Cluster productions in intermediate-energy proton-nucleus reactions

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Tenaya Lodge at Yosemite

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Actual Condition of Intranuclear Cascade Model

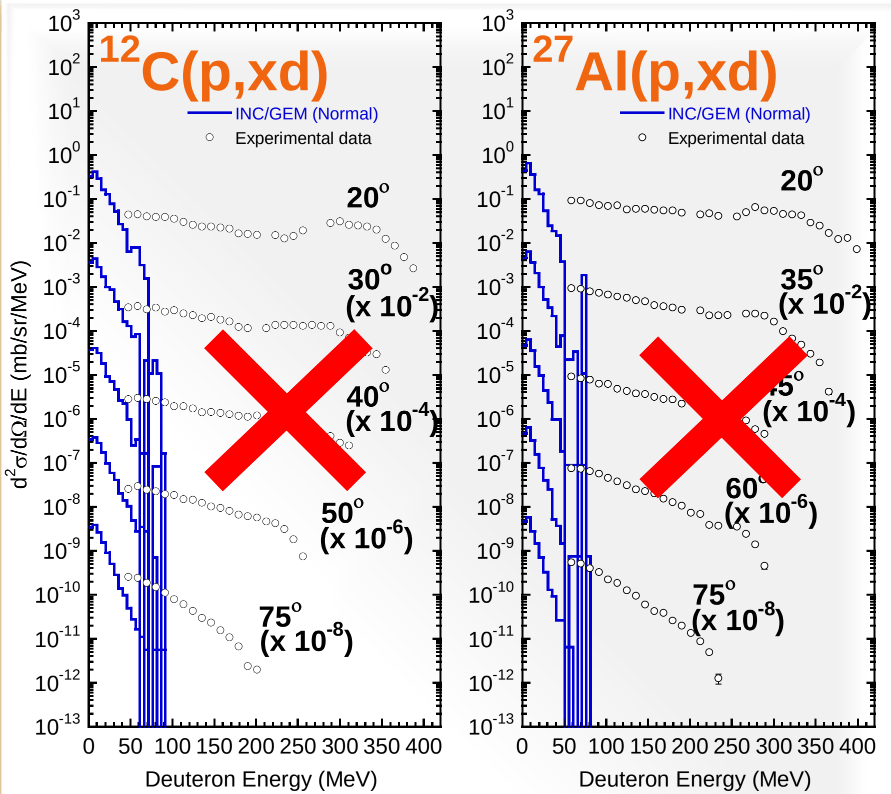
- Conventional intranuclear cascade (INC) models

✓ **Neutron** and **proton** productions

➡ **PREDICTABLE!**

✓ **Cluster** productions

➡ **UNPREDICTABLE!**



392 MeV proton induced
DEUTERON production DDXs

Mechanism of Cluster Productions

- **P.E. Hodgson and E. Betak, *Phys. Rep. 374, 1-89 (2003)***

  "The mechanisms of cluster reactions show special features such as the competition between *pickup* and *knockout* processes and the contributions of several successive steps in the reaction."

- **C. Kalbach, *Phys. Rev. C 71, 034606 (2005)***

  Pre-equilibrium exciton model (below about 100 MeV, phenomenorogical)

