Intranuclear cascade model for cluster production reaction

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Intranuclear cascade (INC) model

Spallation reactions at intermediate-energies
DDX of (p,p’x), (p,nx), , ,
nucleon spectra from nucleon-induced reactions
reasonable prediction in a wide energy range

Particle transport simulation; PHITS, Geant4, ...

Intensive developments of simulation tools require predictive power in cluster productions.

INC advantage = high flexibility $\neq$ exact theory

Extension toward any direction

physics modeling:

reasonable, appropriate, consistent, , ,

$\rightarrow$ generalization; target, energy, cluster

Deep understanding of the process is essential.

Physics model in INC :

succession of binary hard collisions

Repulsive interaction

No attractive interaction

Cluster formation is not included.

Do we add an attractive interaction?

1st question

INC = binary hard collisions

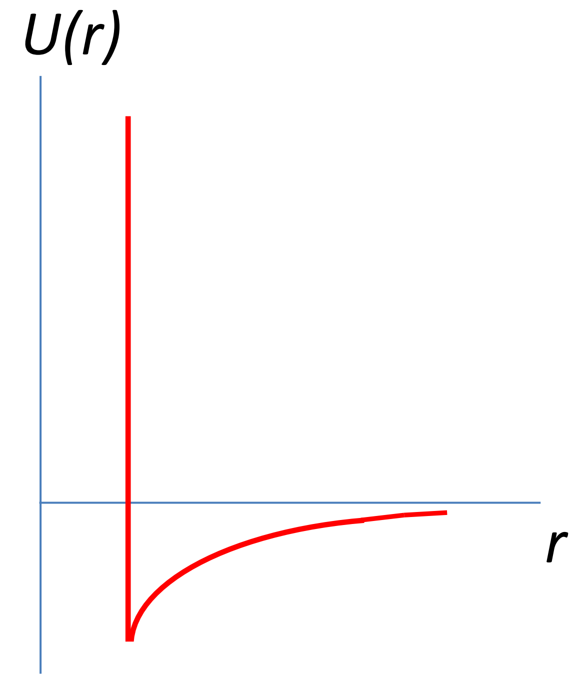
What is the hard collision?

hard repulsive core

Large q

$\longrightarrow$ continuum state

- particle like picture



Soft collision = shallow part of potential

potential scattering ; elastic, inelastic

direct reaction wave function

- wave like picture

Clustering;

Which picture, particle or wave ?

n + p $\longrightarrow$ d + γ

No chance for classical particles to be bound at positive energies.

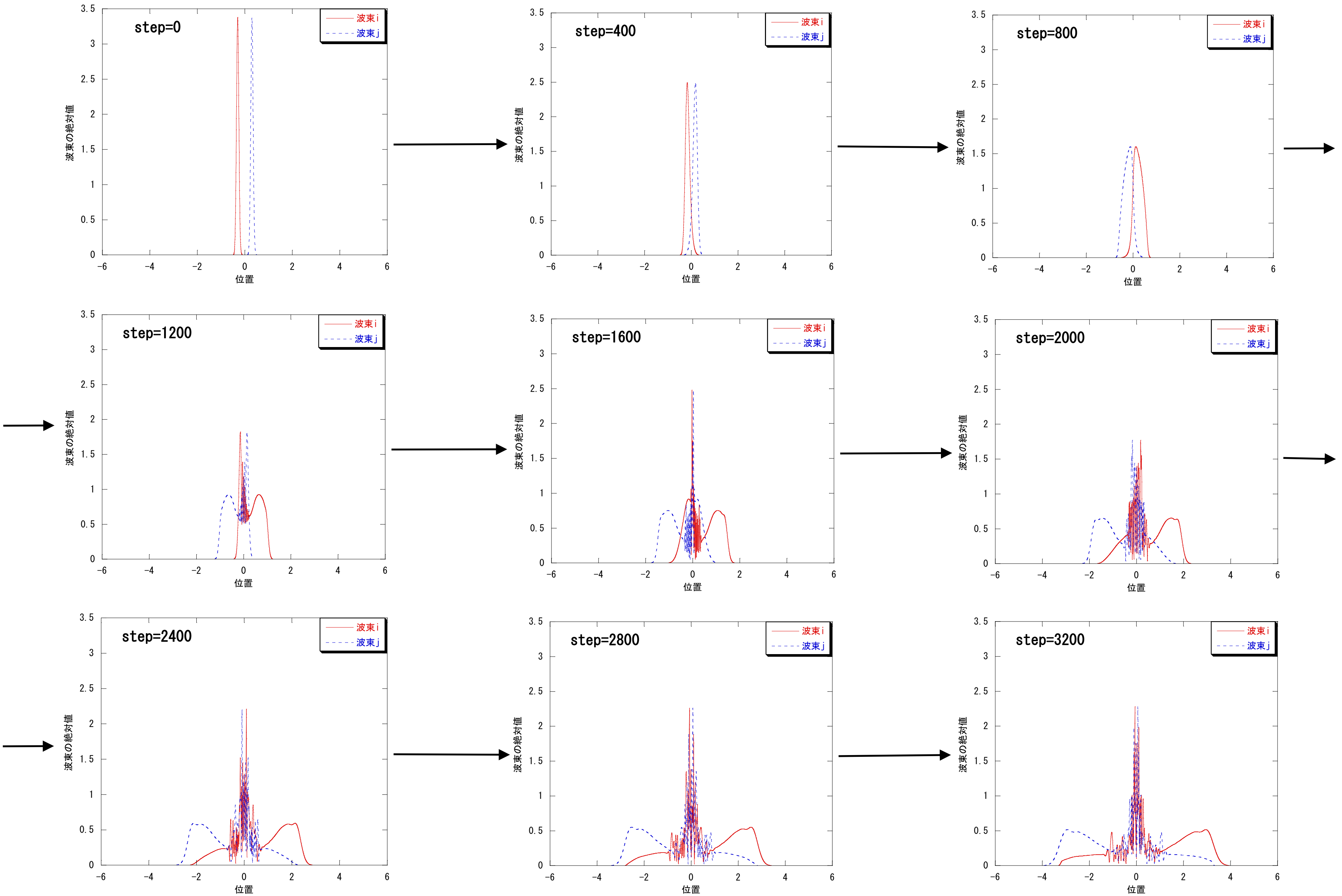
➡ attractive force is not essential

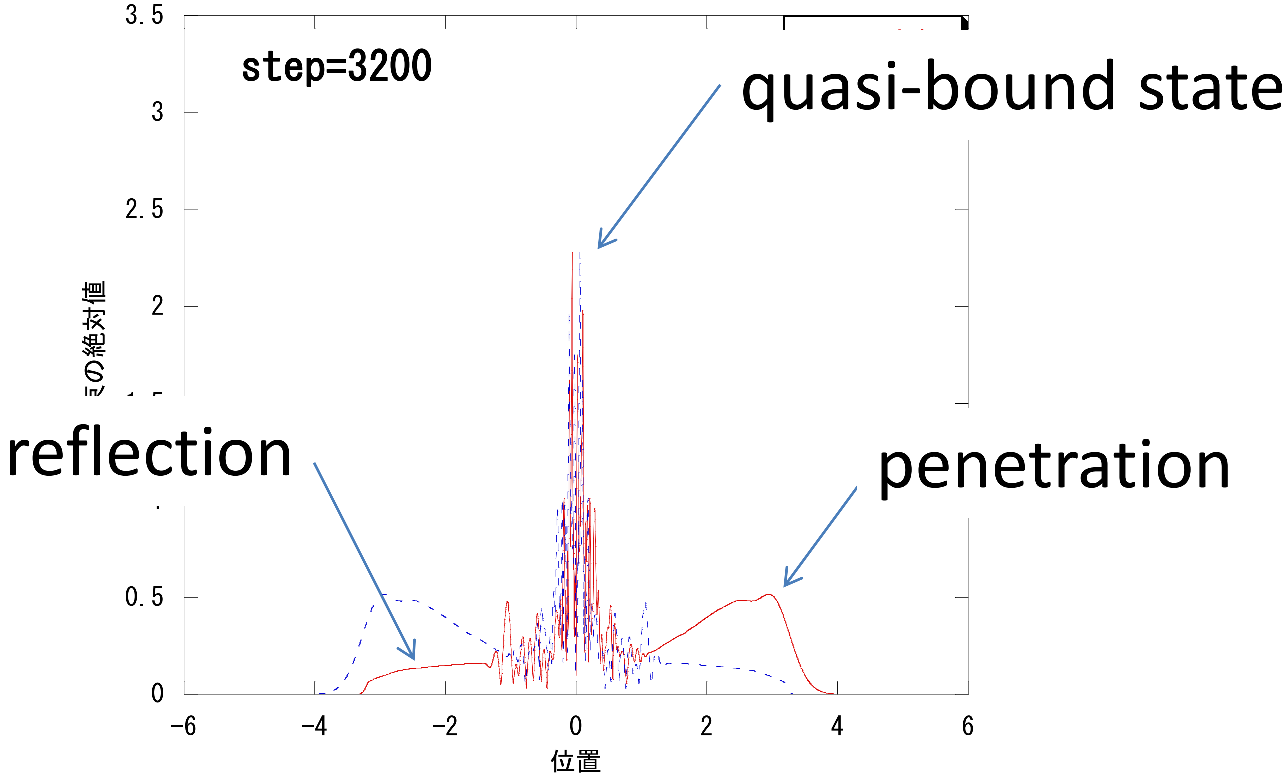
Wave?

