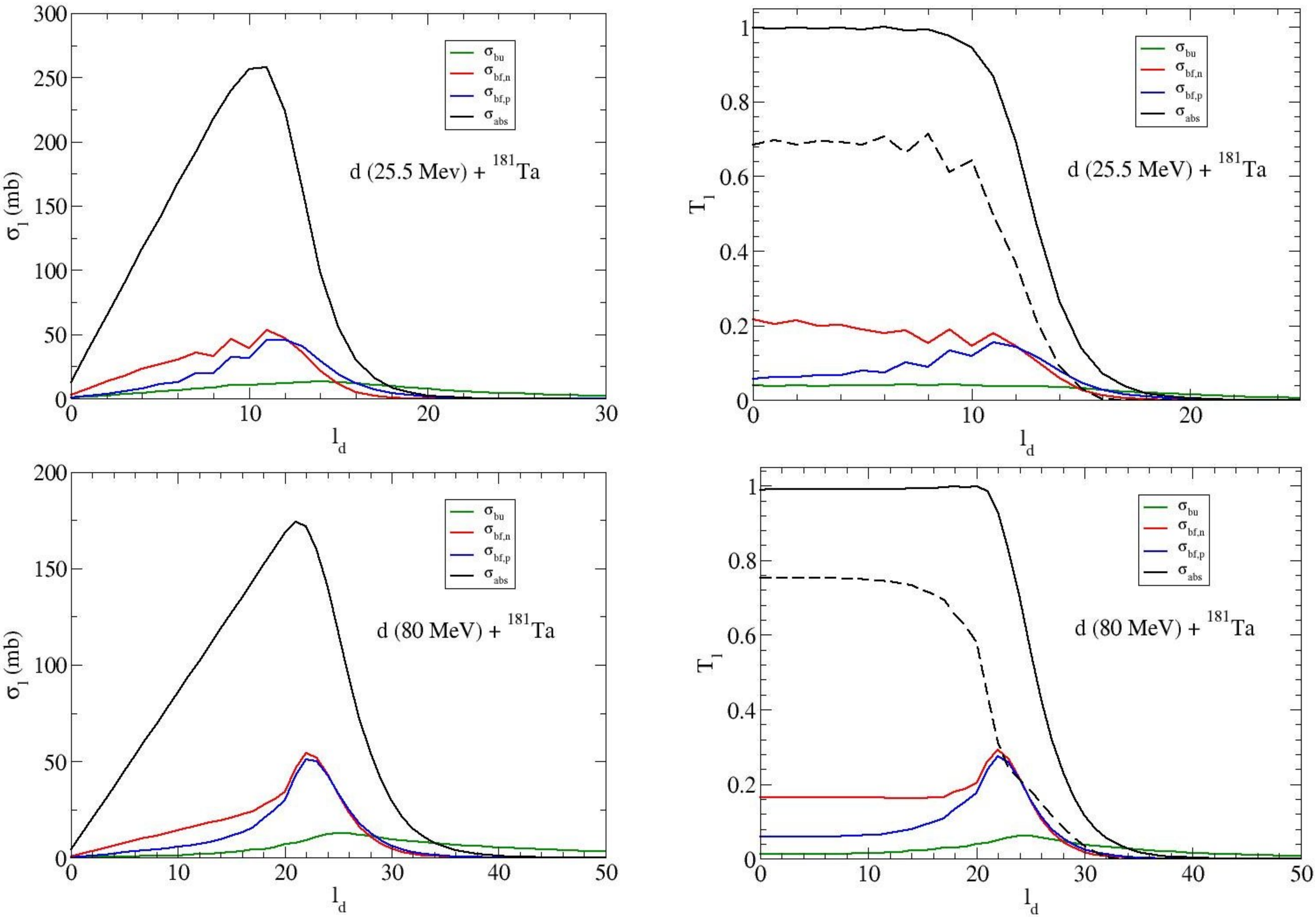
D. Bleuel et al., NIM B **261** (2007) 974.

The authors warn that the Ta spectra are suspect.

They estimate energy loss in the target as 0.4 MeV for Ti and 0.6 MeV for Ta.

