

## improvements to the physics of the INCL model

---

A. Boudard<sup>1</sup>   J. Cugnon<sup>2</sup>   J.-C. David<sup>1</sup>  
P. Kaitaniemi<sup>1</sup>   S. Leray<sup>1</sup>   D. Mancusi<sup>1</sup>

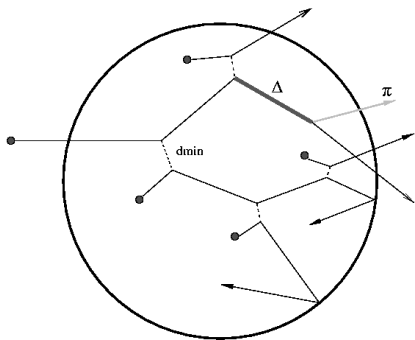
<sup>1</sup> CEA-Saclay, Irfu/SPhN, France

<sup>2</sup> University of Liège, Liège, Belgium

24<sup>th</sup> April 2012

ANDES annual meeting

## nucleon- and light-ion-induced nuclear reactions between $\sim 150$ MeV and $\sim 3$ GeV



- ▶ University of Liège & CEA-Saclay
- ▶ Binary nucleon-nucleon collisions
- ▶ Signs of **thermalisation**  $\rightarrow$  stop cascade
- ▶ Nucleus (remnant) left in an excited state
  - ▶ Coupling to a de-excitation code

mean free path  $>$  wavelength

mean free path > wavelength

$$\Lambda = \frac{1}{\rho_0 \sigma_{\mathcal{N}} f_{\text{Pauli}}}$$

mean free path > wavelength

$$\Lambda = \frac{1}{\rho_0 \sigma_{\mathcal{N}} f_{\text{Pauli}}}$$

$$\lambda = \frac{h}{p_{\text{lab}}}$$

mean free path > wavelength

$$\Lambda = \frac{1}{\rho_0 \sigma_{NN} f_{\text{Pauli}}}$$

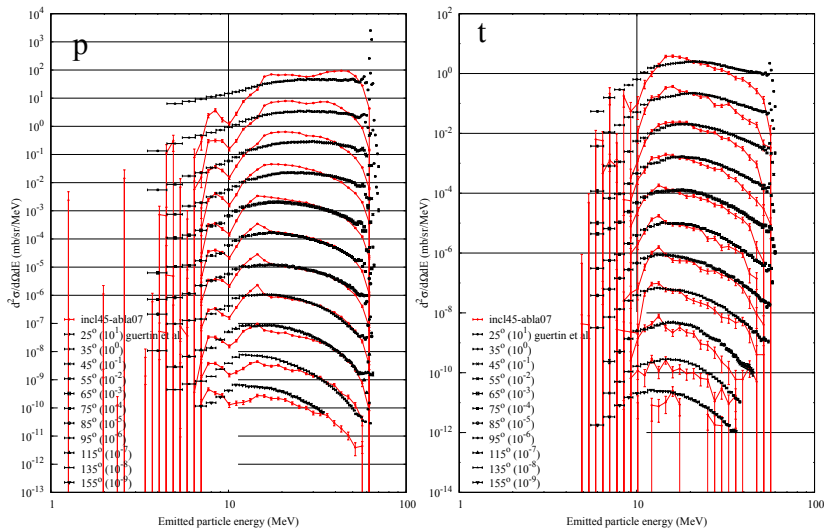
$$\lambda = \frac{h}{p_{\text{lab}}}$$

$$T_{\text{lab}} > 150\text{--}200 \text{ MeV}$$

For  $T < 150$  MeV:

- ▶ ternary collisions
- ▶ interference between collisions
- ▶ quantum effects
- ▶ **limited** applicability