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left(\hat{T} + V(x,t)\right)\psi(x,t)$$

$$\psi(x_i, x_j, t) = \phi_i(x_i, t)\phi_j(x_j, t)$$

Time development of Gaussian wave packets





Cluster (correlation) = particle + wave

MC = Introduce probability to form a cluster

Probability should be determined to fit exp.

2^{nd} question

Which processes should be included ?

Possible processes in forming a (deuteron) cluster

(1) indirect knockout p+<d>
(2) Higher order, rescattering <d>+<N>

(3) Indirect pickup $\Delta p \cdot \Delta x$
(4) Coalescence $\Delta p \cdot \Delta x$ or $\Delta E \cdot \Delta t$?

(5) direct (pickup, knockout) : shell state excitation
(6) direct formation p+<N> = d + π or γ

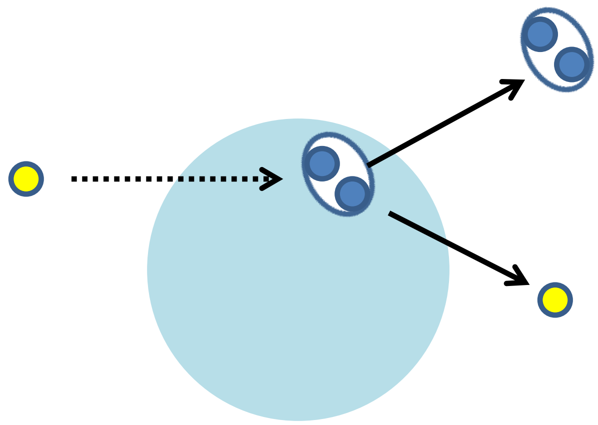
Previous studies on cluster productions

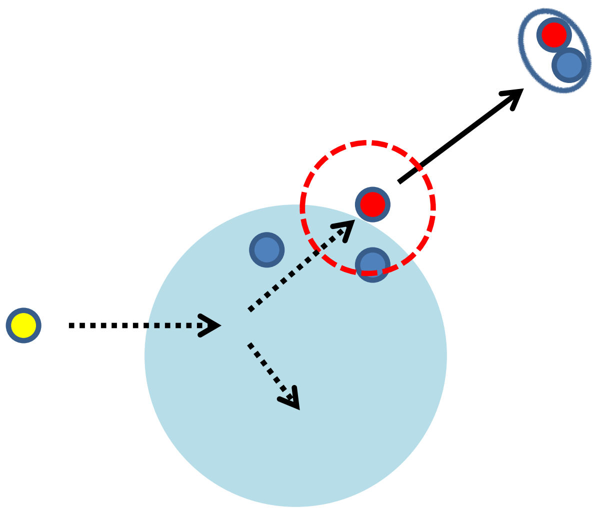
Many theoretical efforts

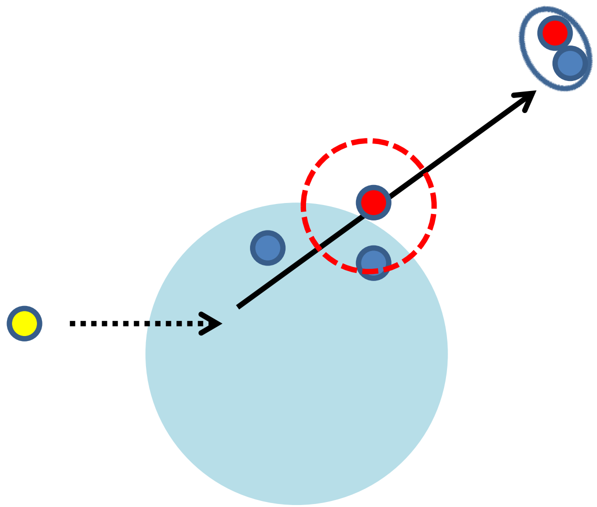
exciton model or hybrid model

two directions:

1. knockout (preformed cluster)
2. coalescence or pickup





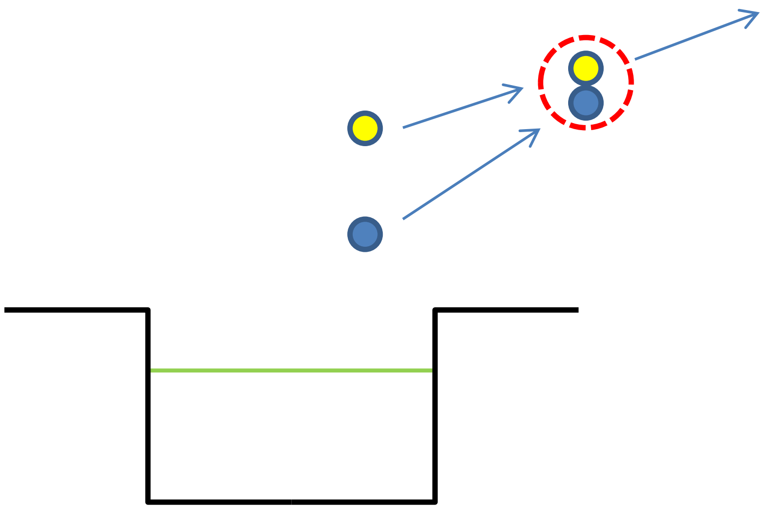


coalescence / pickup

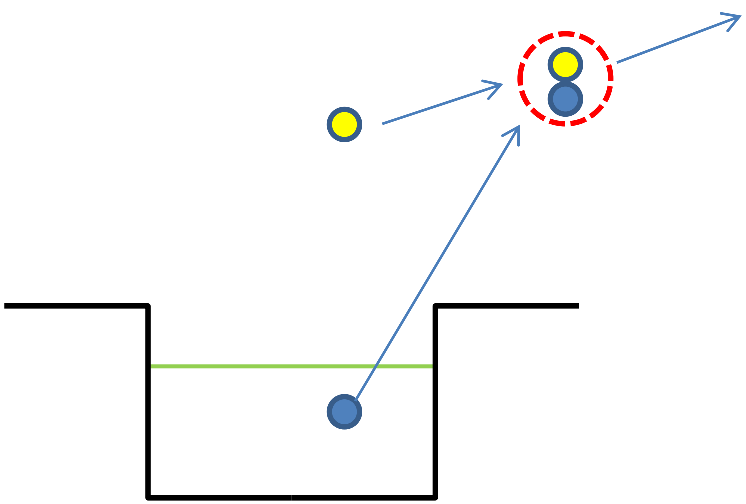
Lower energy, more chance to find a partner.

Responsible for low energy cluster production

$\Delta p \cdot \Delta x < C$



coalescence



pickup

Why opposite pictures in exciton model studies?

Low beam energies below 100 MeV might cause this ambiguity.

higher beam energy 1 GeV?, less ambiguity.

pickup : lower energy part

Phase space limits high energy cluster

knockout : higher energy part of spectra

preformed cluster $\approx$ elementary particle

Both processes should be responsible.

Another ambiguity : knockout

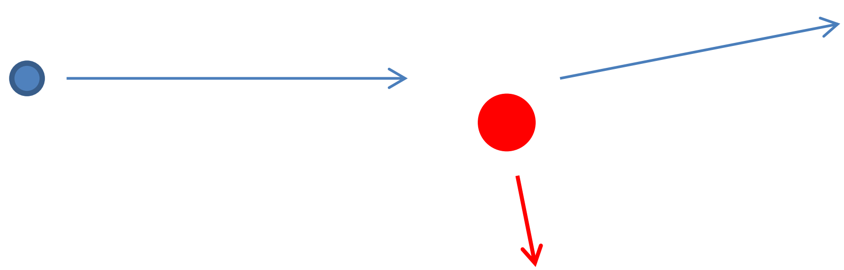
The exciton model does not involve angular momentum.

forward-peaked angular distributions in experimental data

impossible in classical cluster-knockout picture.

