Towards a (more) complete description of deuteron-induced reactions

B. V. Carlson[1], R. Capote[2] and M. Sin[3]

[1]Instituto Tecnológico de Aeronáutica, São José dos Campos SP, Brazil

[2]NAPC-Nuclear Data Section, International Atomic Energy Agency, 1400 Vienna, Austria

[3]Department of Nuclear Physics, University of Bucharest, P.O. Box MG-11, 70709 Bucharest-Magurele, Romania

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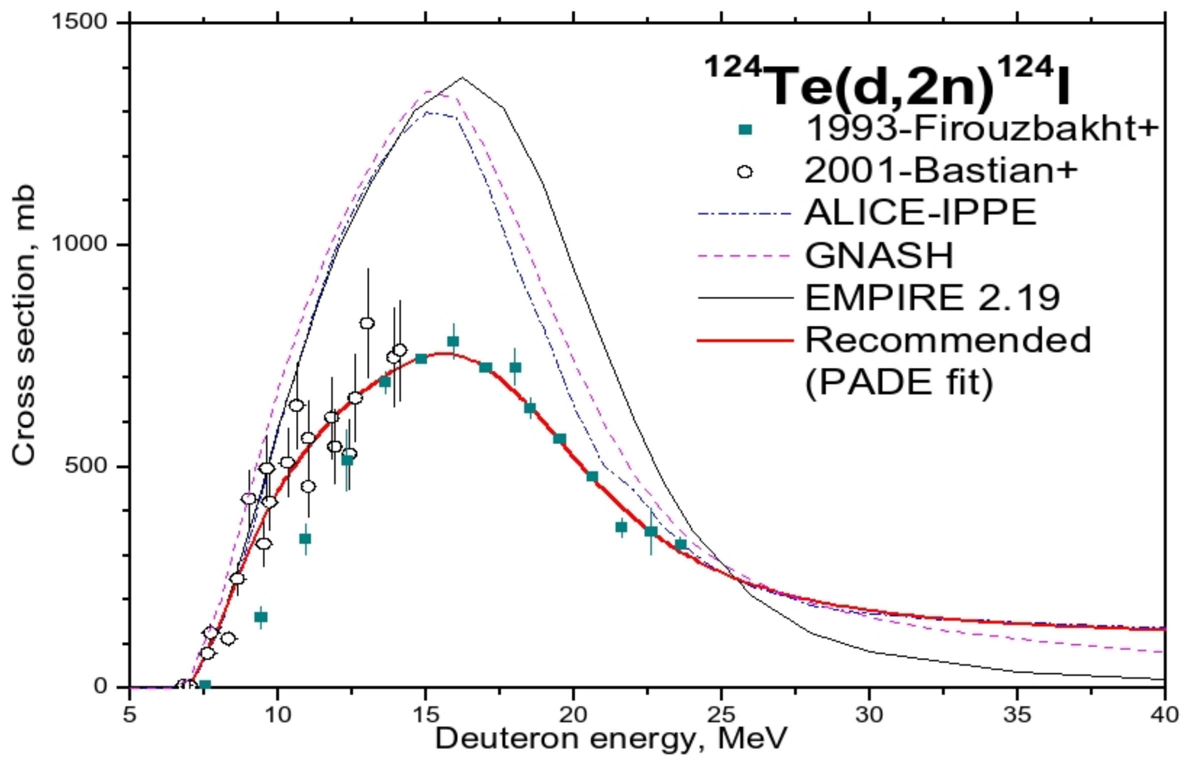
Universitá di Catania, Catania Italy

Direct + compound nucleus reactions

- Our objective - a “complete” description of deuteron induced reactions.
- CN formation is over-predicted when a deuteron optical model is used to calculate absorption.

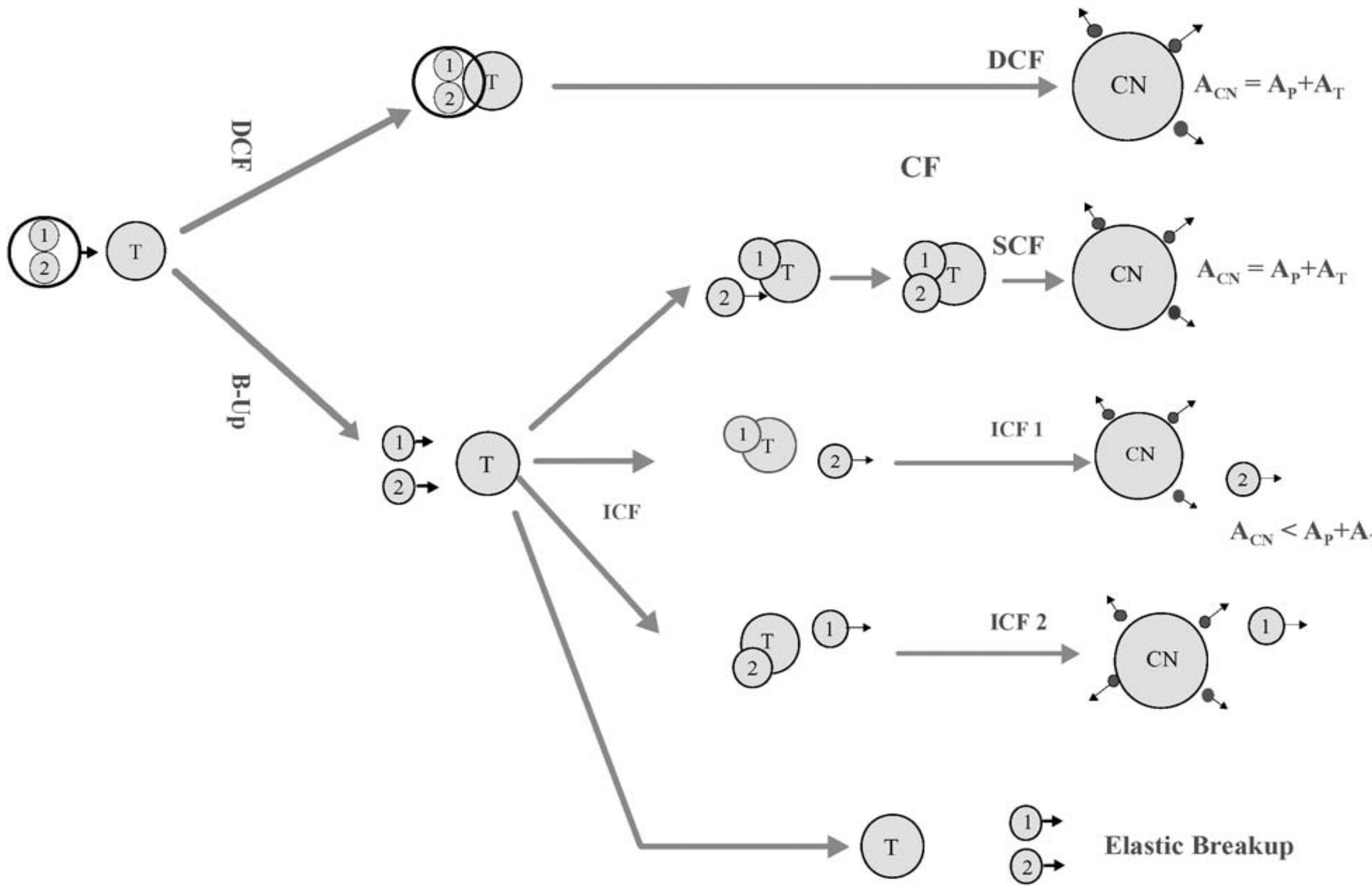


$$\sigma_{abs} = \sigma_{bf,n} + \sigma_{cf}$$

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

Deuteron-induced 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.

Formalism – Elastic Breakup

The differential elastic 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

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

We can rewrite this as

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

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 - II

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 et al. or Haixia et al. potential

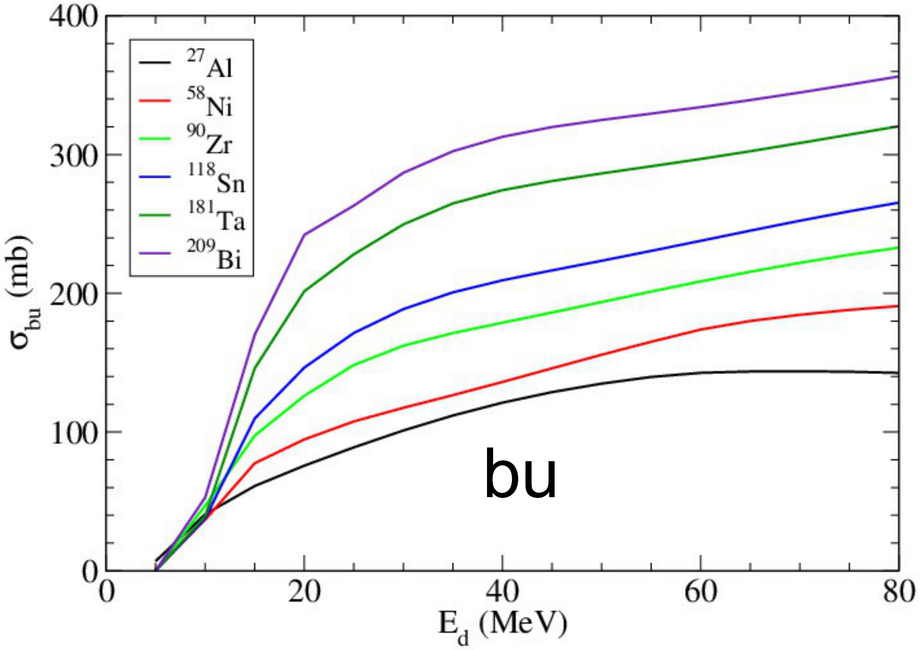
-Calculations performed on a grid of proton/neutron energies with optical potential parameters corresponding to each energy.