  with *pickup* plus *knockout*

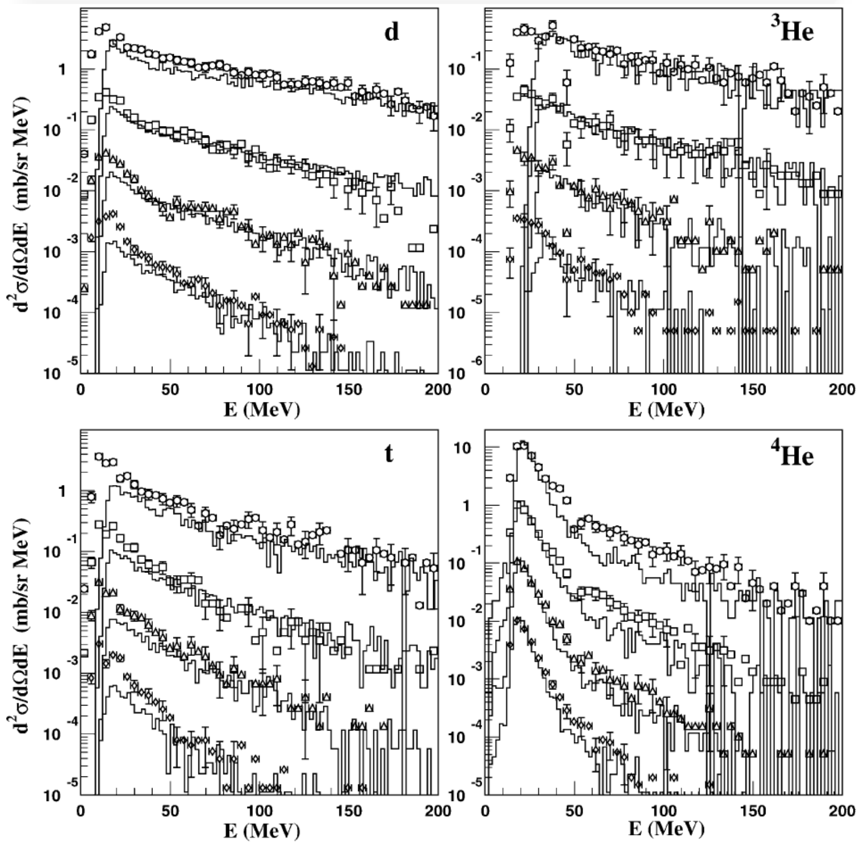
It is necessary to introduce both ***knockout*** mechanism and ***pickup*** mechanism into the INC model as well as the exciton model.

Cluster productions (INC model)

- Liége INC model
  + surface coalescence*

PREDICTABLE?

It is necessary to introduce ***"knockout"*** in addition to ***surface coalescence (pickup)*** into INC model.



p(2.5 GeV) + Au reaction

*) Boudard, et al. Nucl. Phys. A 740 (2004) 195-210

Purpose of This Study

Introduce cluster production mechanism (***pickup (surface coalescence) + knockout***) within the framework of the INC model and investigate their applicability.

In terms of ***"knockout"*** mechanism, we implement it into the INC model in our own original way.