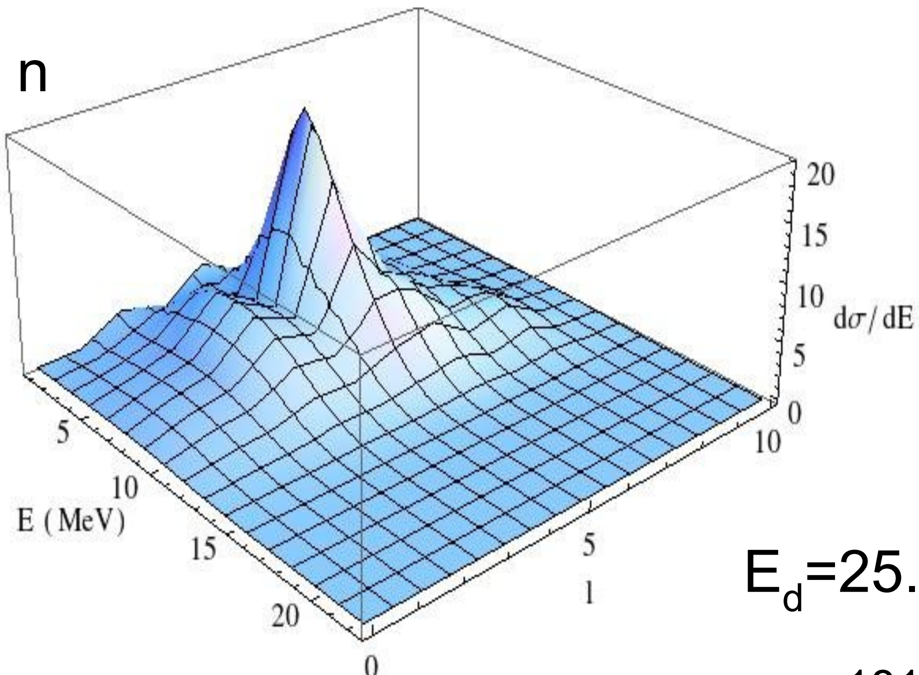
The calculations overestimate both the Ti and the Ta data.