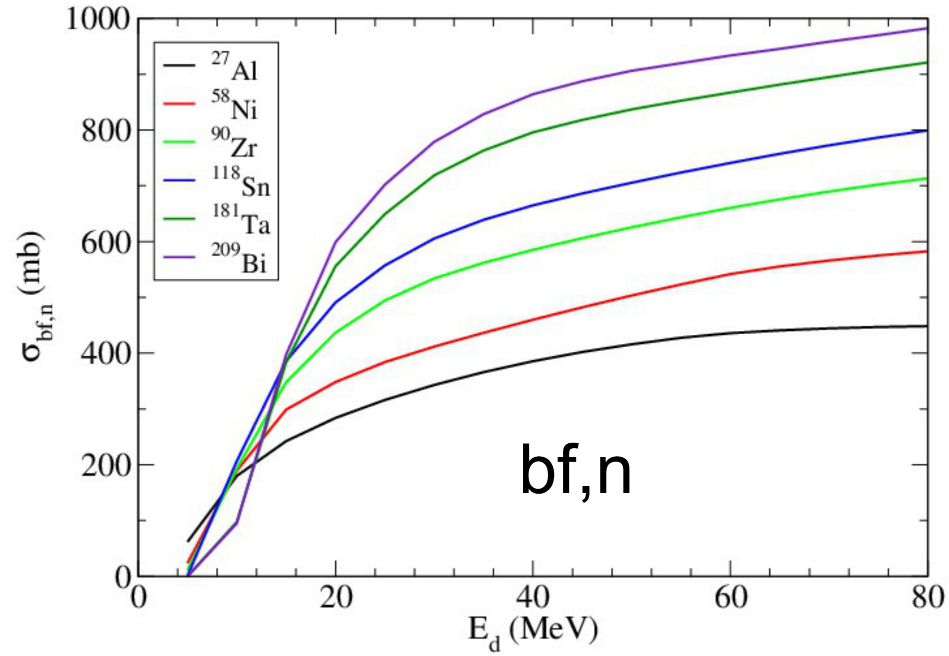
-Vincent-Fortune - complex-plane integration method to speed convergence

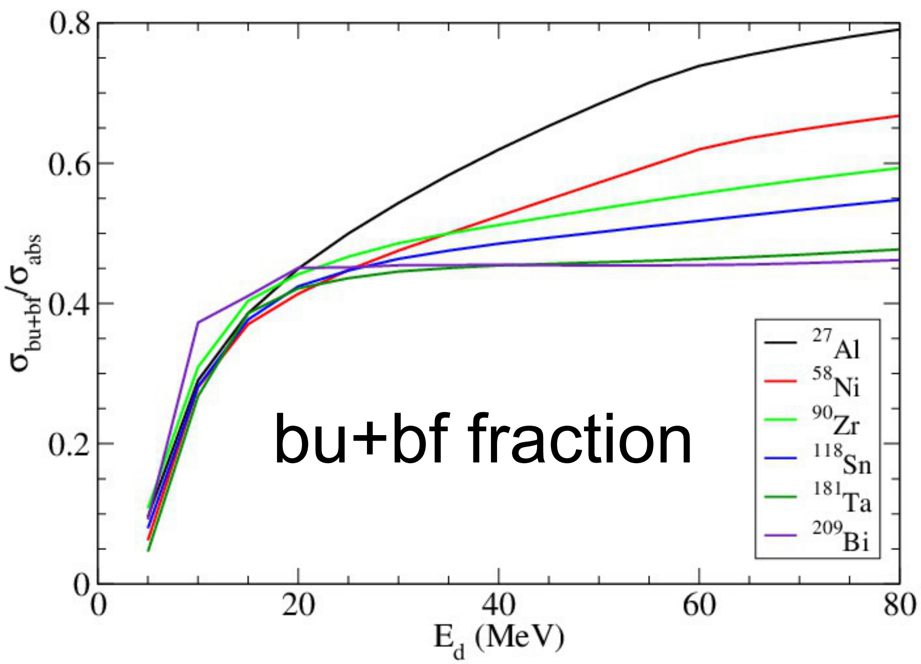
- No free parameters included.

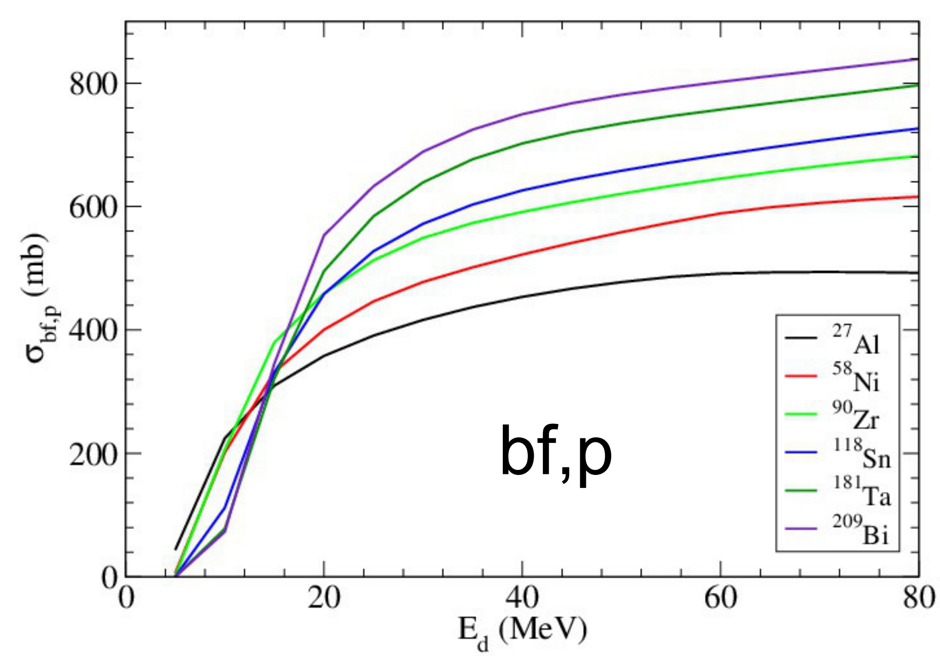
A.J. Koning, J.P. Delaroche, Nucl. Phys. A **713** (2003) 231.
Y. Han, Y. Shi, Q. Shen, Phys. Rev. C **74** (2006) 044615.
Haixia An, Chonghai Cai, Phys. Rev C **73** (2006) 054605.
C.M. Vincent, H.T. Fortune, Phys. Rev. C **2** (1970) 782.