Our INC code

INC model

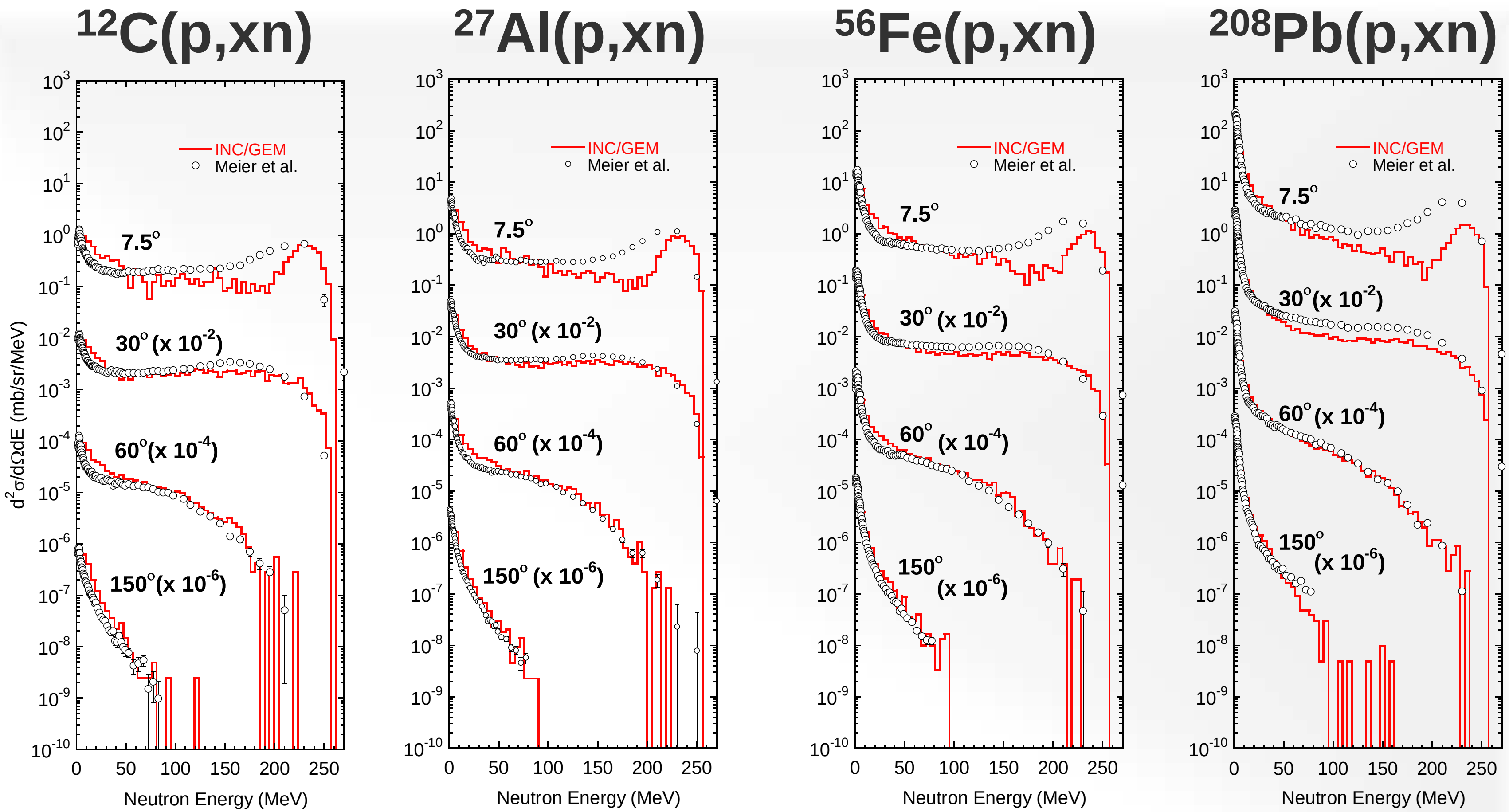
Equation of Motion — Newtonian equation without interaction

Target — Potential: Square well potential
Spatial dist.: Wood-Saxon dist. (Negele's systematics)
Momentum dist.: Uniform Fermi gas dist.