N+<cluster> scattering

cross section, Pauli blocking



(p,dx) reaction has been open question

- very weak binding of a deuteron
- probability to find a deuteron in a nucleus
- real d or virtual ? Pauli principle
- Nd scattering cross section, angular distribution, unknown
- disintegration probability after Nd scattering

(p,dx) spectrum

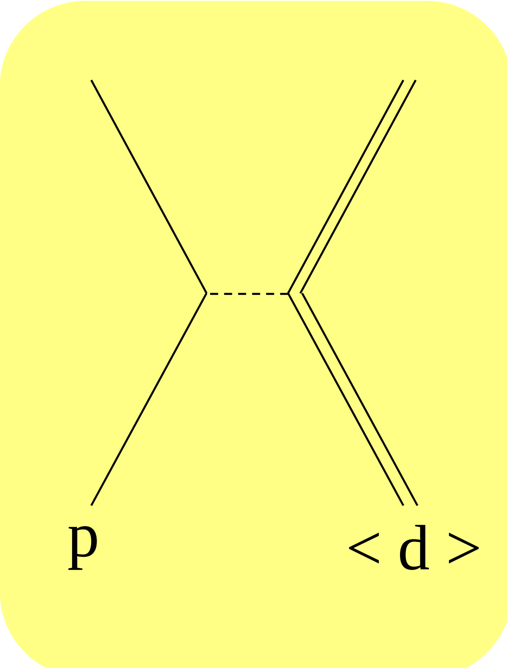
quasi-free like bump at forward angle.

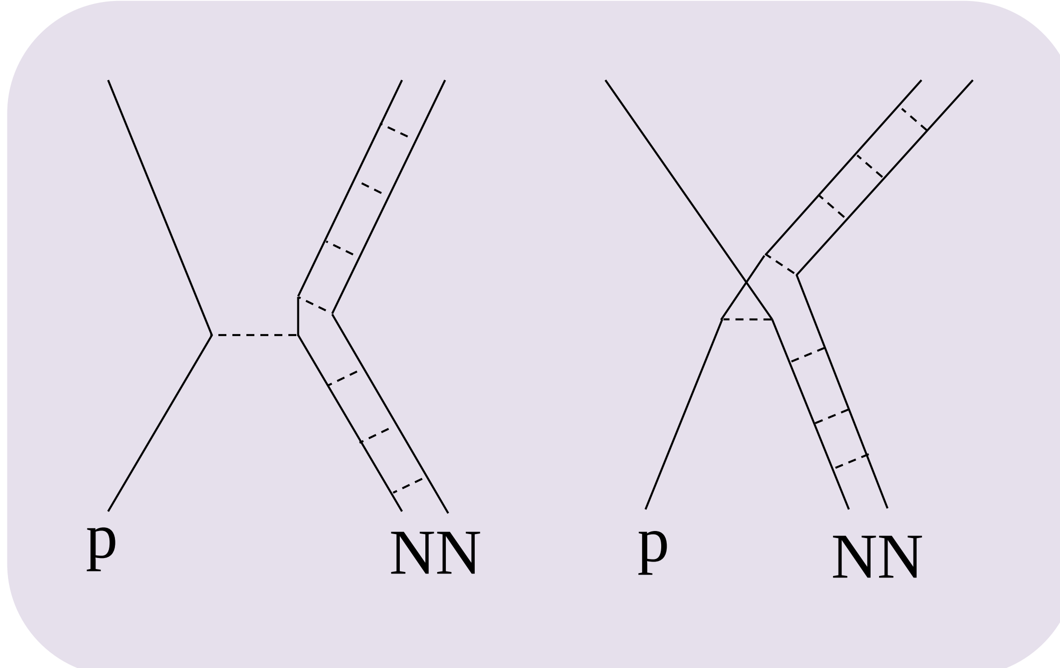
real d + N scattering is not a forward peak distribution

Strongly correlated pn pair

iso-spin forbidden transition in (e,e’d) reaction is explained in terms of the deuteron integration

Cluster knockout





d =
Elementary particle
Non-purterbative

d = composite particle
purterbative

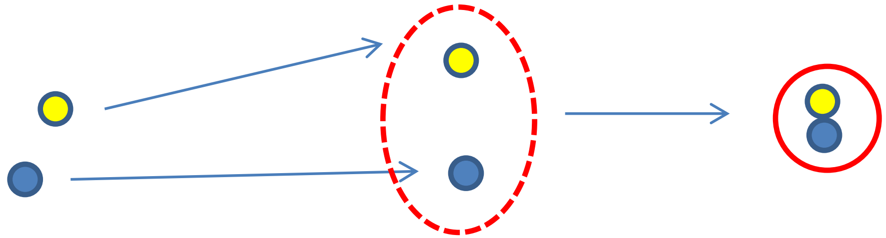
Forward peak ← exchange term
NN cross section
Pauli blocking