Cross sections

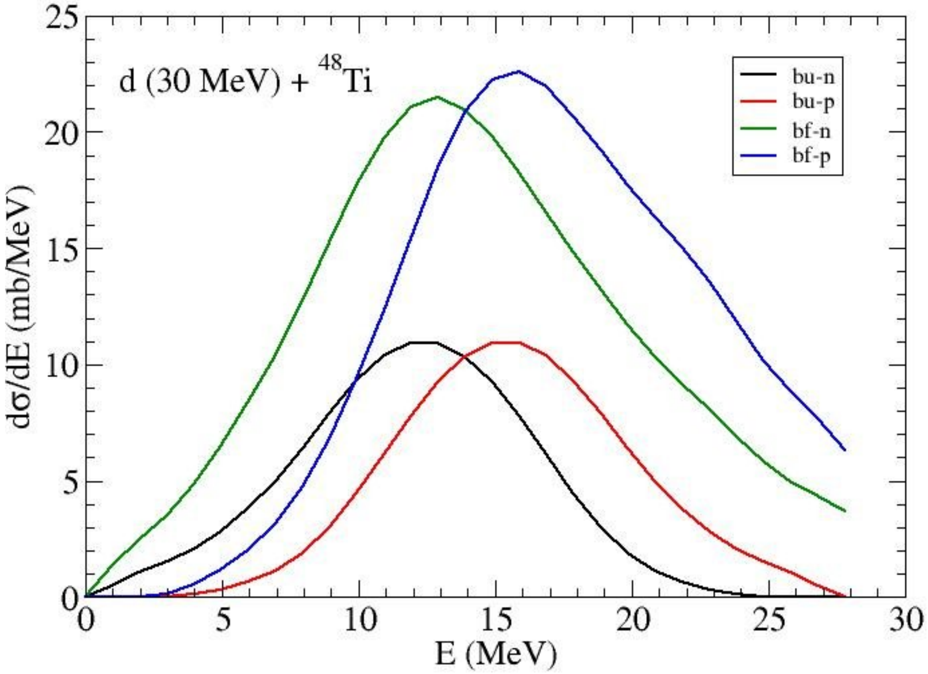








Spectra



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

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

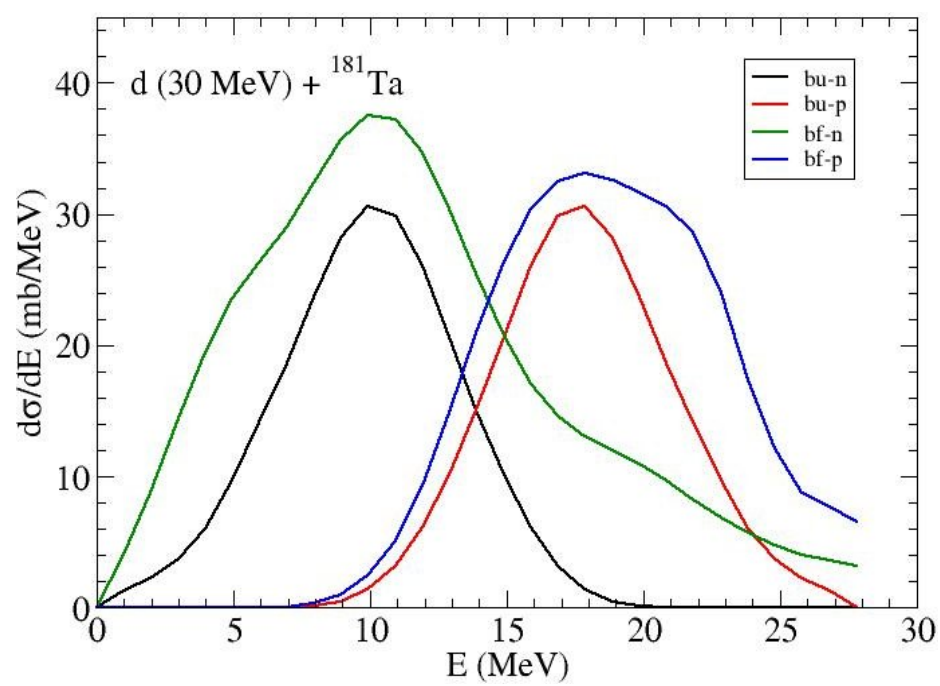
$$R_{int} \approx 1.25(A^{1/3} + 2^{1/3})\ \text{fm}$$

Ti:

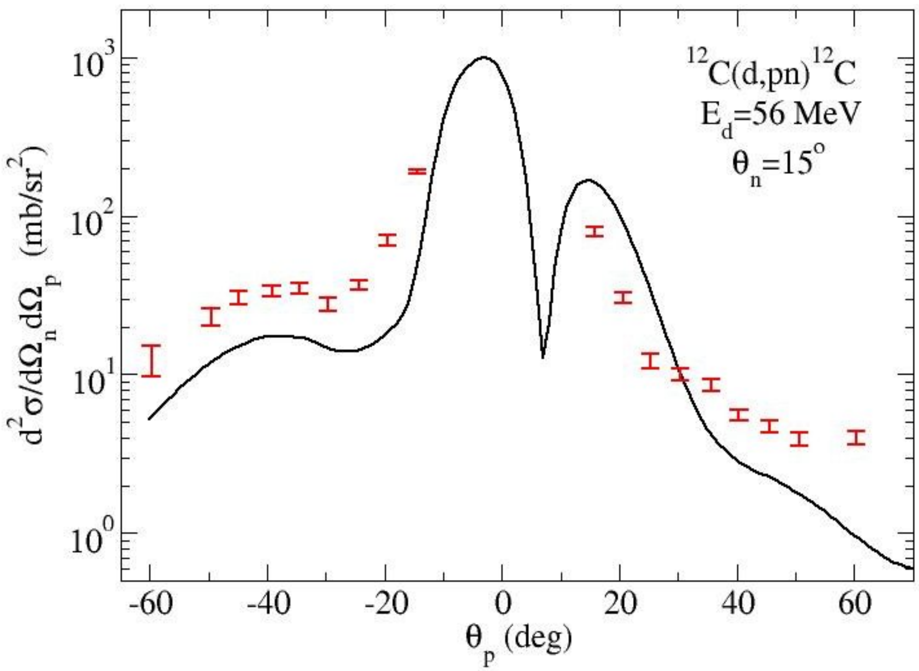
$$R_{bu} \approx 10.6\ \text{fm} \quad R_{int} \approx 6.0\ \text{fm}$$

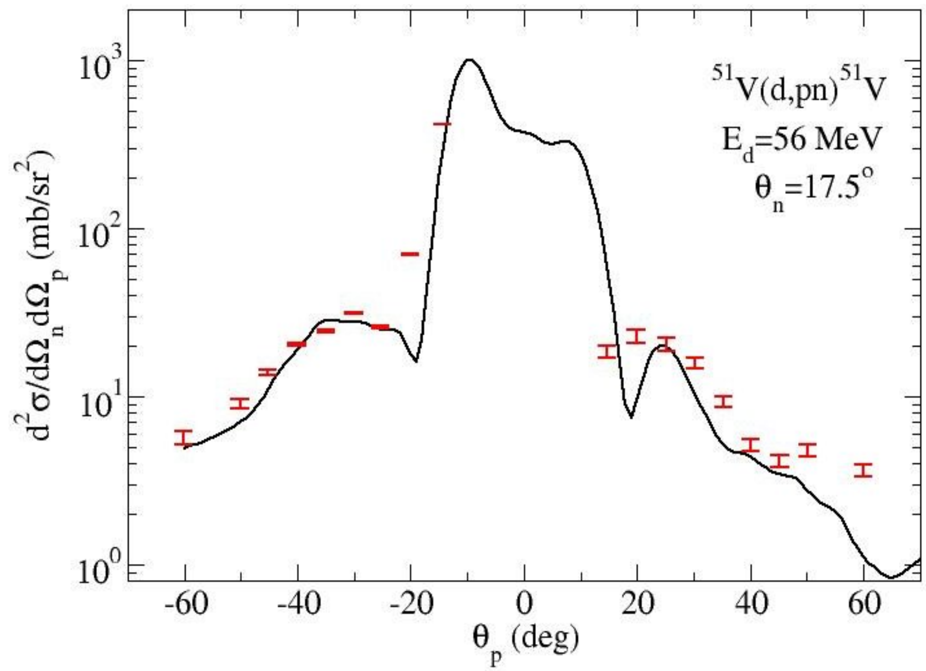
Ta:

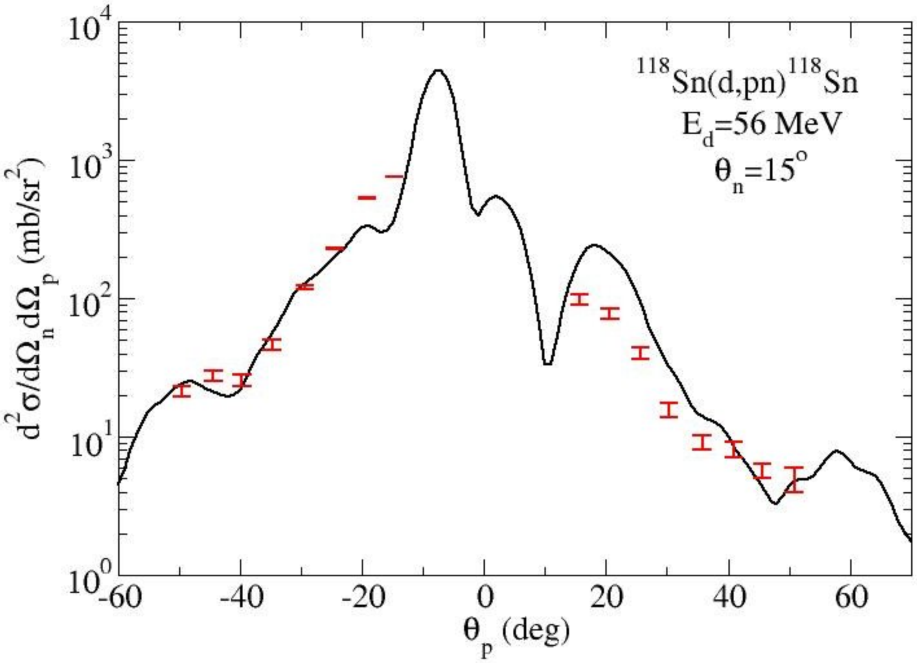
$$R_{bu} \approx 14.6\ \text{fm} \quad R_{int} \approx 8.6\ \text{fm}$$