NN elastic cross section / Angular distribution — Cugnon's systematics

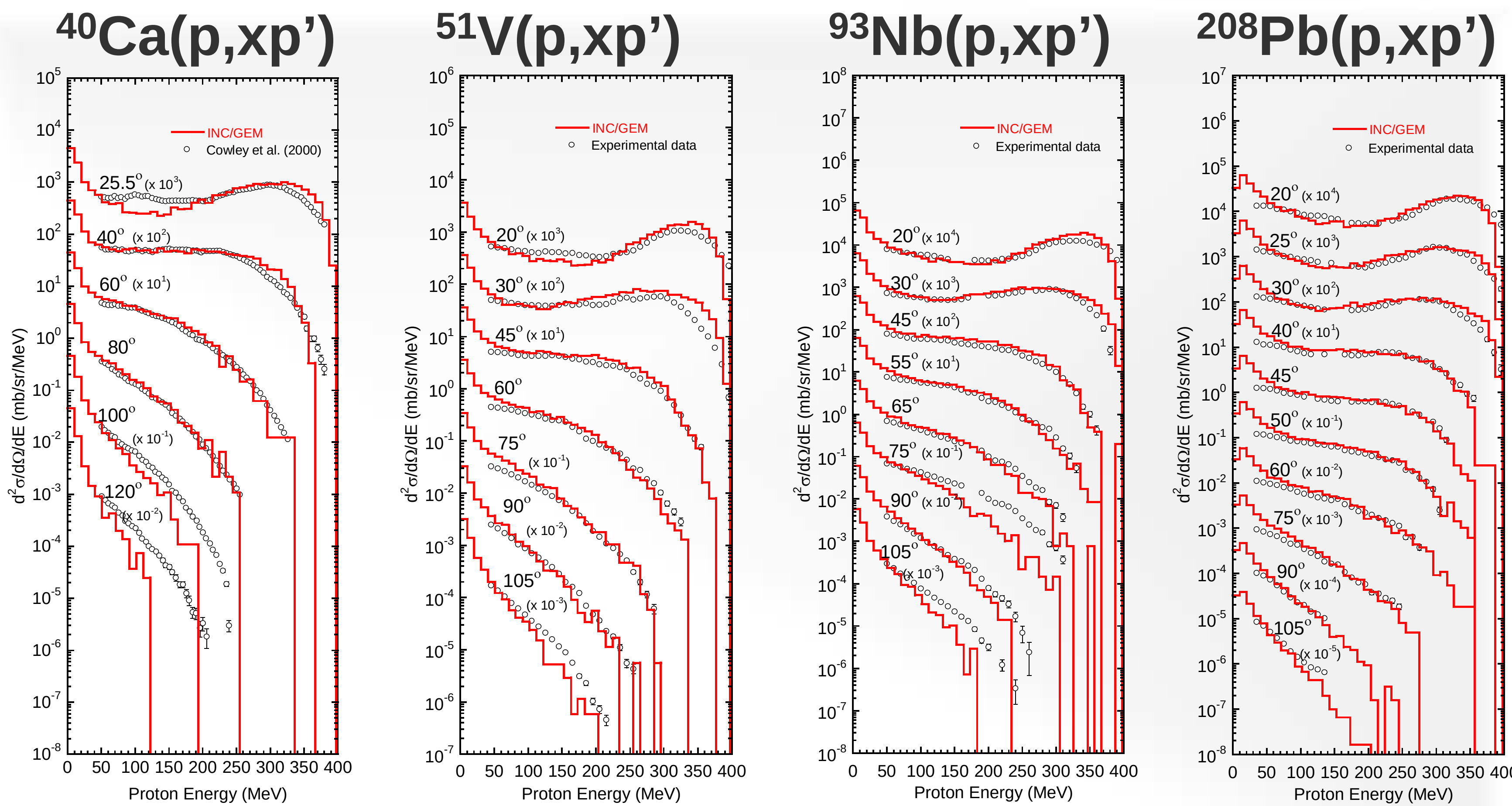
Evaporation stage calculation — GEM code (developed by Furihata)

Comparison with Experimental Data (1)



256 MeV proton induced **NEUTRON** production double-differential cross sections

Comparison with Experimental Data (2)