QMD and AMD

= Molecular dynamics : attractive force

Coalescence like

relative momenta to CM should be small



Particle picture = phase space Δp･Δx

High-energy cluster formation = wave picture

Direct reaction = soft collision

wave function plays a role

Not classical picture

Cluster formation requires binding at positive energy

initial state

gr.st. cluster the higher order in single particle states

(1) indirect knockout p+<d>

(2) Higher order, rescattering <d>+<N>

$$|Gr\rangle = c_1 |(s.p.)_A\rangle$$

$$+ \ c_2 |(s.p.)_{A-2} (d)_2\rangle$$

$$+ \ c_3 |(s.p.)_{A-4} (\alpha)_4\rangle$$

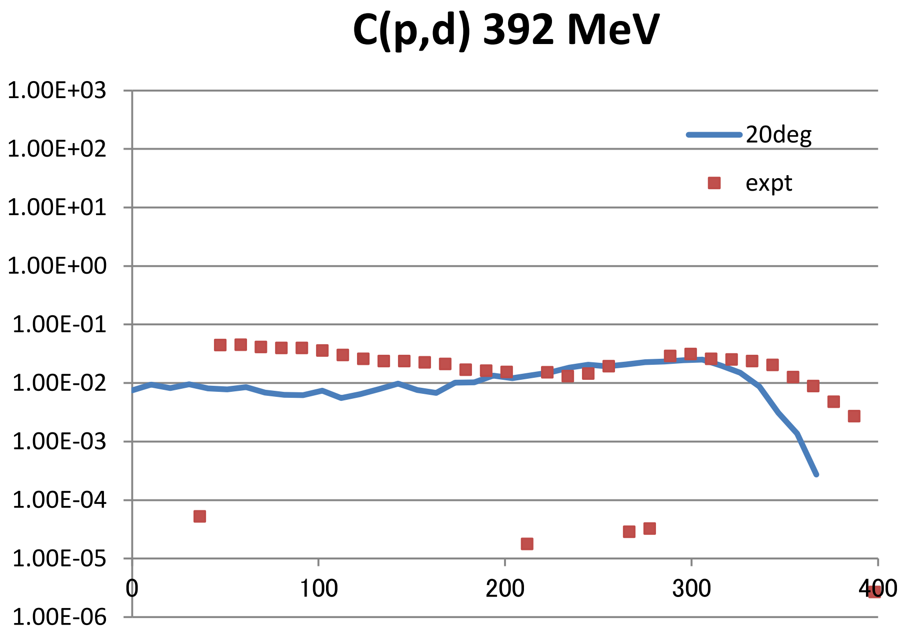
$$+ \ \cdot\cdot$$

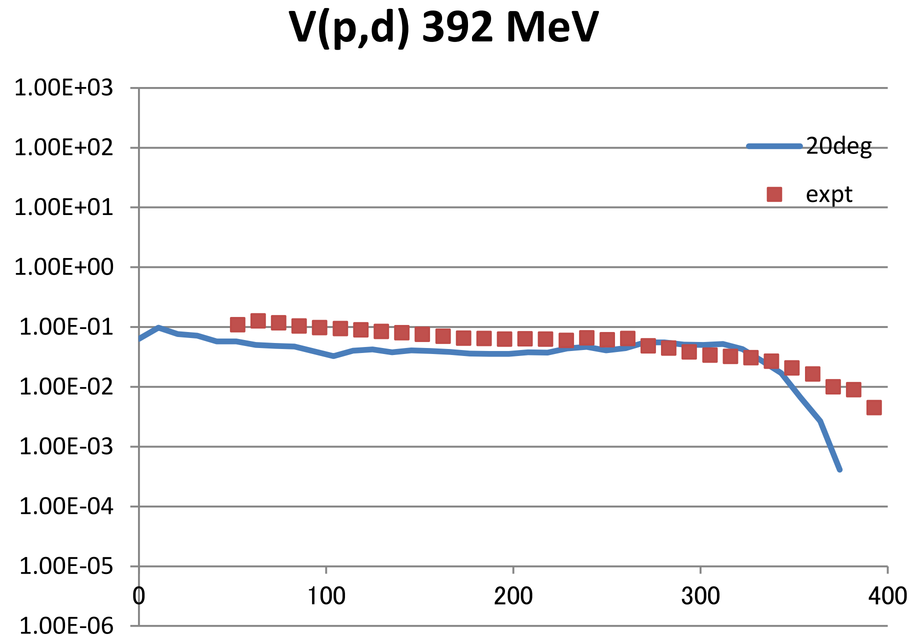
final state

(3) Indirect pickup $\Delta p \cdot \Delta x$

(4) Coalescence $\Delta p \cdot \Delta x$

only knockout





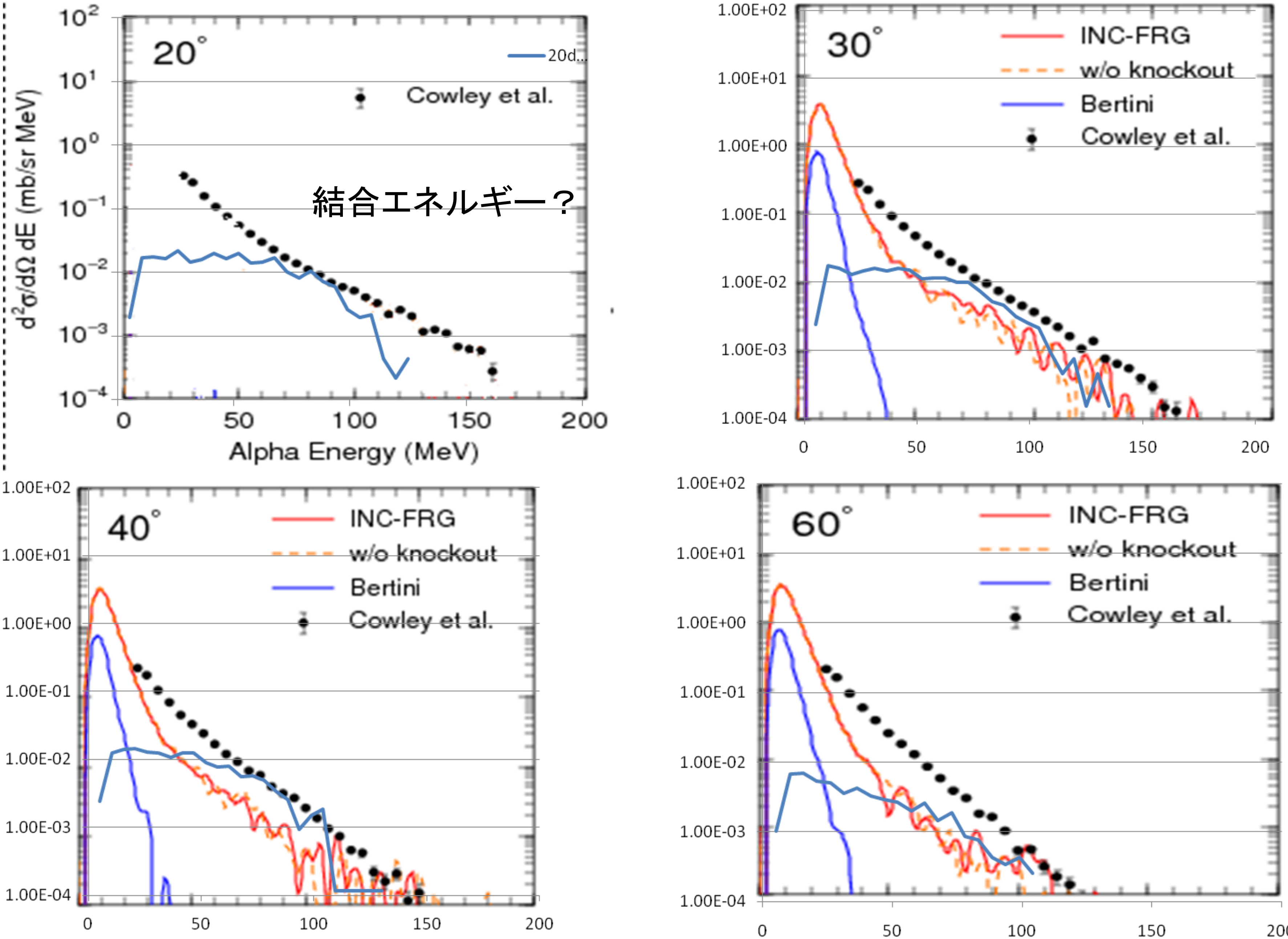
only knockout

Lower energy： indirect pickup、coalescence、evaporation

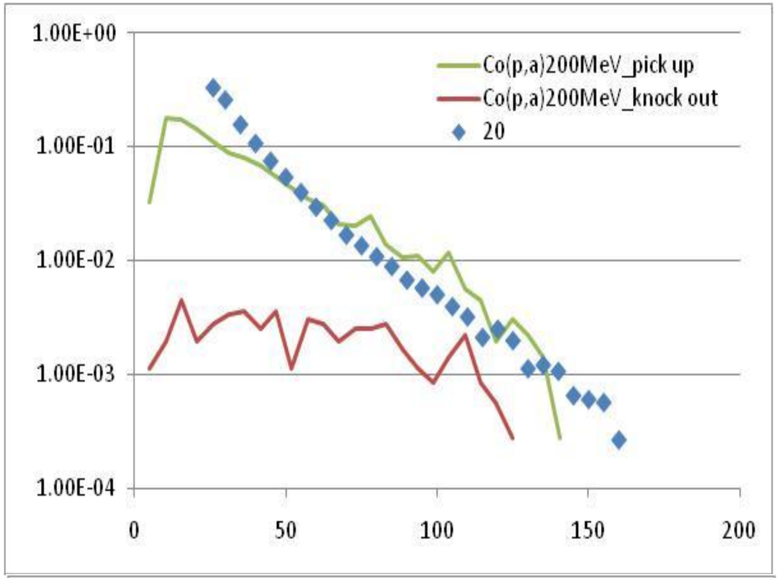
Highest energy ：

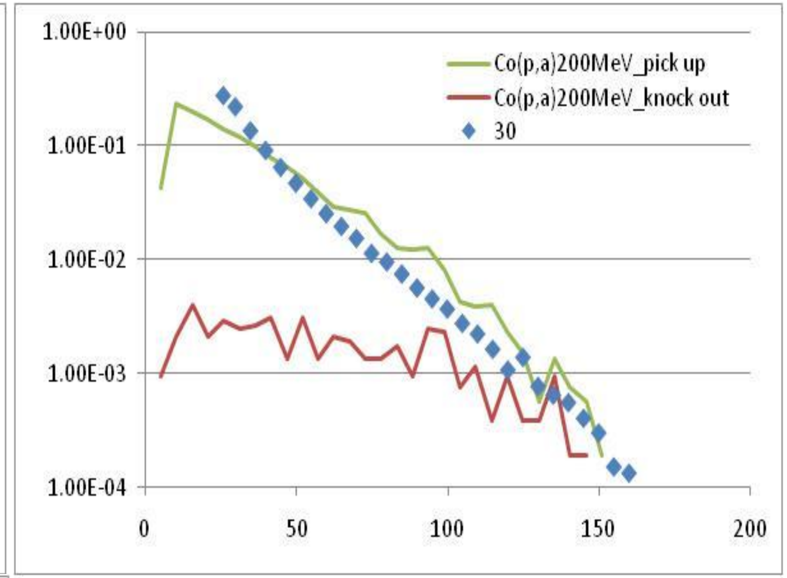
- p + <n> = d
- p + <N> = d + pi
- direct pickup