Angular Momentum Distributions - l_d

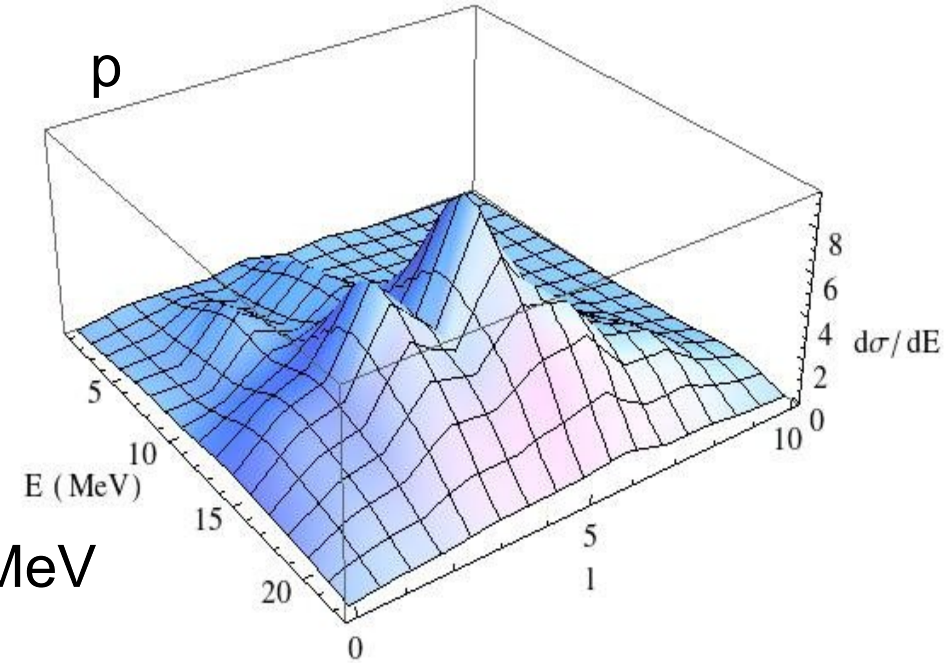


bf CN formation distributions – E_p, l_p or E_n, l_n

n



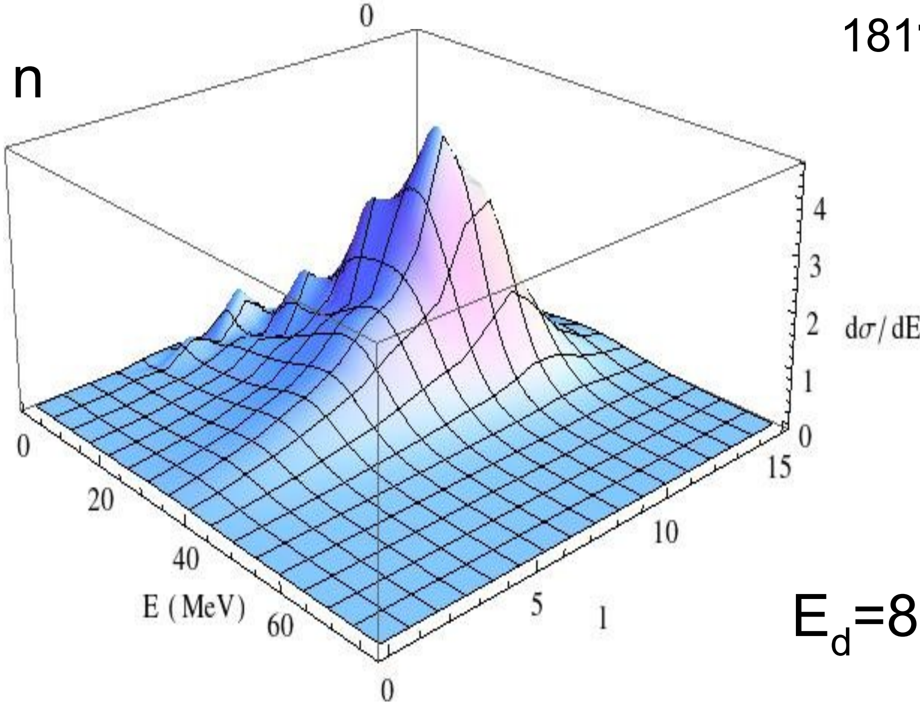
p



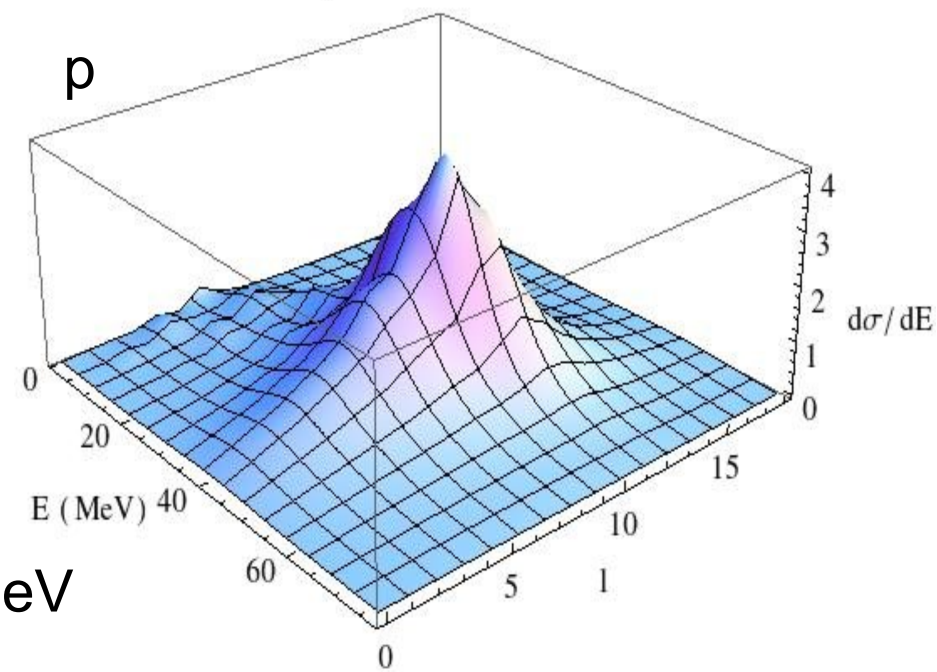
E_d=25.5 MeV

^{181}Ta

n

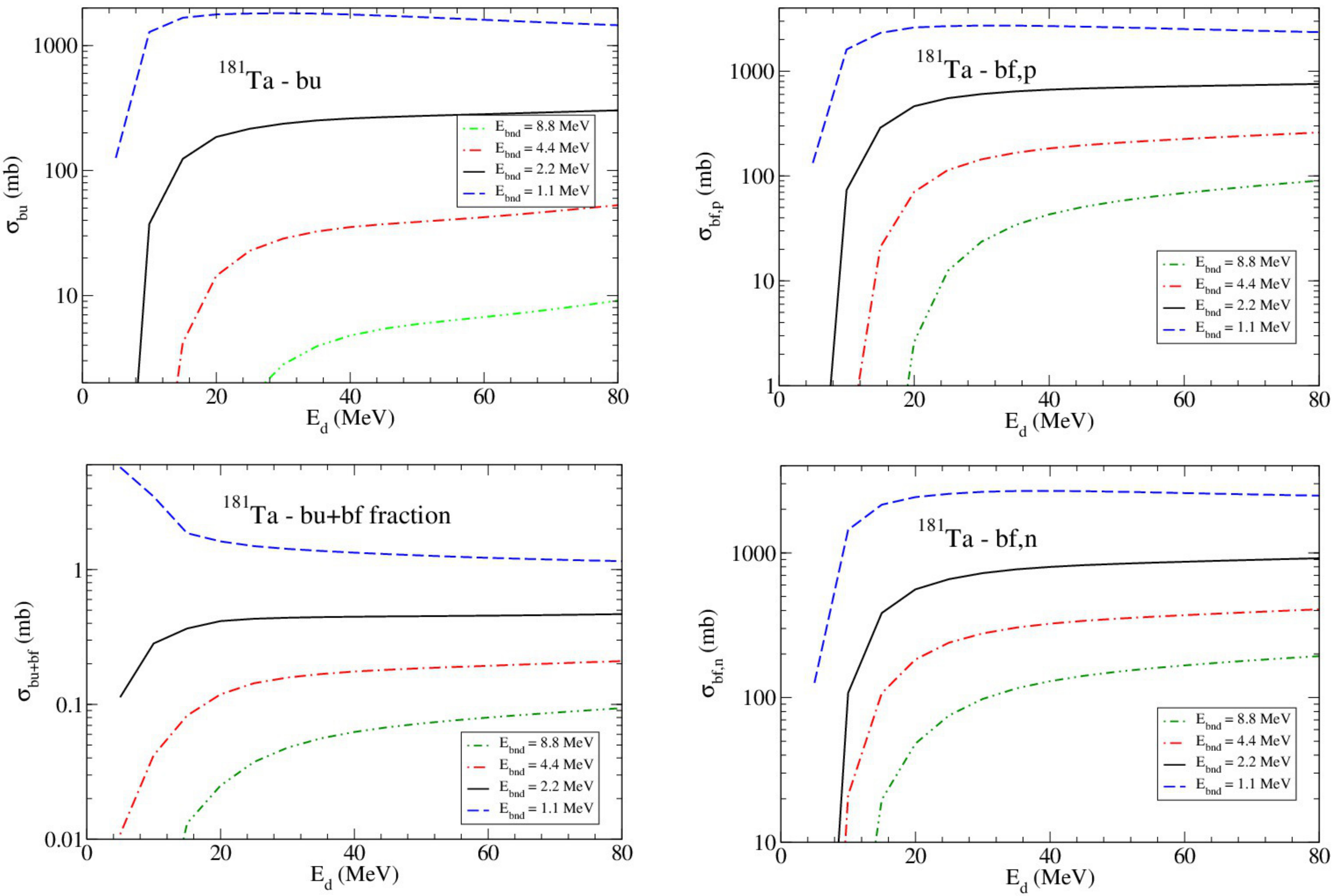


p



E_d=80 MeV

Dependence on binding energy



Summary

- Deuteron bu and bf cross sections are calculated in the zero-range post form DWBA approximation.

- The bu cross sections are similar to those of G. Baur et al.

- The bf cross sections are reasonable but display several surprising features:
   - The bf,n cross section is usually larger than the bf,p one.
   - Although the absorption is surface-dominated, there is still substantial absorption of low partial waves.
   - The bf energy – angular momentum distributions display unexpected structure.

- Optical potentials corresponding to Green's functions?
- Finite range effects? Three-body corrections?

We are adapting the bu-bf code as a module in the EMPIRE-3 reaction model code to perform calculations including pre-equilibrium and equilibrium statistical decay.

EMPIRE-3.2 – www.nndc.bnl.gov/empire/