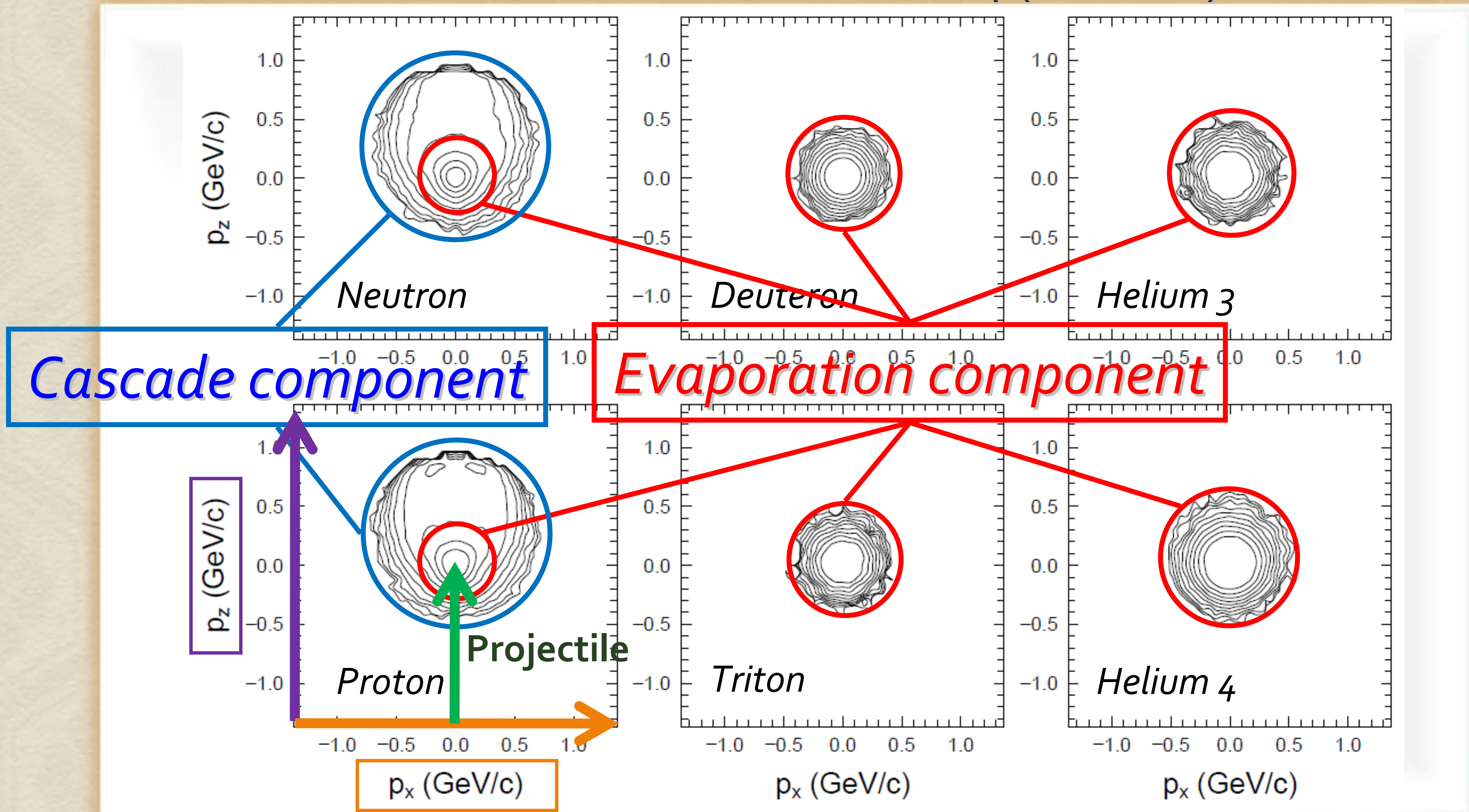


392 MeV proton induced **PROTON** production double-differential cross sections

Contour Plot of Momentum distributions of Secondary Particles

INC + GEM

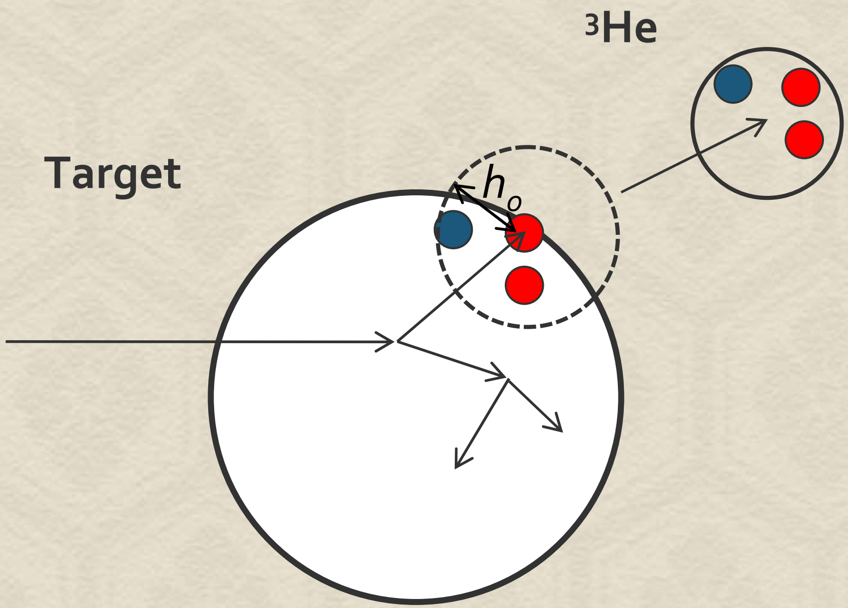
p(392 MeV) + ^{27}Al reaction



Mechanism of Cluster Productions (1)

☐ Surface Coalescence* (pickup)

When a nucleon is ready to get across and leave the nuclear surface, it picks up nucleons and they form a cluster.