Coincidence Angular Distributions - bu





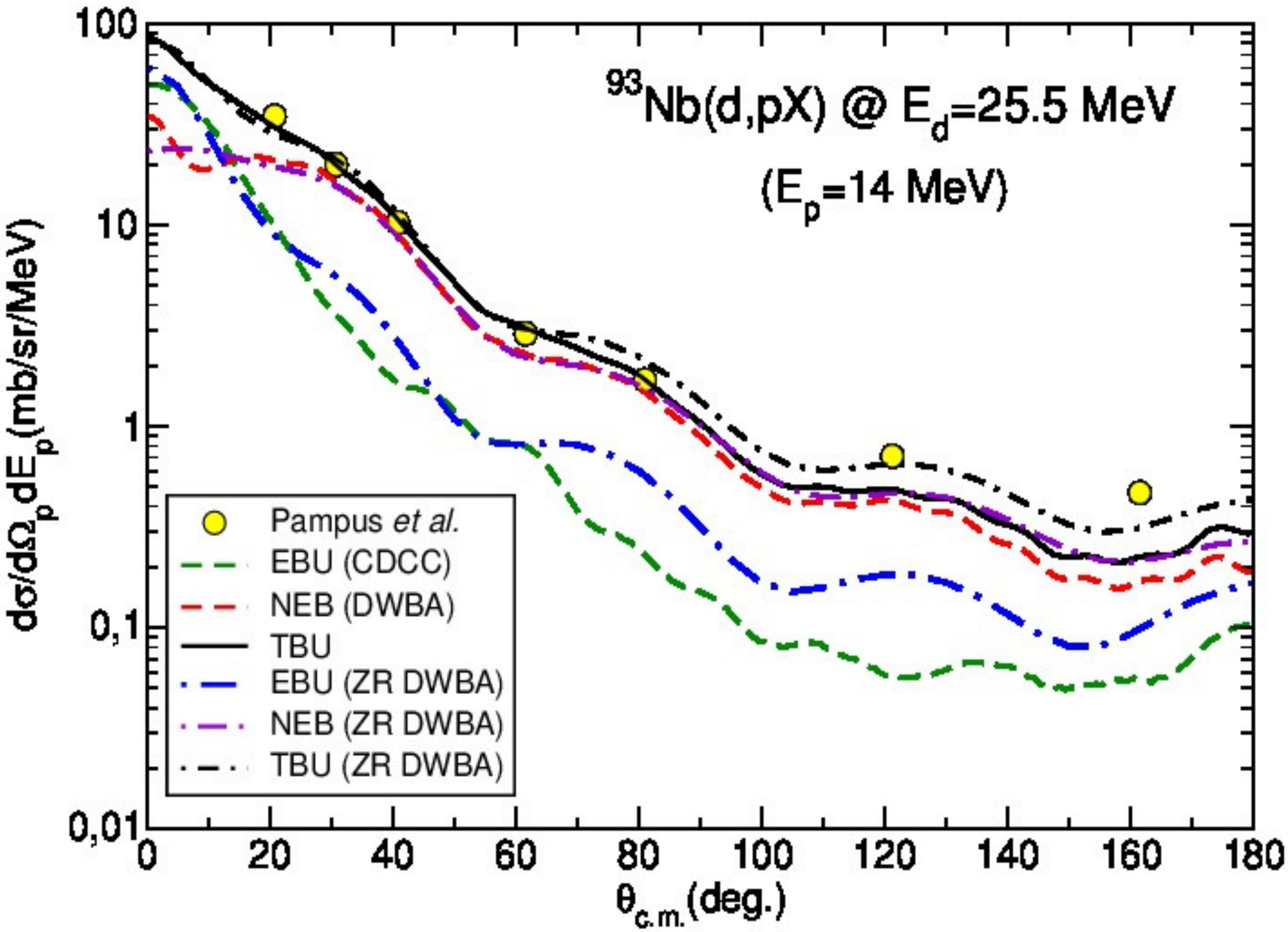


M. Matsuoka et al., Nucl. Phys. **A391** (1982) 357.

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.