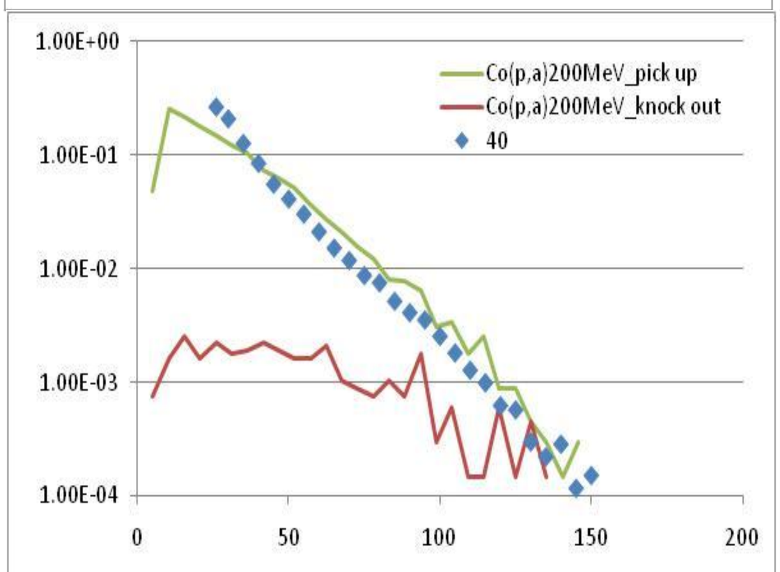
Co(p, α) at 200 MeV　only knockout

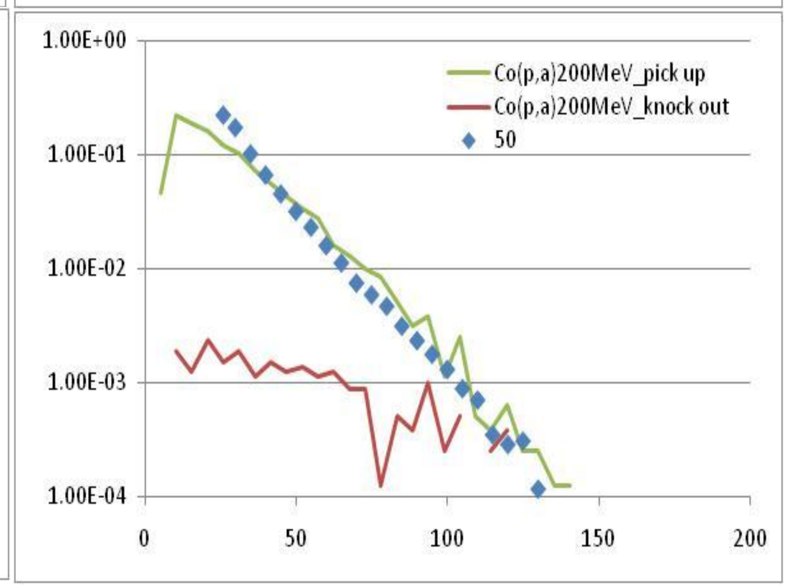


Co(p, α) at 200 MeV pickup

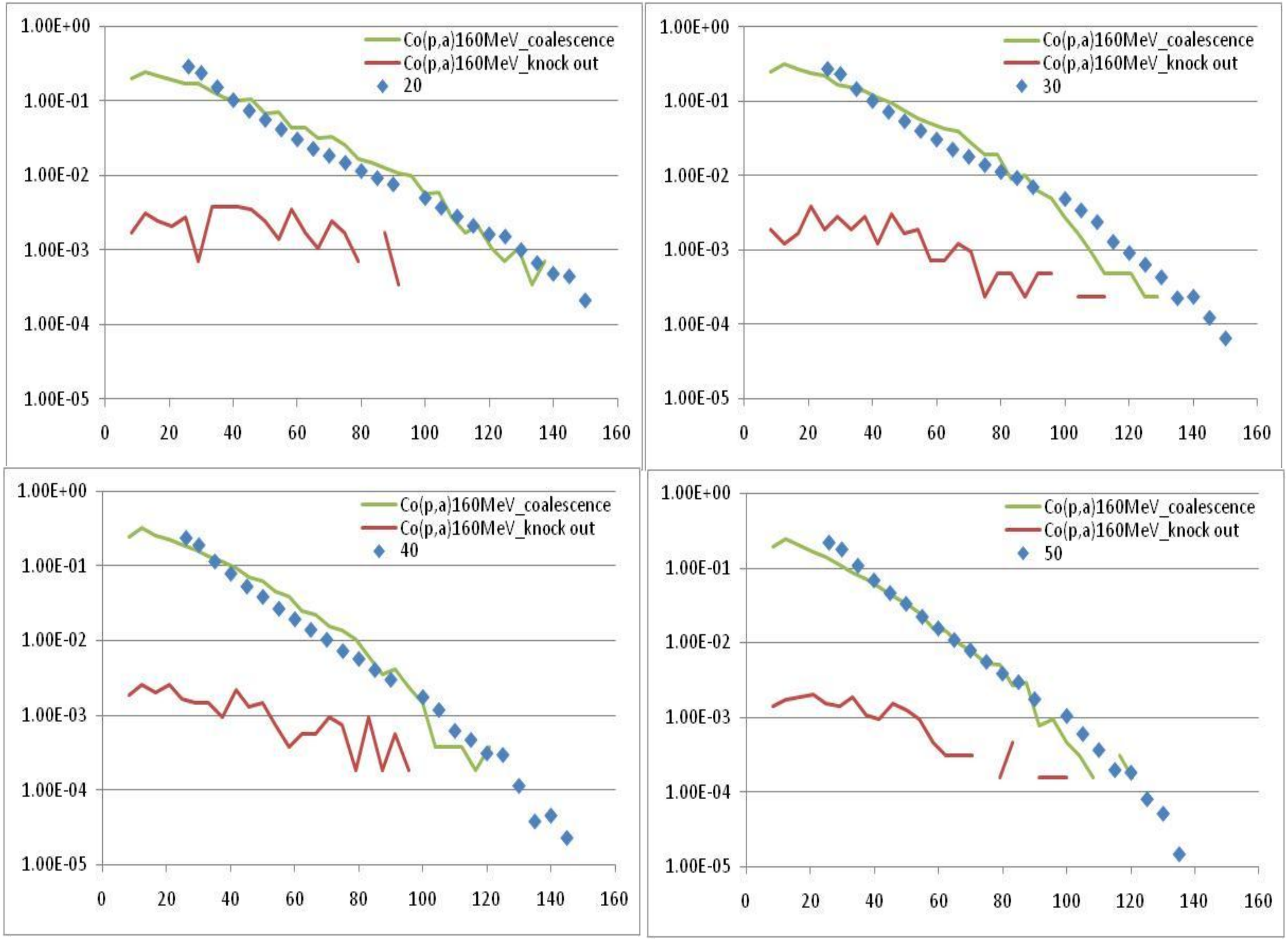






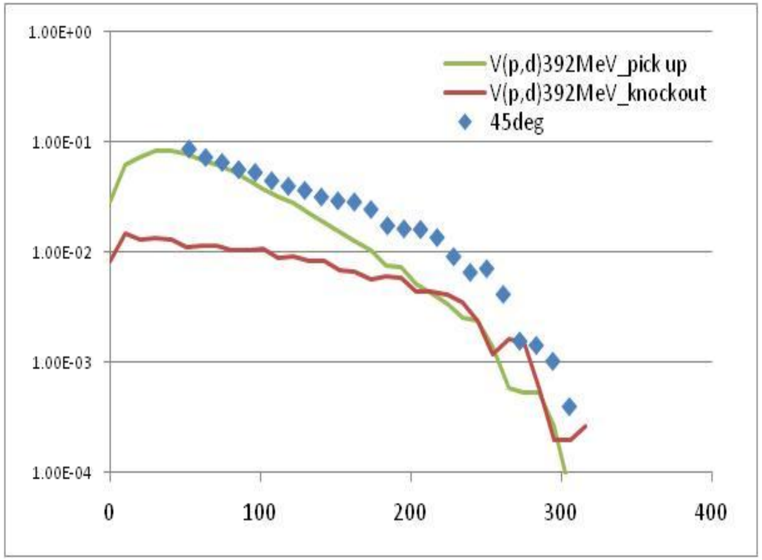


Co(p, α) at 160 MeV pickup

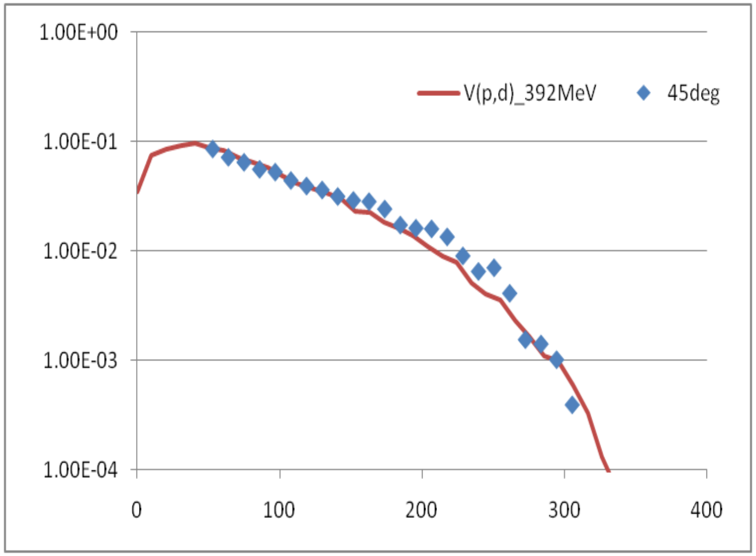


V(p, d) at 392 MeV

pickup (green), and **knockout (red)**

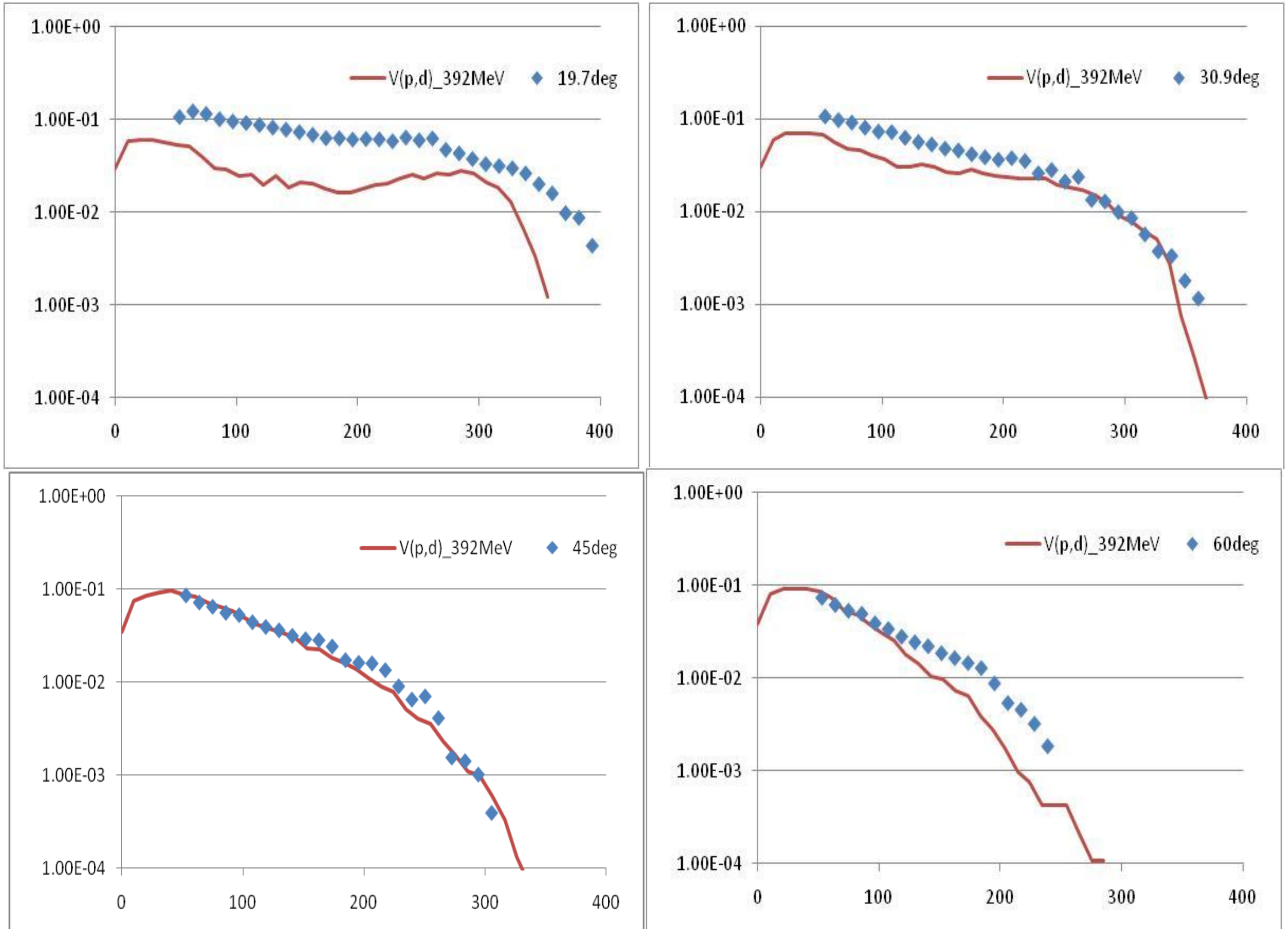