# Surprise: $Pb(p,x)p$ , $Pb(p,x)t$ , 63 MeV



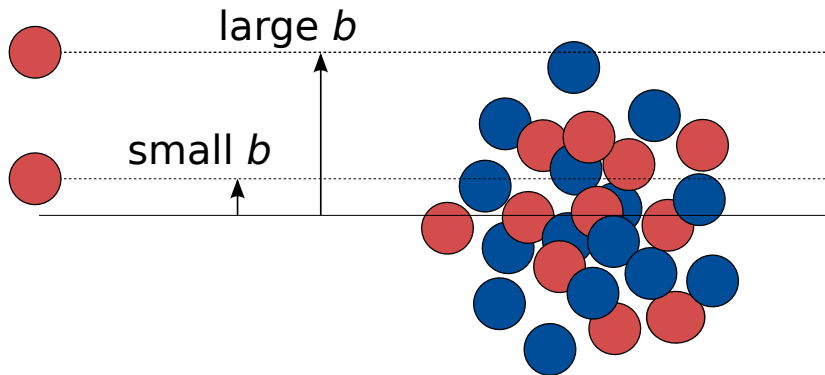
Guertin *et al.*

Eur. Phys. J. A23 (2005) 49

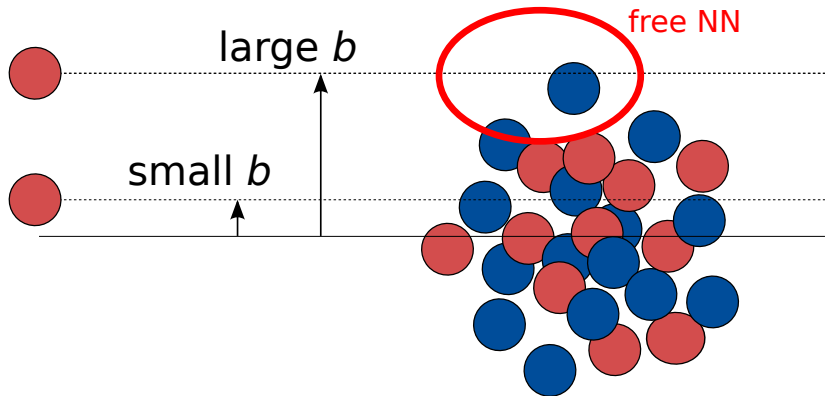
model: INCL+ABLA07



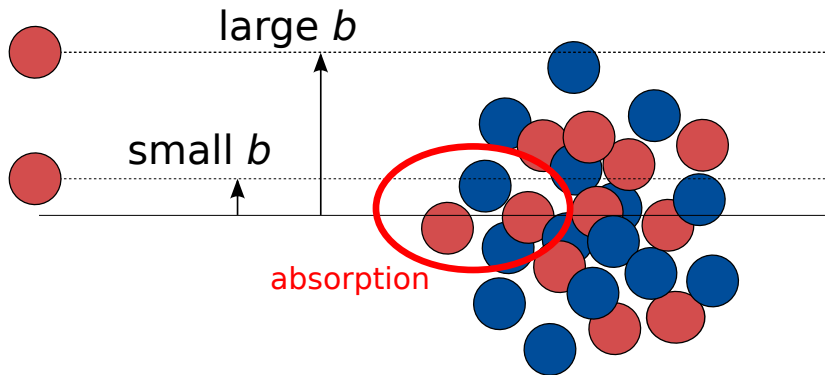
at low energy...



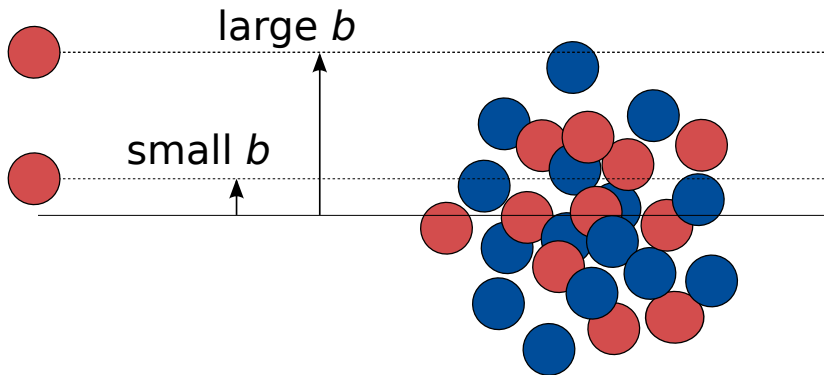
at low energy...



at low energy...



at low energy...



Dynamics plays some role in a limited interval of impact parameters

## old ingredients (in INCL4.5)

- ▶ strict Pauli blocking on first collision
- ▶ free nucleon-nucleon cross sections

## new ingredients (in INCL4.6)

for all projectiles:

- ▶ Coulomb distortion
- ▶ reaction Q-values from mass tables

for composite projectiles:

- ▶ frozen Fermi motion
- ▶ complete fusion at low energy

## old ingredients (in INCL4.5)

- ▶ strict Pauli blocking on first collision
- ▶ free nucleon-nucleon cross sections

## new ingredients (in INCL4.6)

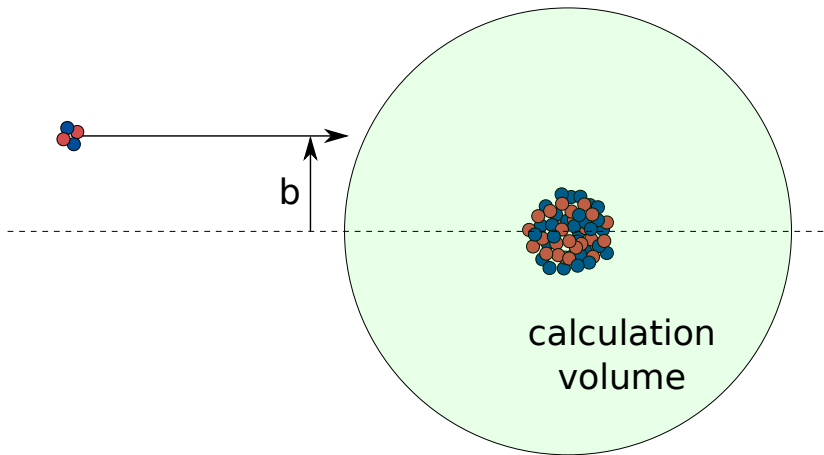
for all projectiles:

- ▶ **Coulomb distortion**
- ▶ reaction Q-values from mass tables

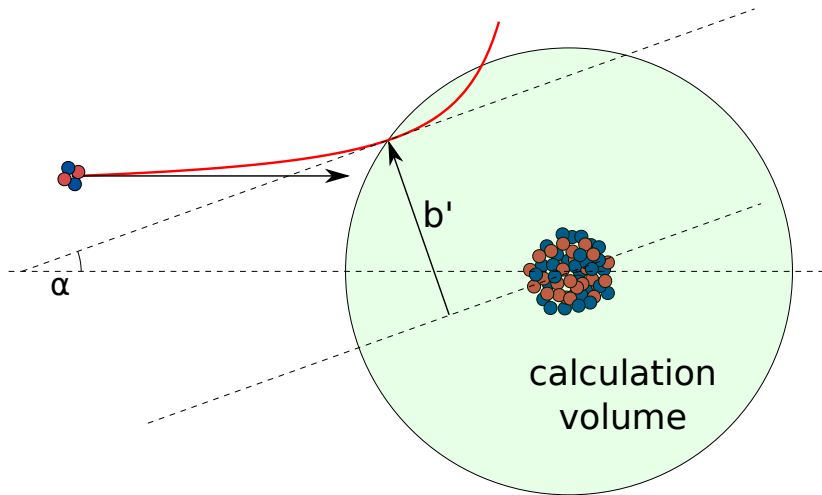
for composite projectiles:

- ▶ frozen Fermi motion
- ▶ complete fusion at low energy

## Coulomb distortion for composite projectiles



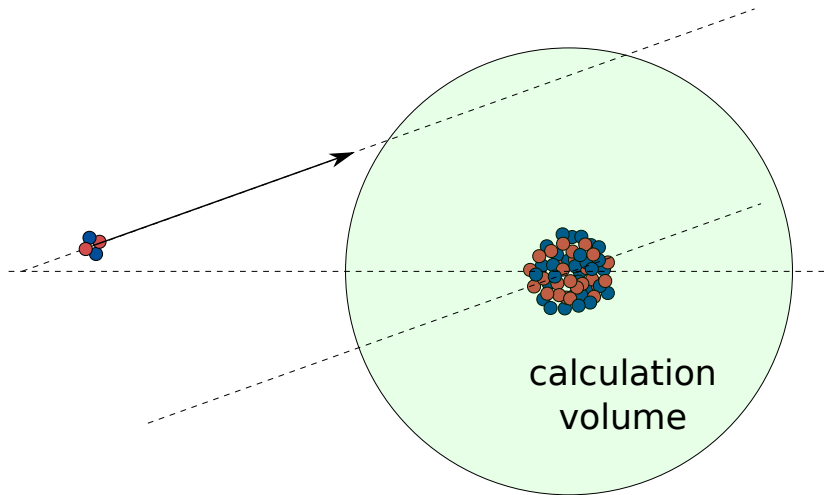
# Coulomb distortion for composite projectiles





## Coulomb distortion for composite projectiles

---



## old ingredients (in INCL4.5)

- ▶ strict Pauli blocking on first collision
- ▶ free nucleon-nucleon cross sections

## new ingredients (in INCL4.6)

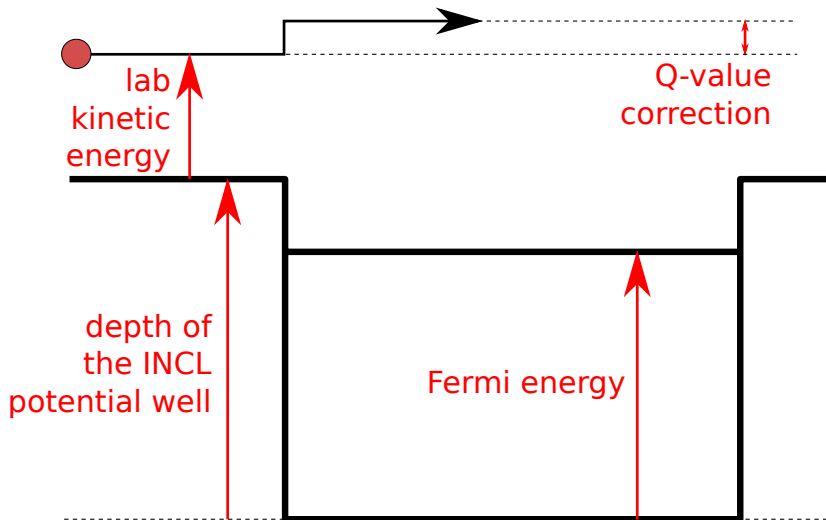
for all projectiles:

- ▶ Coulomb distortion
- ▶ reaction Q-values from mass tables

for composite projectiles:

- ▶ frozen Fermi motion
- ▶ complete fusion at low energy

# Q-values from experimental masses



## old ingredients (in INCL4.5)

- ▶ strict Pauli blocking on first collision
- ▶ free nucleon-nucleon cross sections

## new ingredients (in INCL4.6)

for all projectiles:

- ▶ Coulomb distortion
- ▶ reaction Q-values from mass tables

for composite projectiles:

- ▶ frozen Fermi motion
- ▶ complete fusion at low energy

## old ingredients (in INCL4.5)

- ▶ strict Pauli blocking on first collision
- ▶ free nucleon-nucleon cross sections

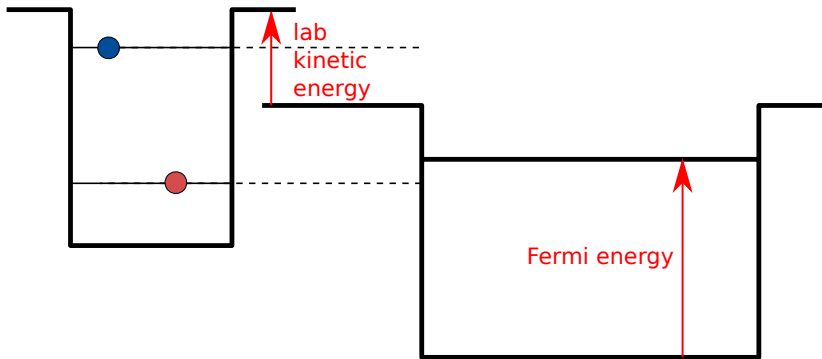
## new ingredients (in INCL4.6)

for all projectiles:

- ▶ Coulomb distortion
- ▶ reaction Q-values from mass tables

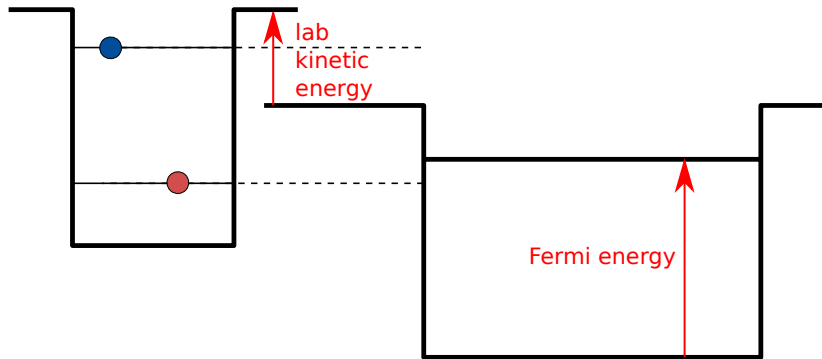
for composite projectiles:

- ▶ frozen Fermi motion
- ▶ complete fusion at low energy



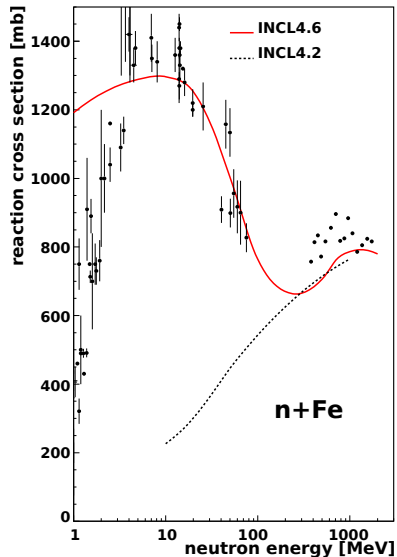
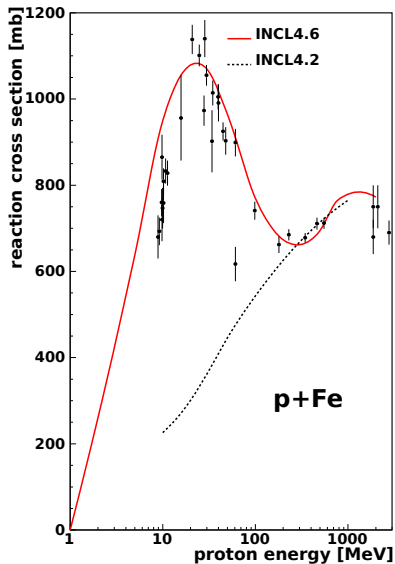
⇒ fusion with projectile nucleons that satisfy