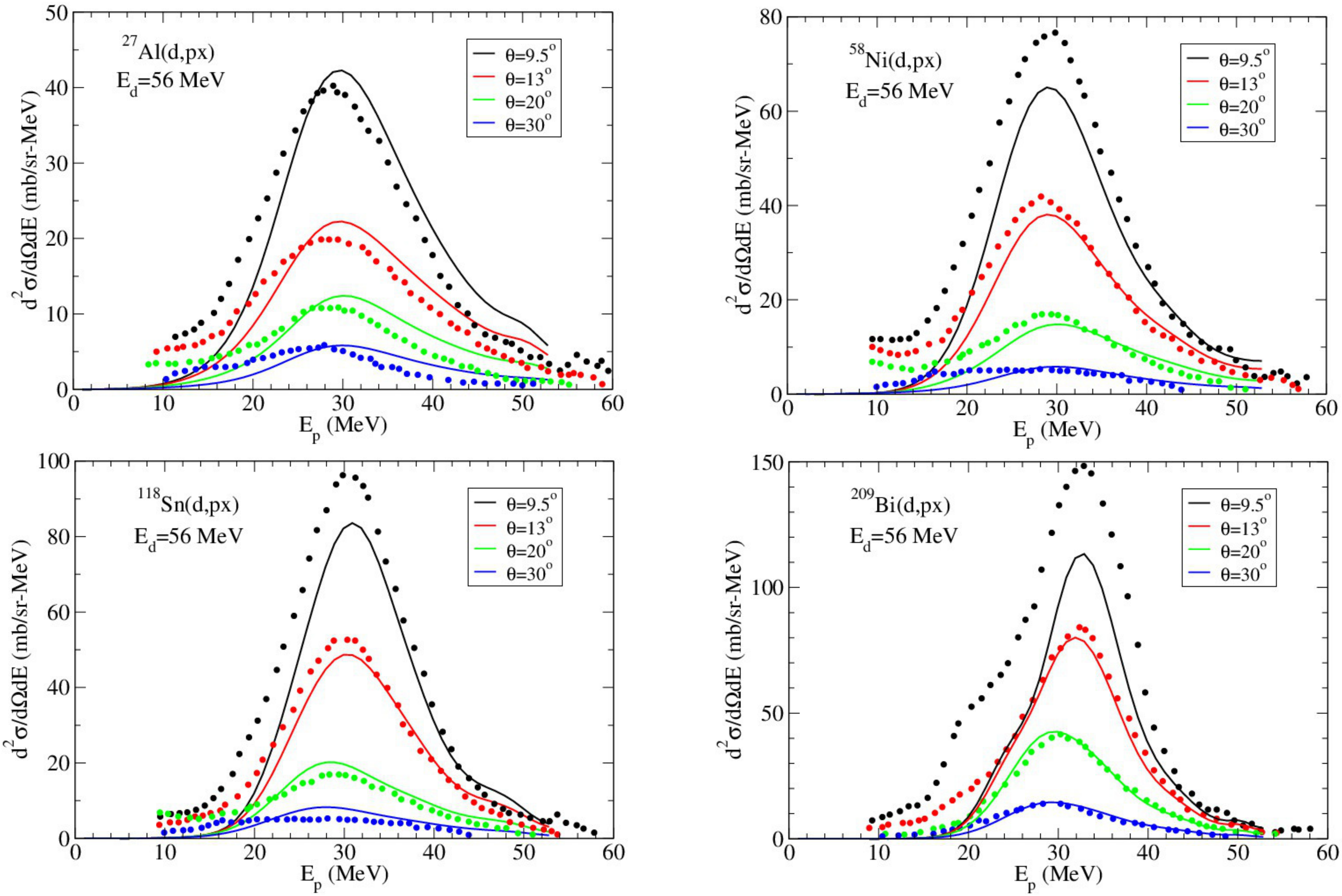
Double Differential Spectra - bu + bf,p



J. Pampus et al., Nucl. Phys. **A311** (1978) 141.
Jin Lei, A. M. Moro, submitted for publication.

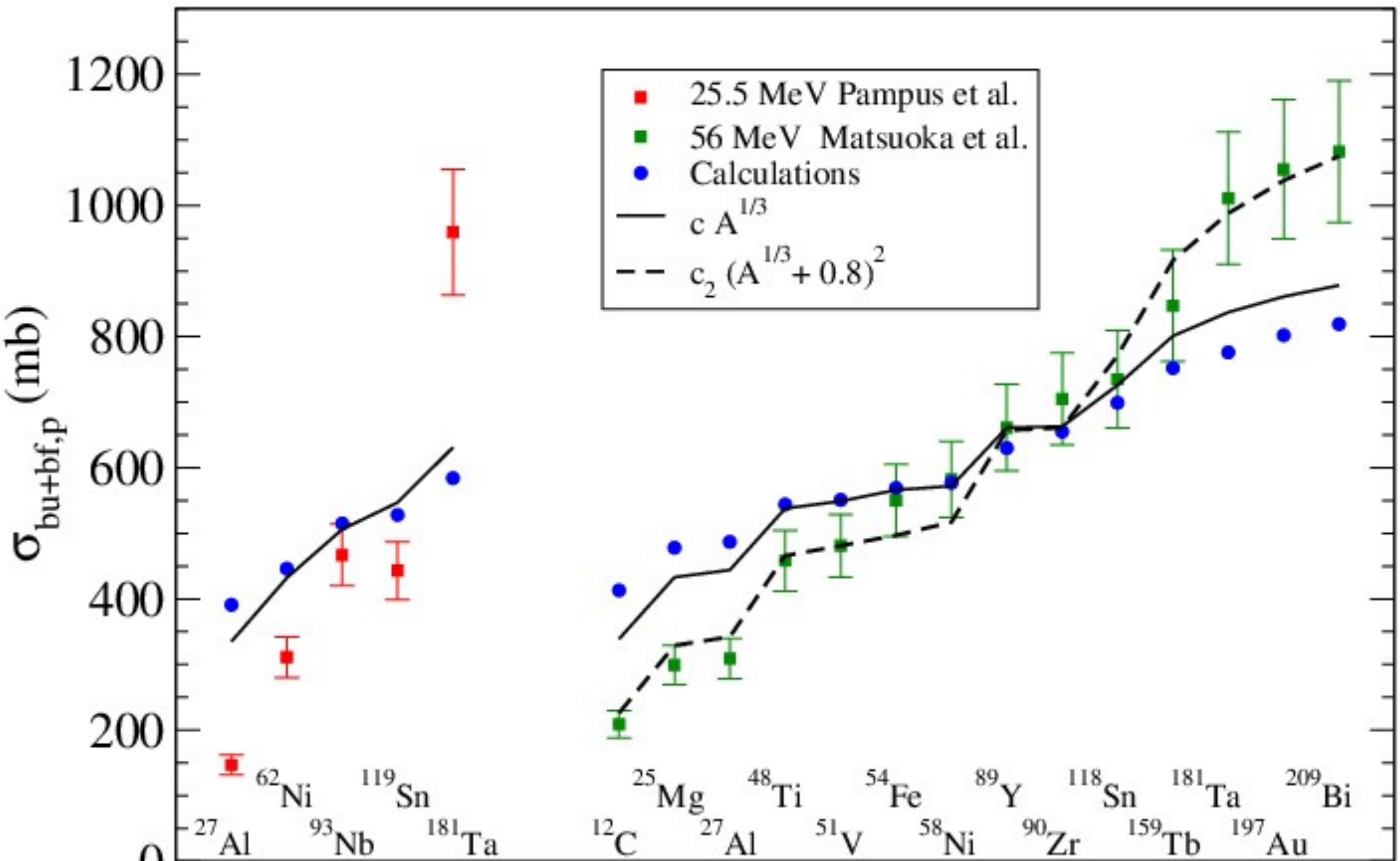
Figure courtesy of A. M. Moro

Double Differential Spectra- bu + bf,p



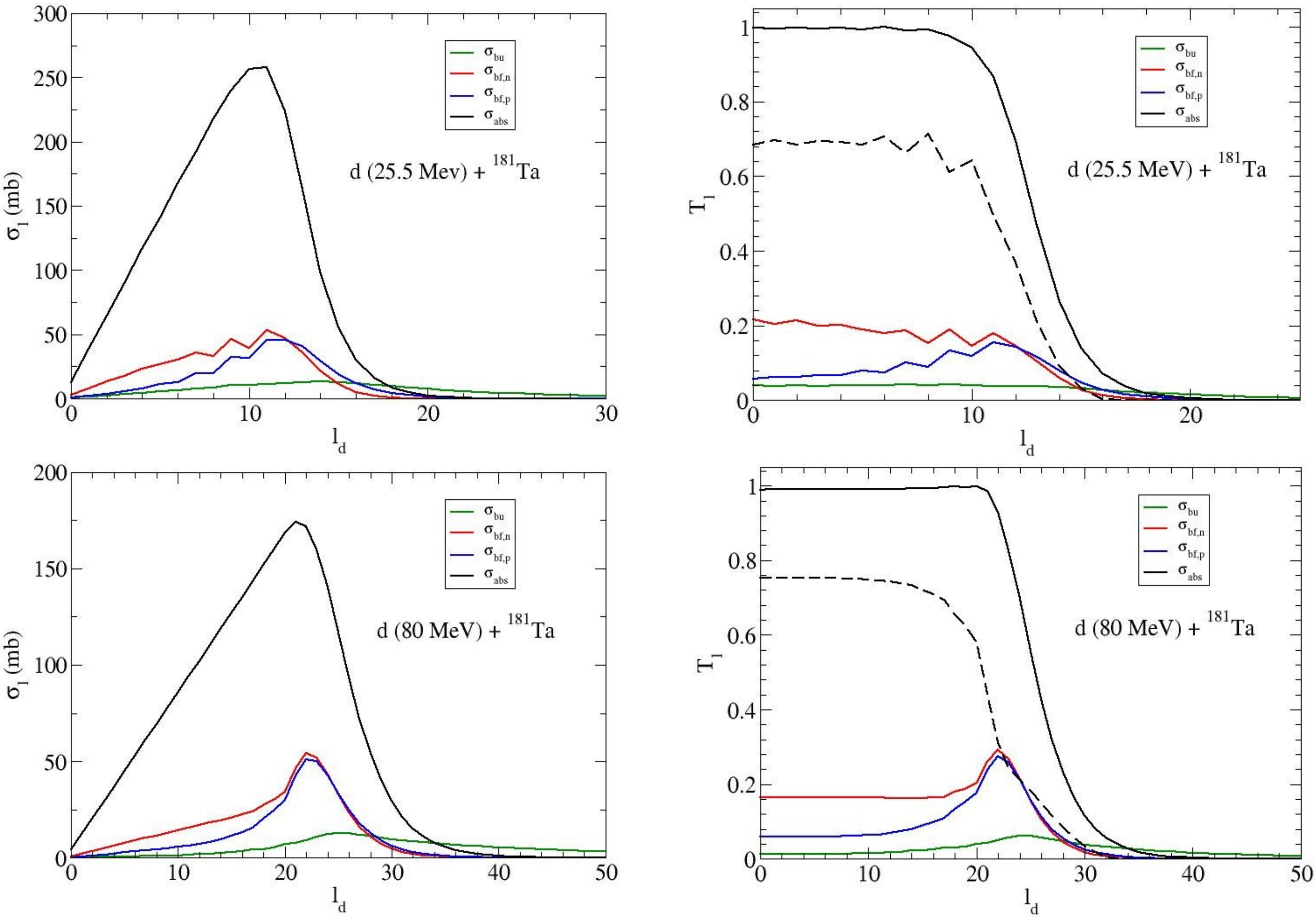
N. Matsuoka et al., Nucl. Phys. **A345** (1980) 1.

Cross sections – bu + bf,p



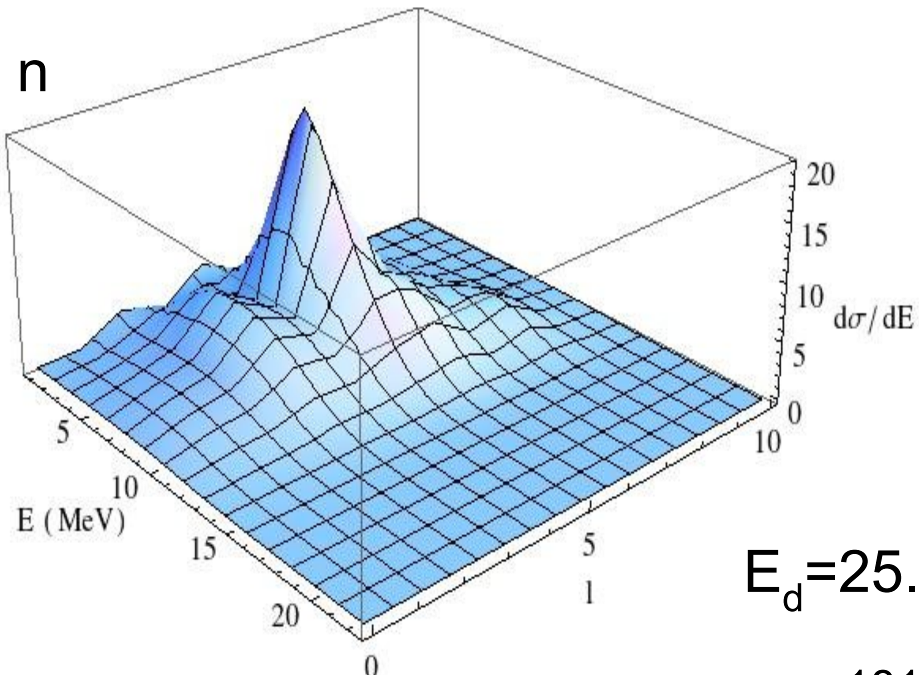
J. Pampus et al., Nucl. Phys. **A311** (1978) 141.
M. Matsuoka et al., Nucl. Phys. **A345** (1980) 1.