Pickup;
Underestimate high-energy part

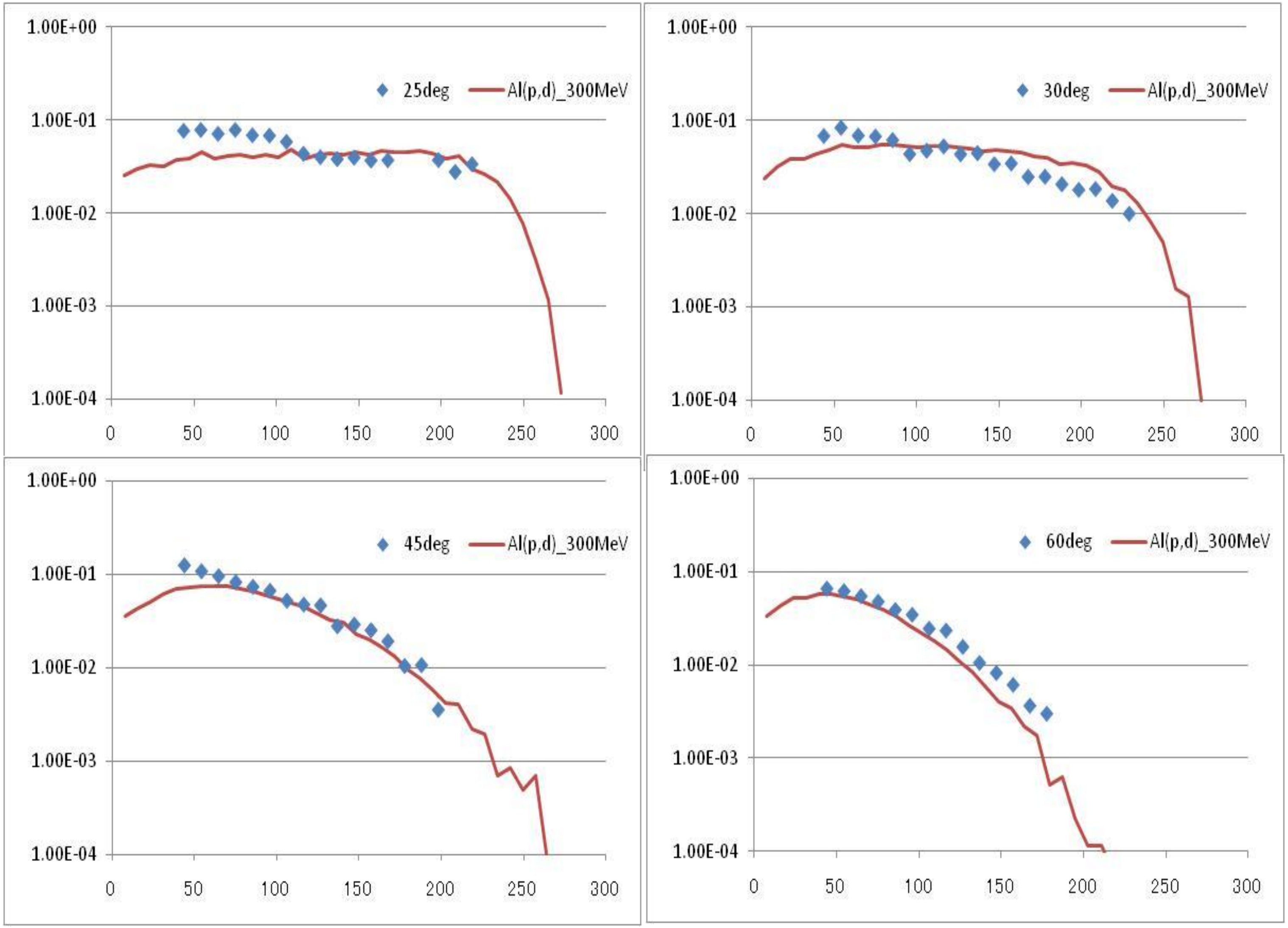


Sum of pickup and knockout

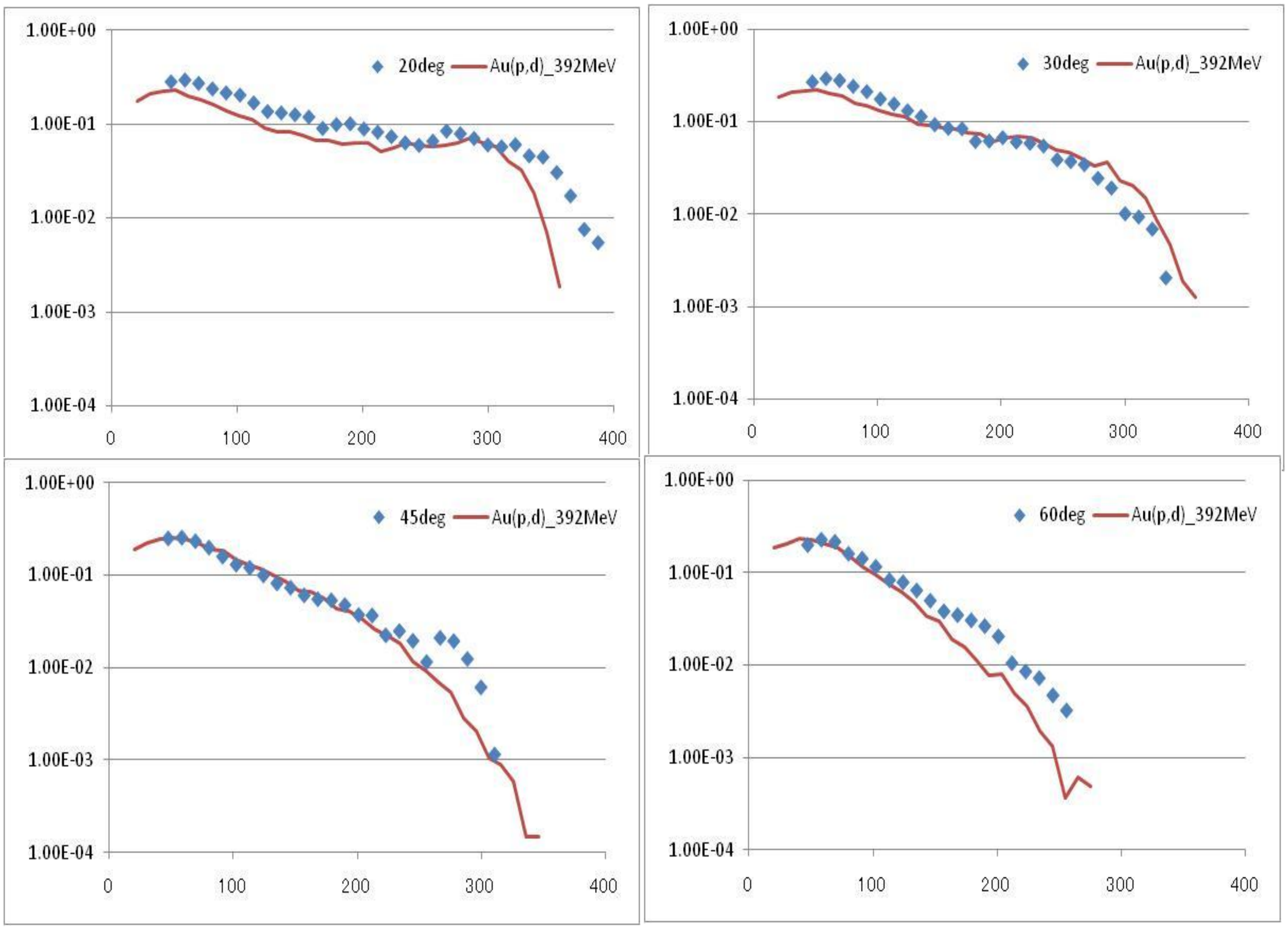
V(p, d) at 392 MeV pickup + knockout



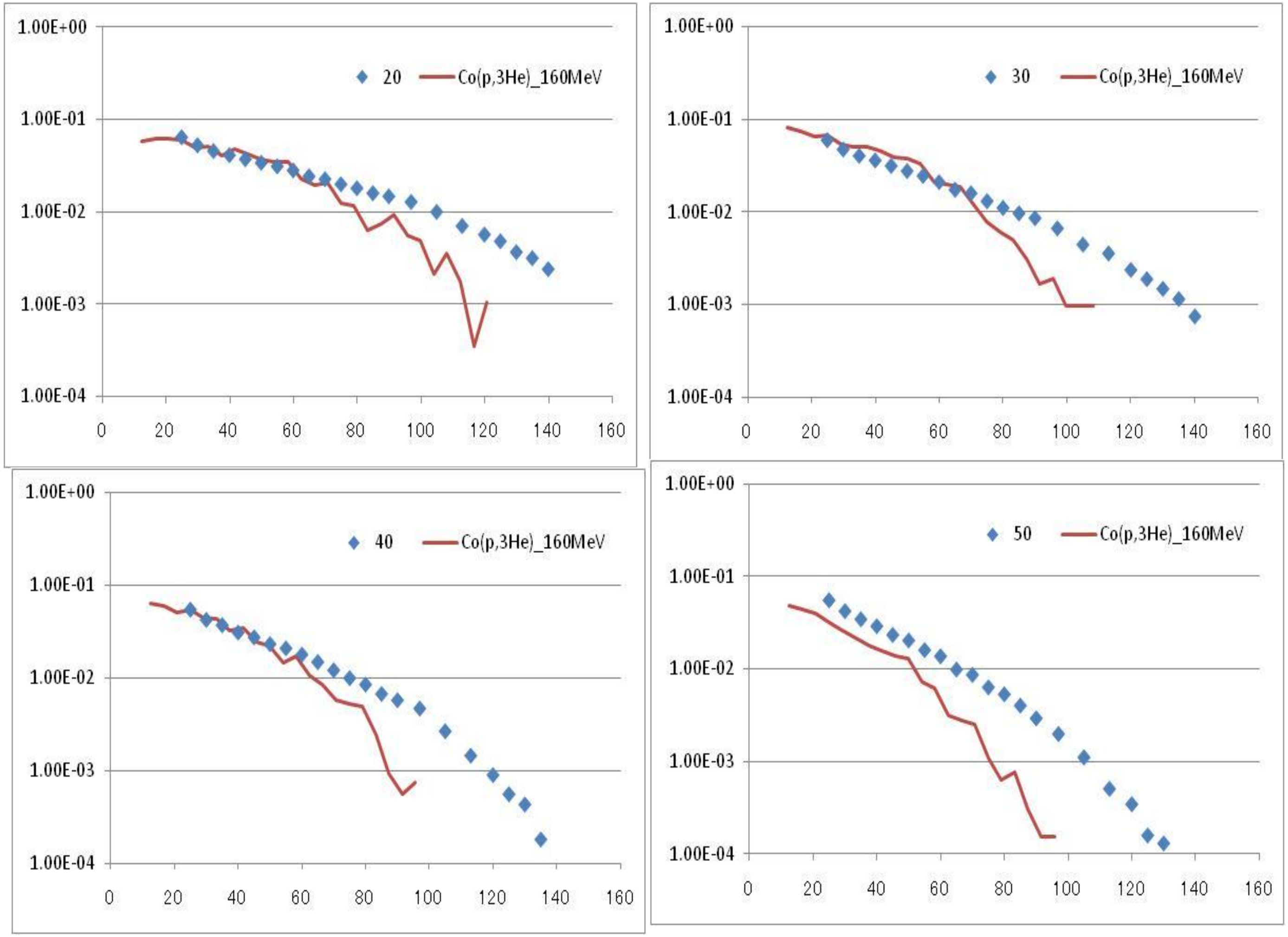
Al(p, d) at 300 MeV pickup + knockout



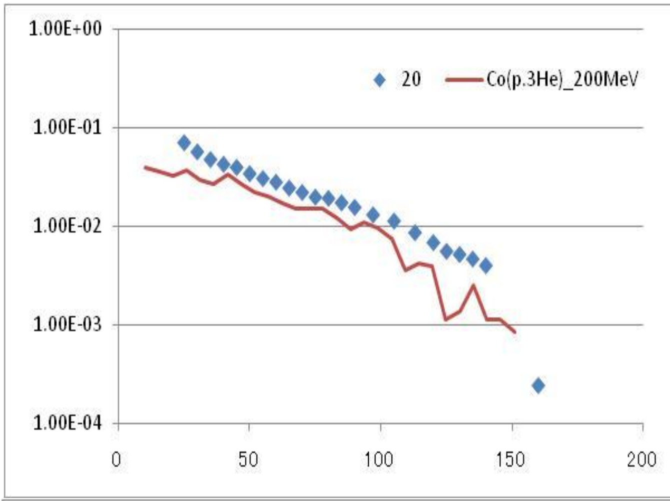
Au(p, d) at 392 MeV pickup + knockout

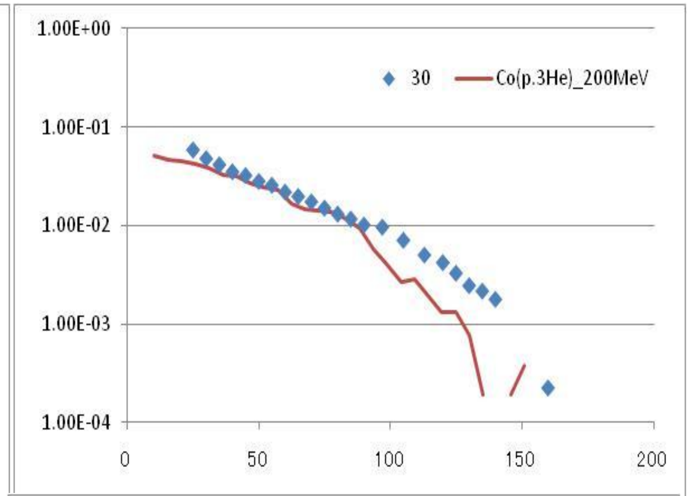