$$r < R_0 + \sqrt{\sigma_{NN}/\pi}$$

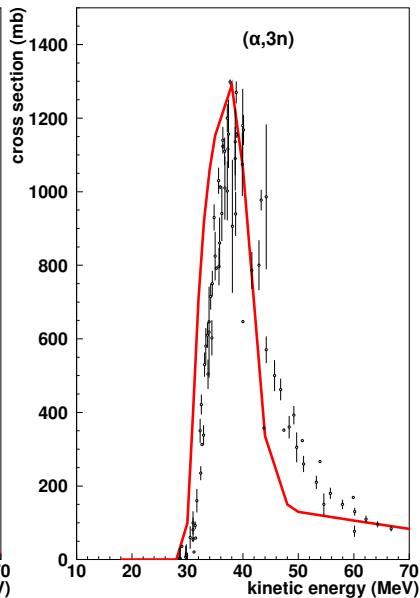
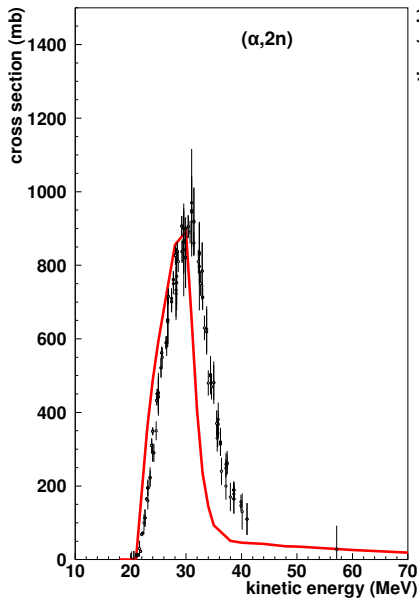


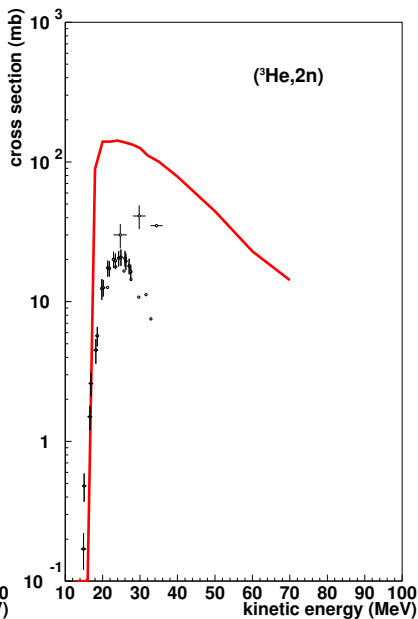
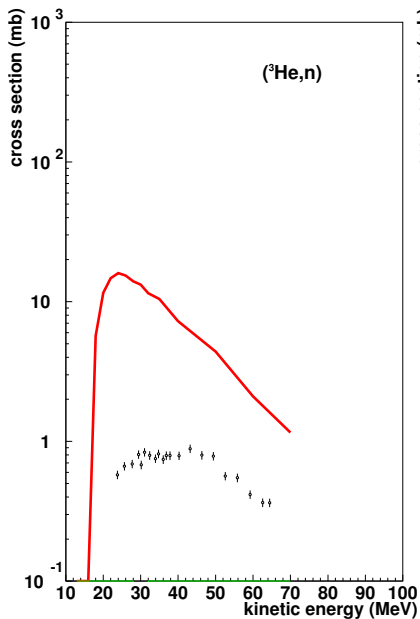
smooth transition to cascade

# reaction cross sections









## Introducing INCL++

code rewritten **from scratch** in modern **C++**

by P. Kaitaniemi and DM

- ▶ physics-wise and **equivalent** to INCL4.6
- ▶ **no** CPU penalty
- ▶ **available** in GEANT4 v9.5

### Improved the **predictive power** of INCL at low energy

#### **Crucial** ingredients:

- ▶ Coulomb distortion
- ▶ reaction Q-values from mass tables
- ▶ frozen Fermi motion
- ▶ complete fusion at low energy

#### **Future** development:

- ▶ extension to **light-ion-induced** reactions (up to oxygen)

## Sub-task 4.4.1: Improving the high energy models

(Sub-task Leader: ULG)

Participant: 

### *GSI duties*

Improvement of the de-excitation code ABLA.

### *Deliverable*

D4.2 New versions of the INCL4 and ABLA models improved in the 150-600 MeV domain (report and codes) (M30 = October 31, 2012) (ULG)

### *Status of the work: ABLA07v2*

The work goes on. No delay in deliverables expected.

## Latest improvements in the de-excitation code ABLA:

1. Implementation of a new parameterization of the barrier for the emission of LCPs and IMFs and its position, according to W.W. Qu et al., NPA 868 (2011) 1.
2. Faster sampling of mass and nuclear charge of evaporated IMFs.