Breakup Angular Momentum Distributions - l_d

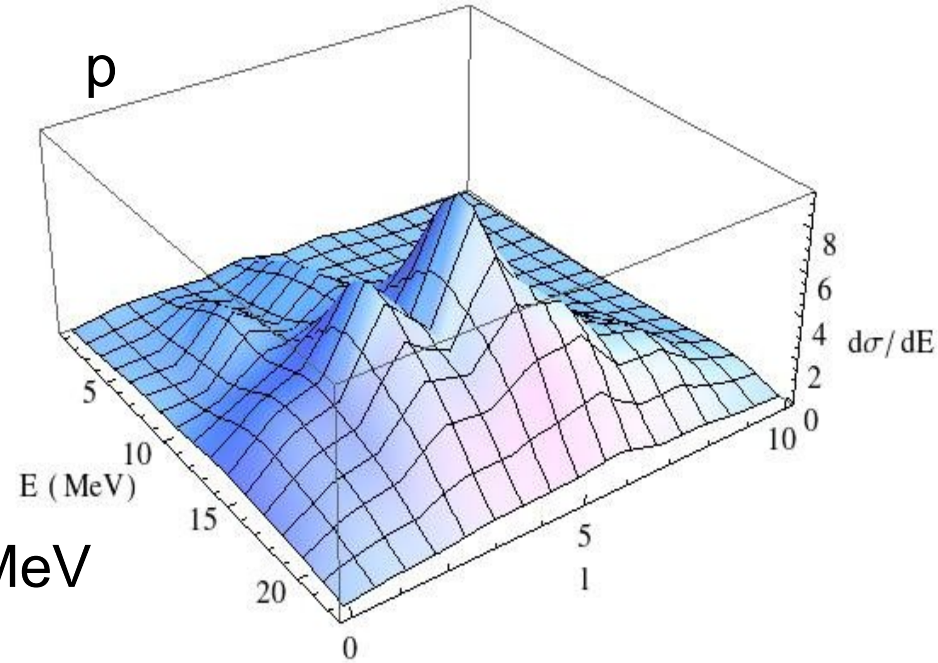


bf CN formation distributions – E_p, l_p or E_n, l_n

n



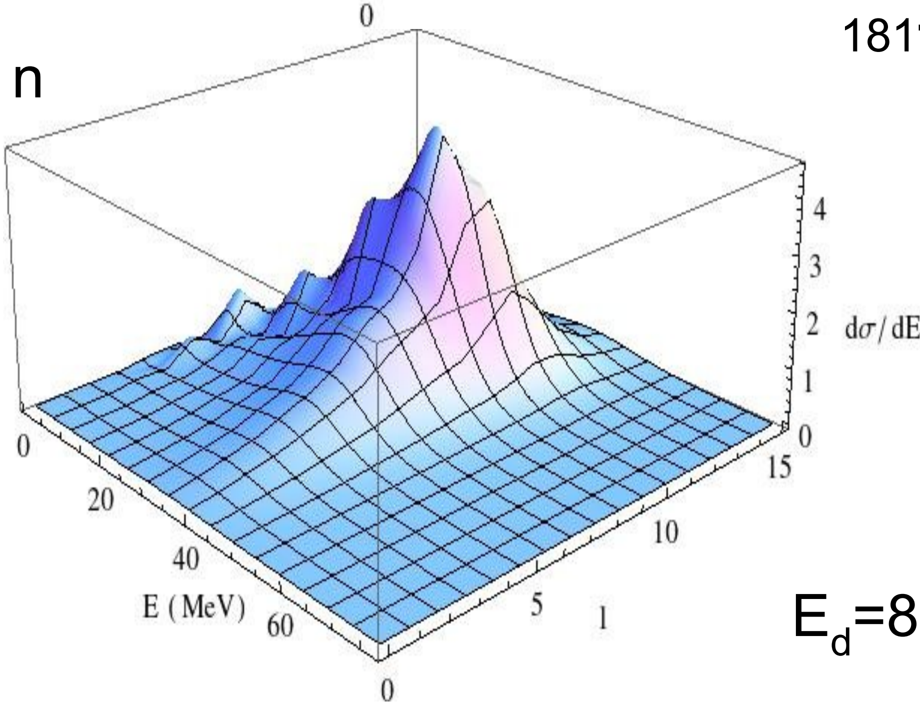
p



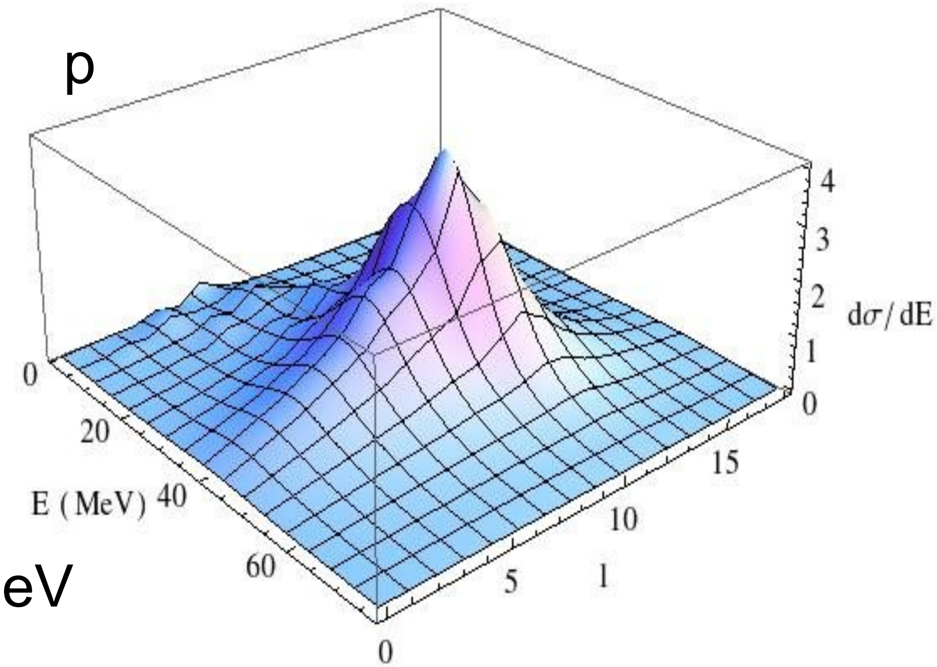
E_d=25.5 MeV

^{181}Ta

n



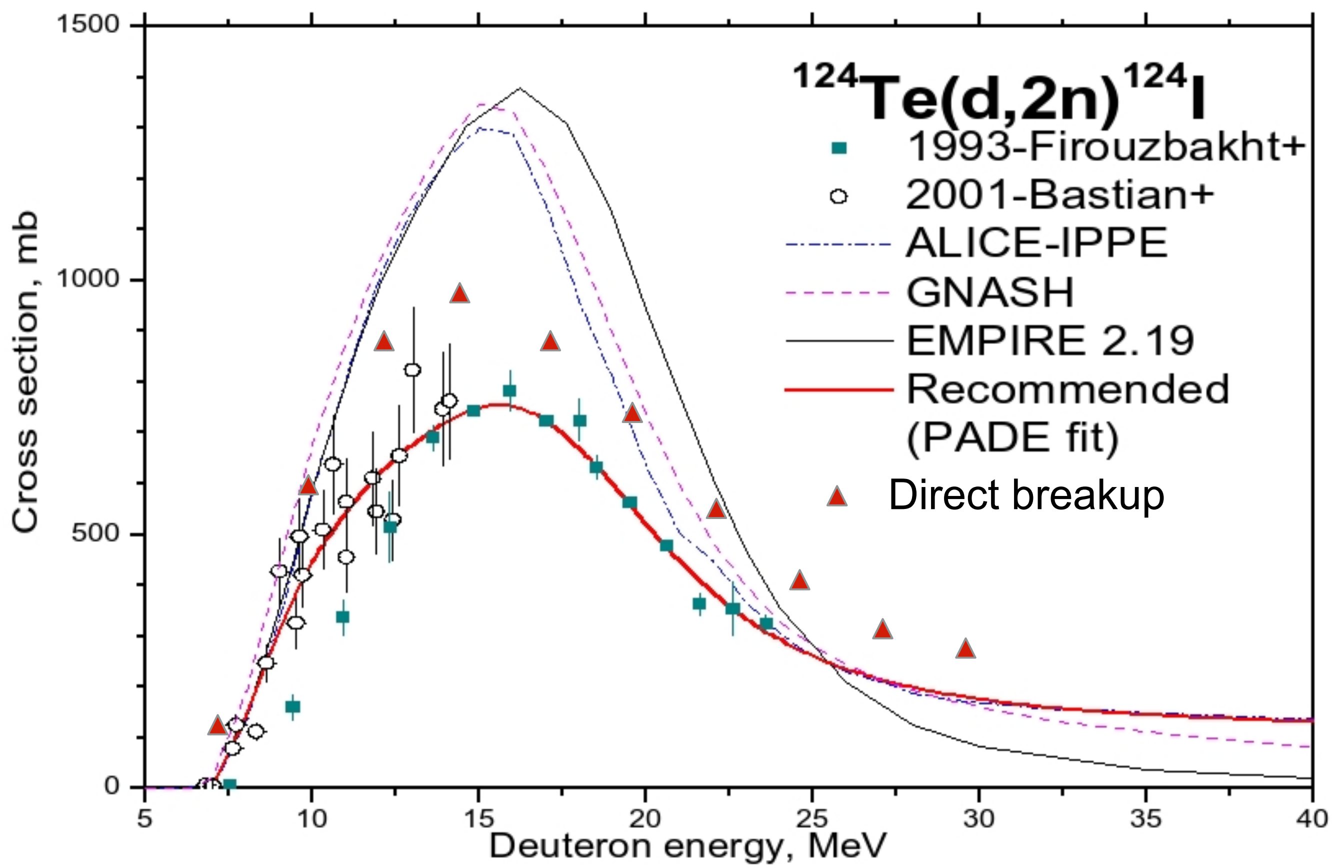
p



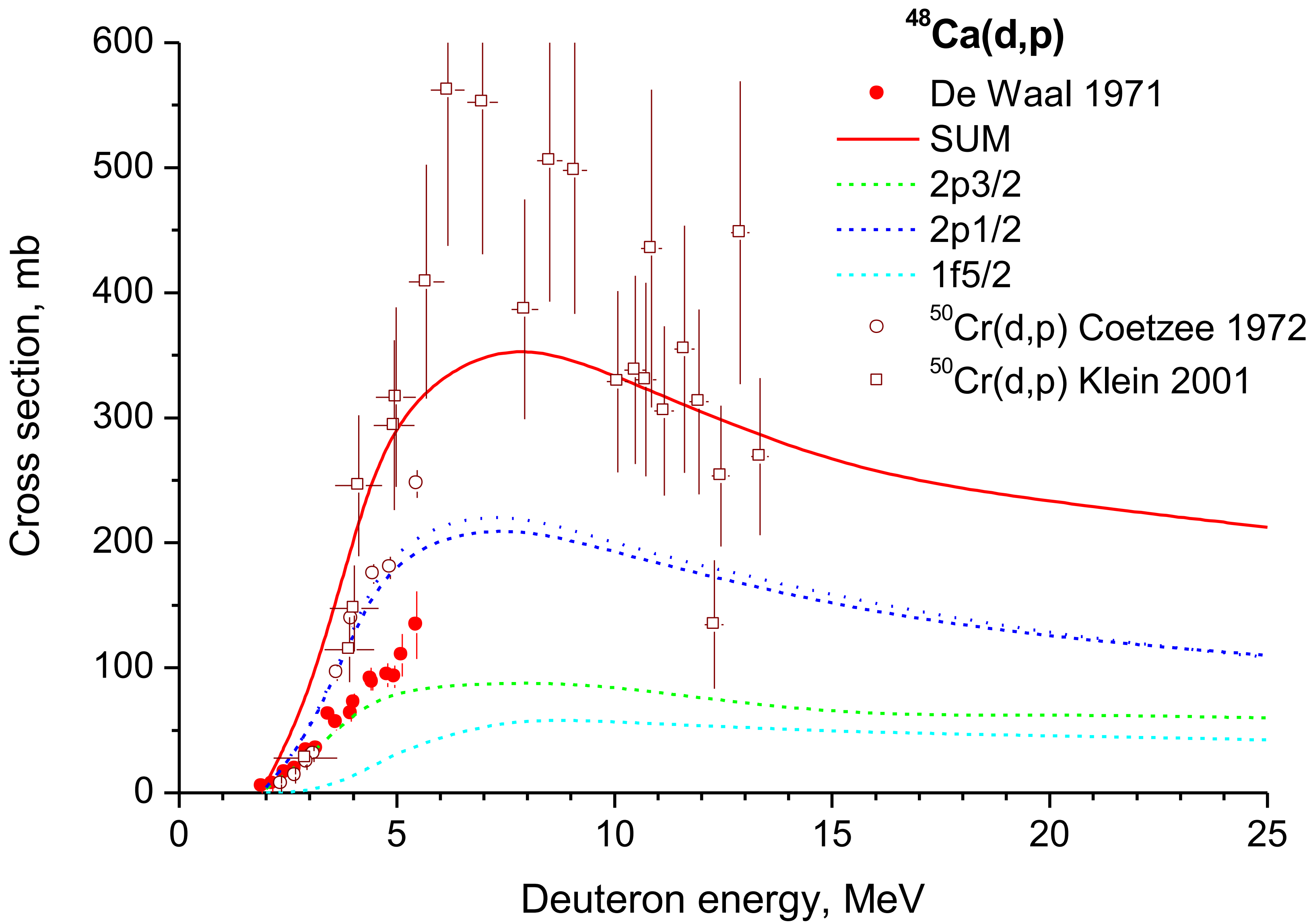
E_d=80 MeV

Compound nucleus formation – EMPIRE3.1

- EMPIRE3.1 – direct, pre-equilibrium and equilibrium statistical decay code (M. Herman et al., NDS **108** (2007) 2655, available from the NNDC-BNL);
- Deuteron breakup taken into account in flux lost and formation of d, p and n + target compound nuclei;
- Only equilibrium statistical decay is taken into account at the moment;
- Pre-equilibrium decay will be included in the near future.



DWBA description of the integral (d,p) cross sections for ^{48}Ca and ^{50}Cr



From A. Ignatyuk

Summary

- We calculate deuteron bu and bf cross sections 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 surprising amount of structure.