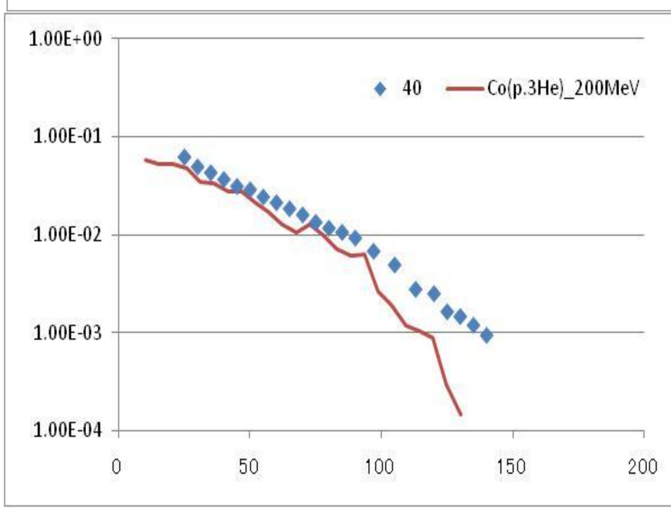
Co(p, 3He) at 160 MeV pickup + knockout

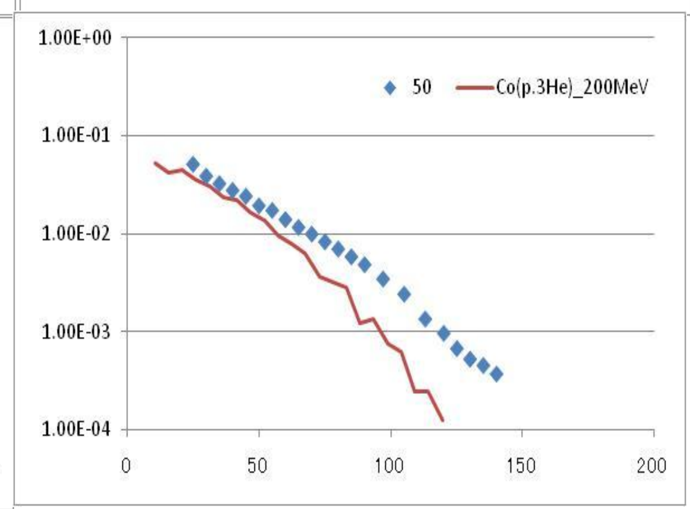


Co(p, 3He) at 200 MeV   pickup + knockout





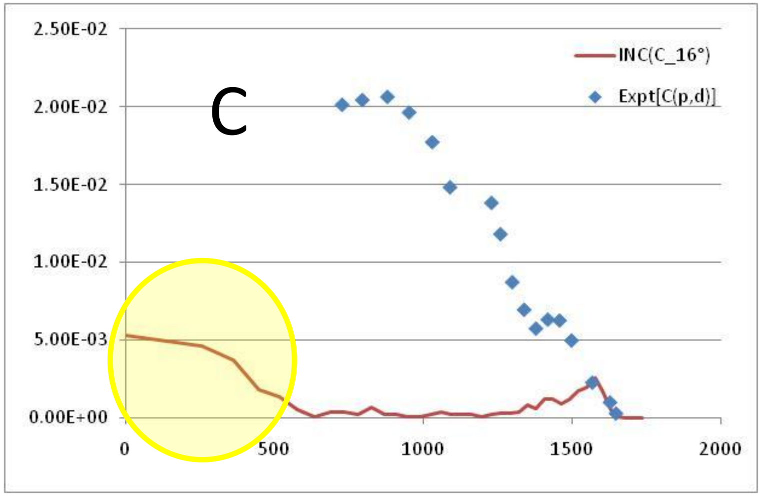




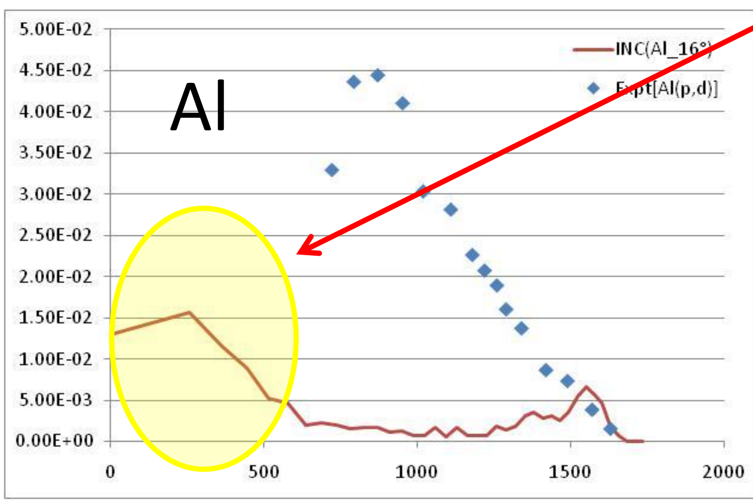
(p,d) at 670 MeV, 16deg

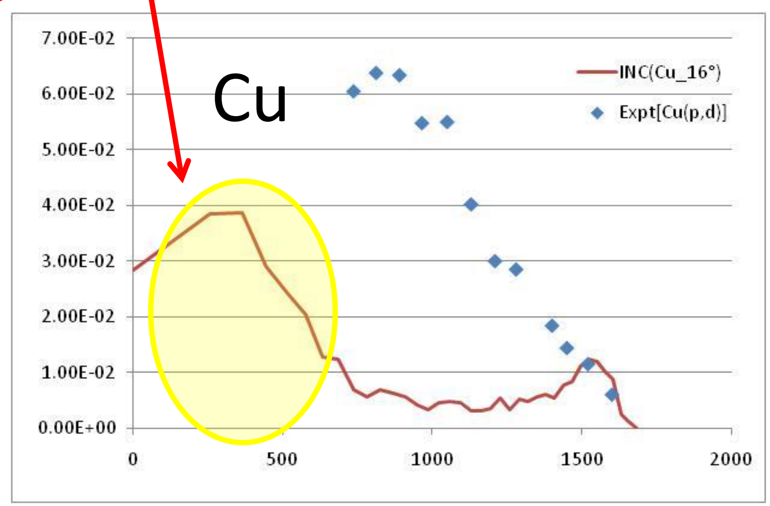
Only elastic NN scattering

Inelastic influences KO
need more KO



pickup ; No high-energy





Summary

INC light cluster production (p,d), (p,3He), (p, α)
pickup and knockout

Case 1; **More pickup**

Overall good accounts
for (p,d), (p,3He), (p, α)
underestimation: 392-MeV (p,d) 20deg
670-MeV (p,d) 16 deg

Case 2; **only knockout**

Overall good accounts for (p,d), (p, α)
670-MeV (p,d) 16 deg ???

$\leq$ 400 MeV good

$\geq$ 600 MeV Δ, π, knockout/pickup