*Points 1. and 2. make code almost a factor of two times faster as compared to the previous version.*

3. Inclusion of  ${}^6\text{He}$  as evaporative LCP additional to  ${}^{1,2,3}\text{H}$  and  ${}^{3,4}\text{He}$ .
4. Possibility to use experimental ground-state masses.

# Multiplicities of evaporated n and LCPs

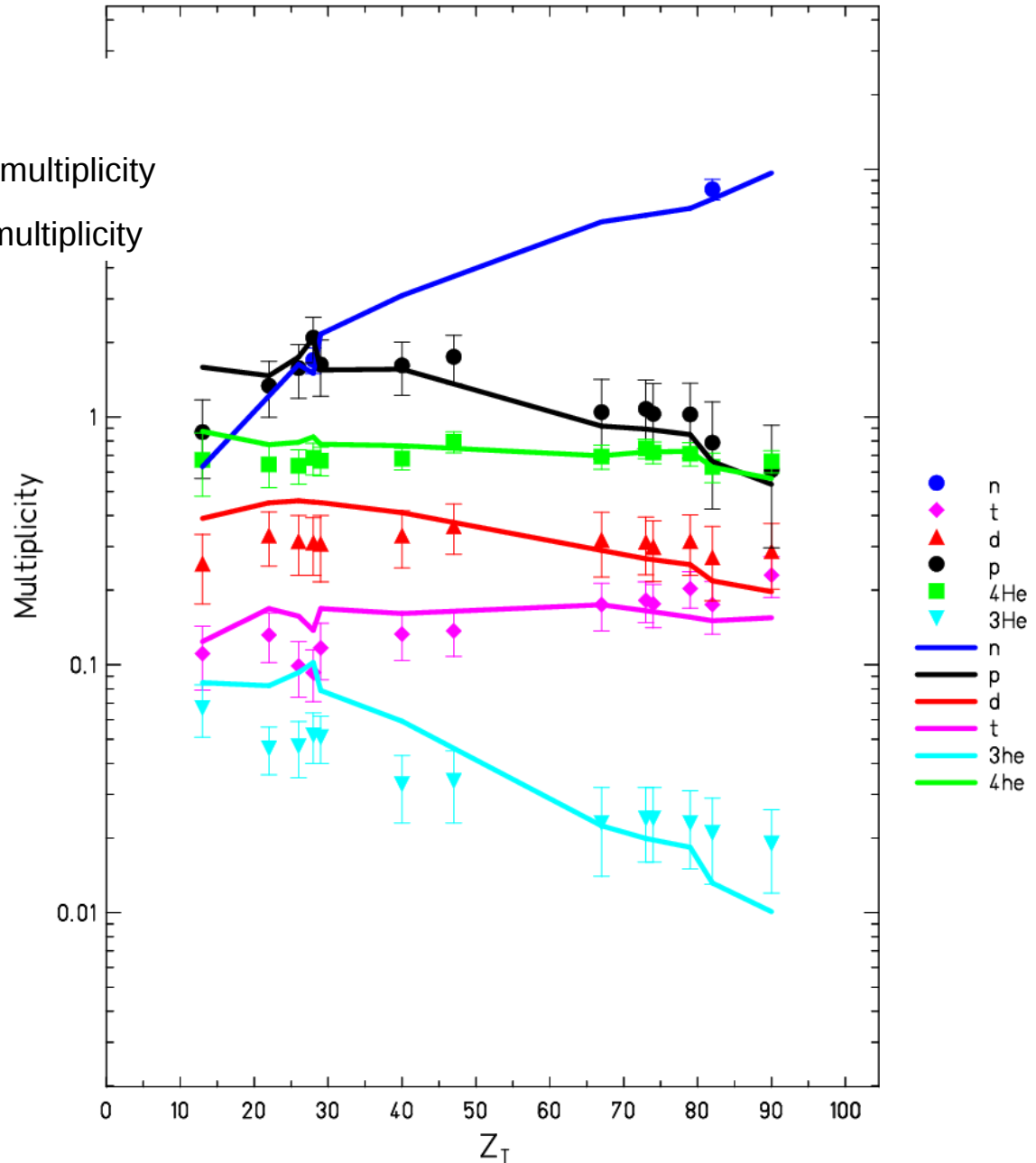
1200 MeV p + target

Average evaporated neutron (2-20 MeV) multiplicity

Average evaporated LCPs (0-100 MeV) multiplicity

**Points** – experimental data taken from the Spallation benchmark database

**Lines** – ABLA's predictions



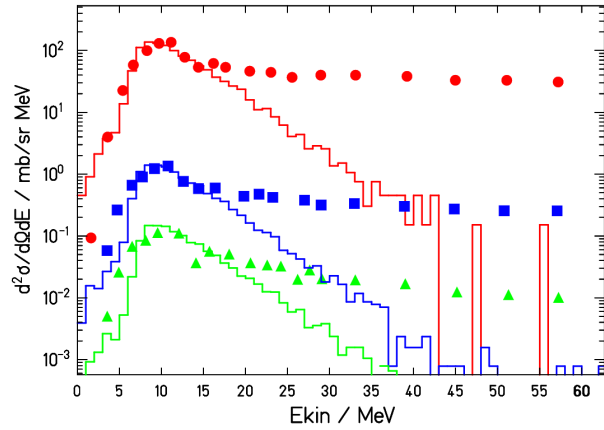
# Double differential cross sections for LCPs