-The bu-bf calculation has been integrated in the EMPIRE-3 reaction model code to perform calculations including equilibrium statistical decay – pre-equilibrium decay next.

- (d,p) and (d,n) stripping channels to be included soon.

- **Optical potentials? Inelastic breakup or fusion?**
- **Finite range effects? Three-body corrections?**

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

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

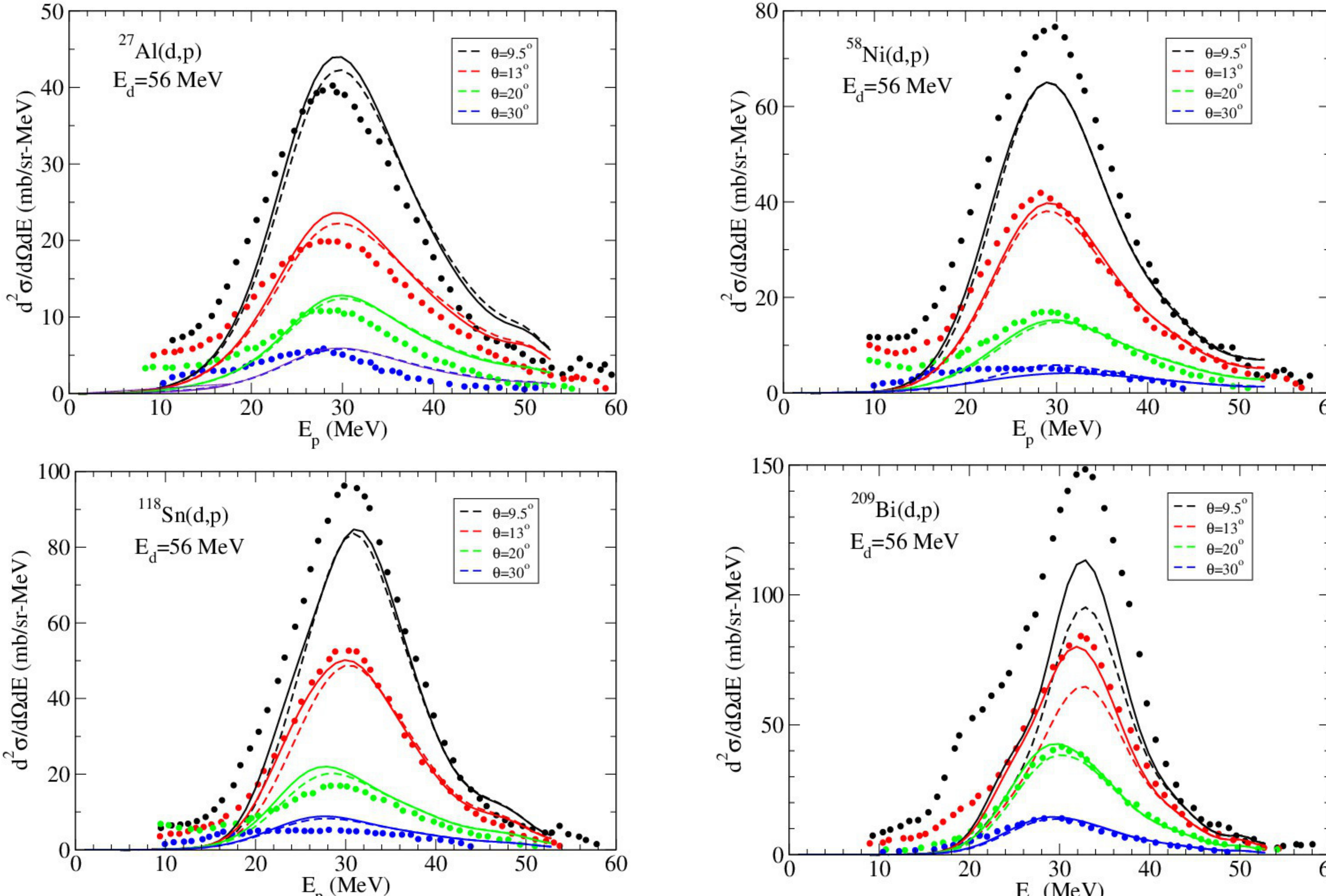
With this, we can write the full elastic breakup amplitude as

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

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

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

Coulomb-corrected DDX - bu + bf,p



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

The optical potential

In the derivation of the inelastic breakup cross section from the inclusive emission cross section,