Only evaporative part of calculated spectra (ABLA) is shown

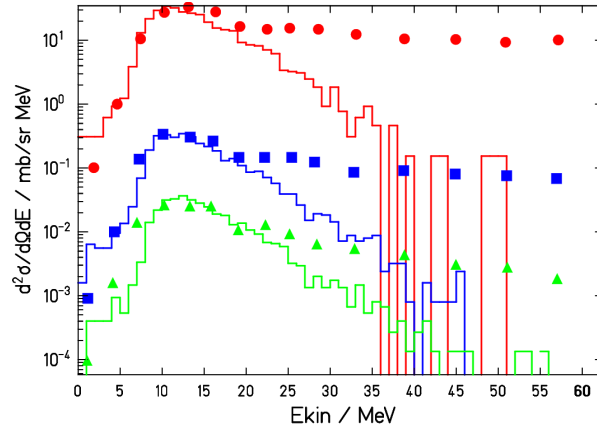
## 1200 MeV p + $^{181}\text{Ta}$

Data von COSY, C.-M. Herbach et al., Nucl. Phys. A 765 (2006) 426

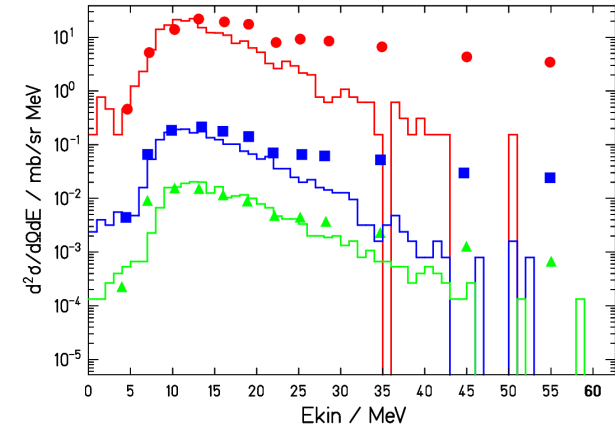
### Proton



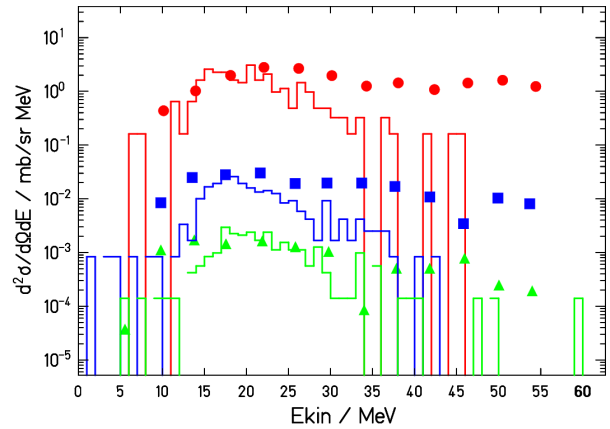
### Deuteron



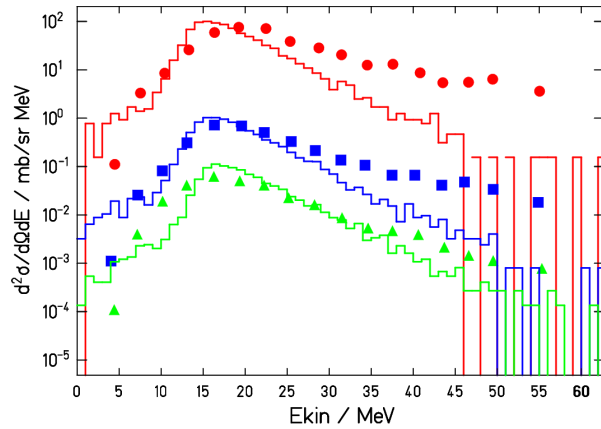
### Triton



### $^3\text{He}$



### Alpha



Scaling factors for displaying:

30 deg \* 10

75 deg \* 0.1

150 deg \* 0.01.

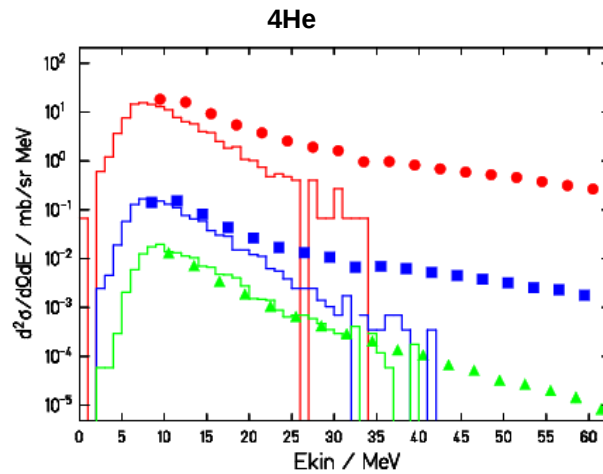
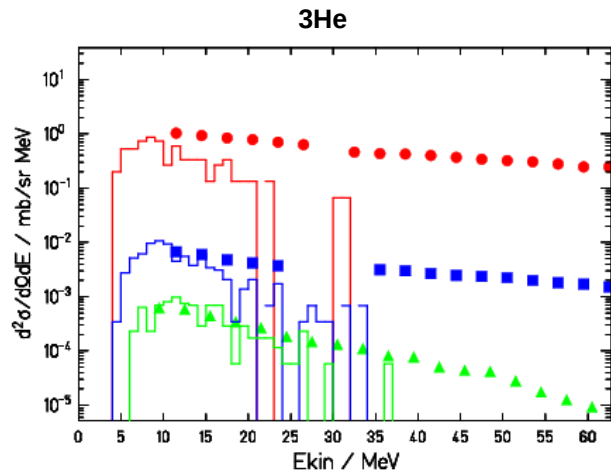
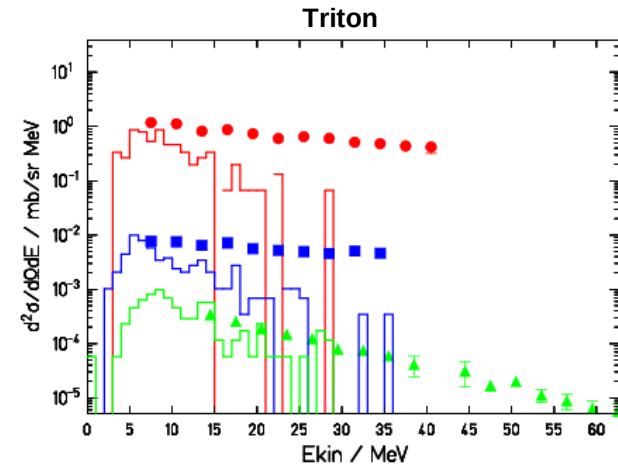
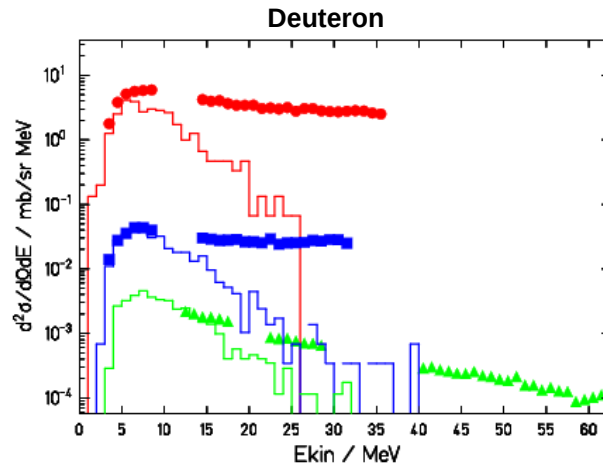
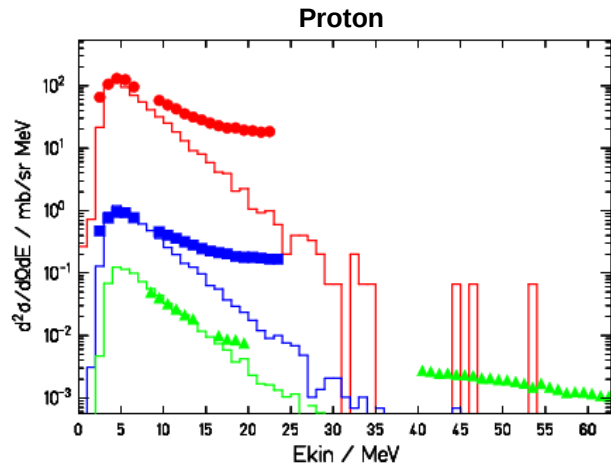


# Double differential cross sections for LCPs

Only evaporative part of calculated spectra (ABLA) is shown

175 MeV  $p + {}^{58}\text{Ni}$

Data von COSY, A.Budzanowski et al., Phys. Rev. C80 (2009) 054604.



Scaling factors for displaying:

30 deg \* 10

75 deg \* 0.1

150 deg \* 0.01.