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

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

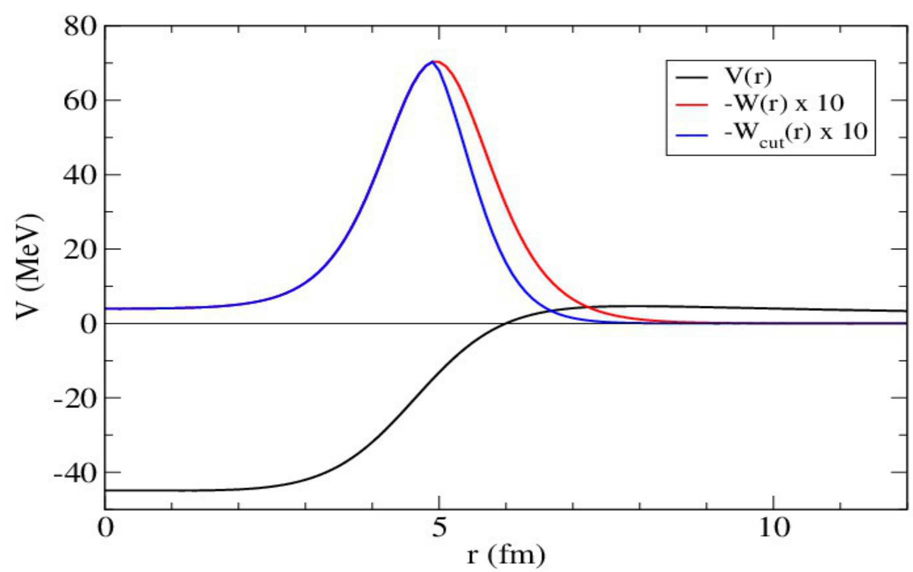
W(r) – should take into account quasi-bound neutron + target states
- but NOT the inelastic scattering states.

Sensitivity study:

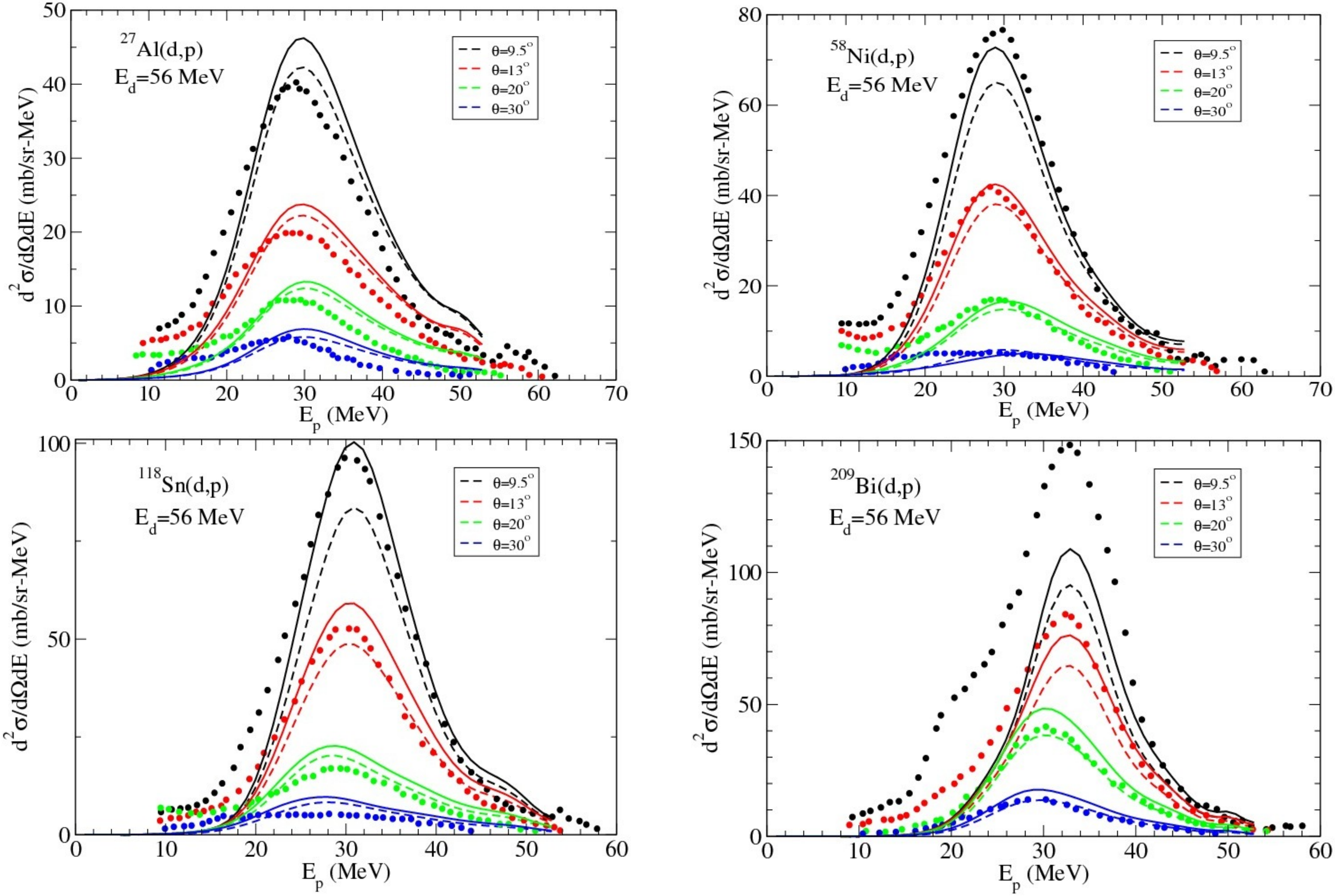
$$W(\vec{r}) \to \frac{2W(\vec{r})}{1 + \exp[(r - r_{cut})/a_{cut}]}$$

$$r > r_{cut} \approx R_W$$

$$a_{cut} = 1.0 \quad \text{fm}$$



DDX - bu + bf,p – with a_{cut} = 1.0 fm



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

(d,p) and (d,n) stripping reactions

We can calculate

$$\frac{d^3\sigma^{st}}{dk_p^3} = \frac{2\pi}{\hbar v_d}\frac{1}{(2\pi)^3}\sum_{lj,c} S_{lj}\left(E_{nA}^c\right)\left|T^{st}(\vec{k}_p;\vec{k}_d)\right|^2 \delta\left(E_d+\varepsilon_d-E_p-E_{nA}^c\right)$$

with

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

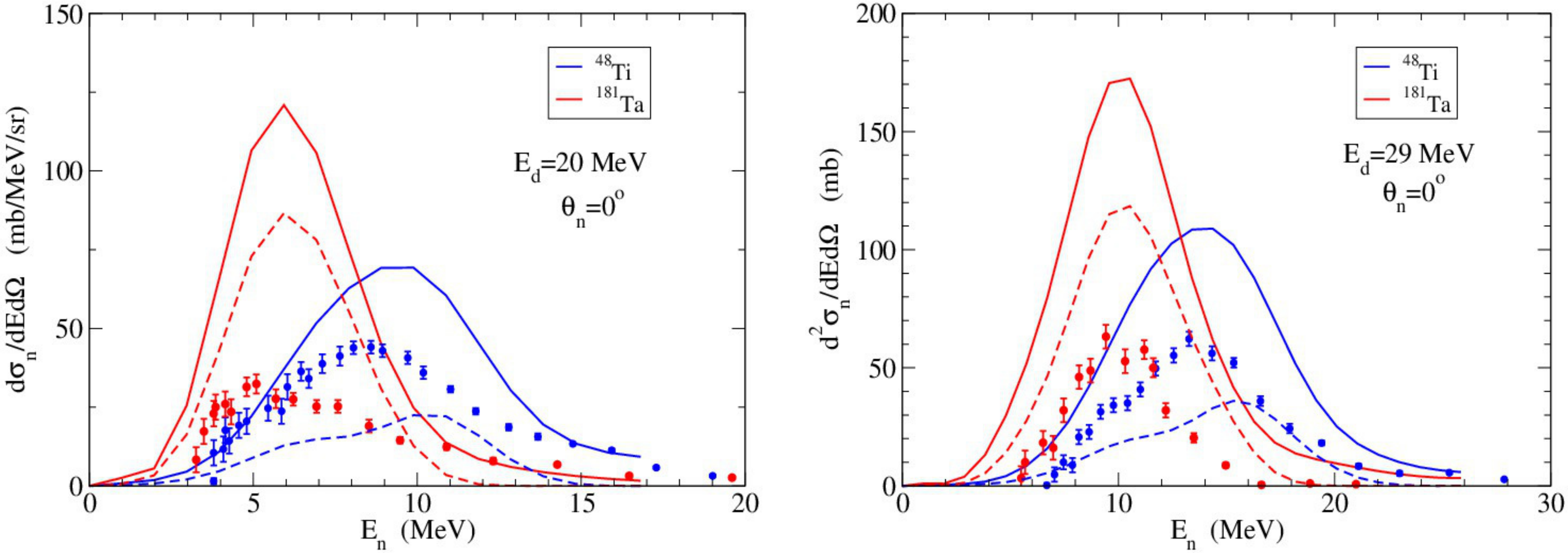
OR we can use

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

with

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

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.