Schematic representation of the *surface coalescence* mechanism

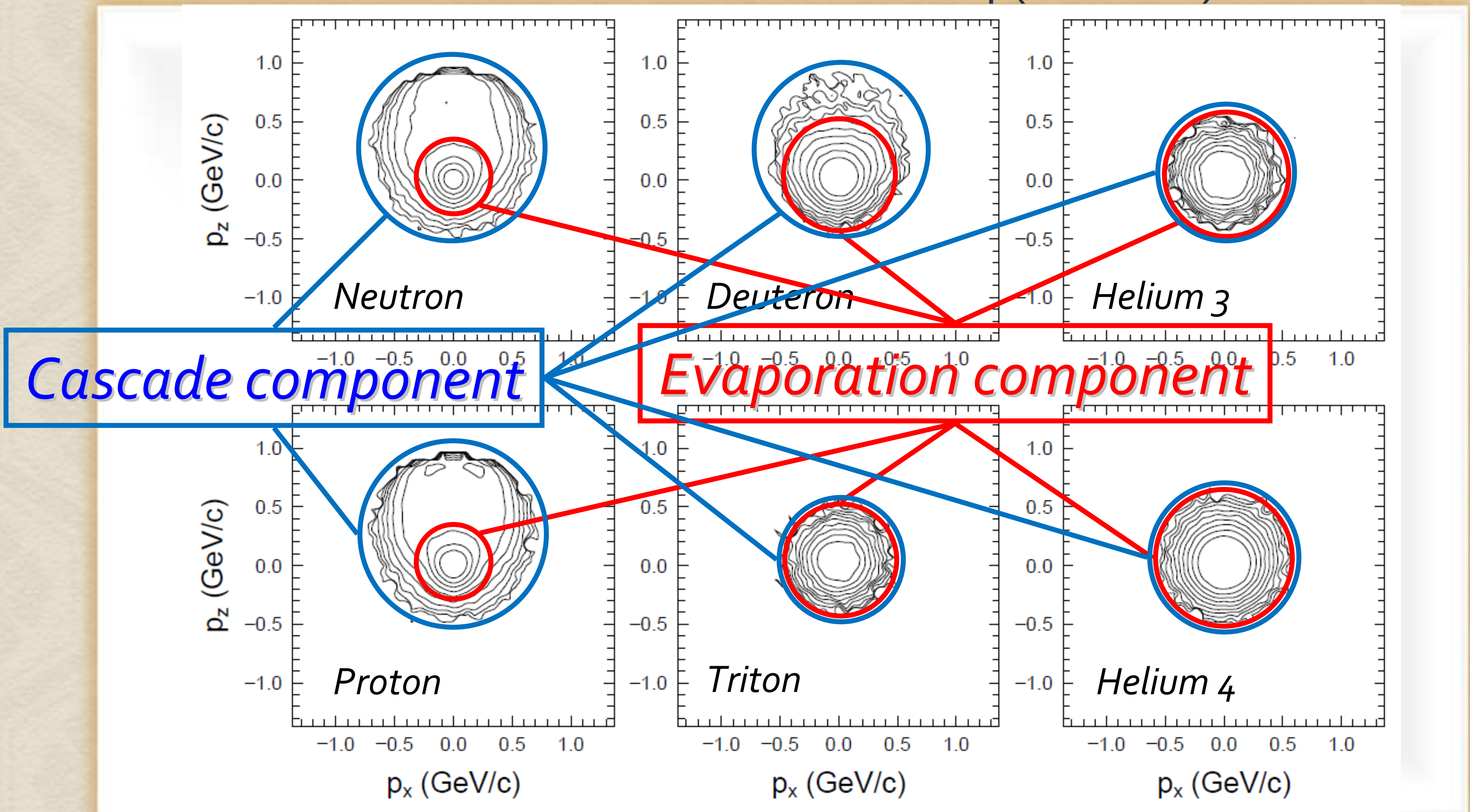
✓Conditional expression

$$r_{ij}\, p_{ij} < h_0, \quad (h_0 = 1800 \text{ fm MeV}/c)$$

*) A. Boudard, *et al. Nucl. Phys. A 740 (2004) 195-210*

Contour Plot of Momentum Distribution of Secondary particles

INC with **Surface Coalescence** + **GEM** p(392 MeV) + ^{27}Al reaction



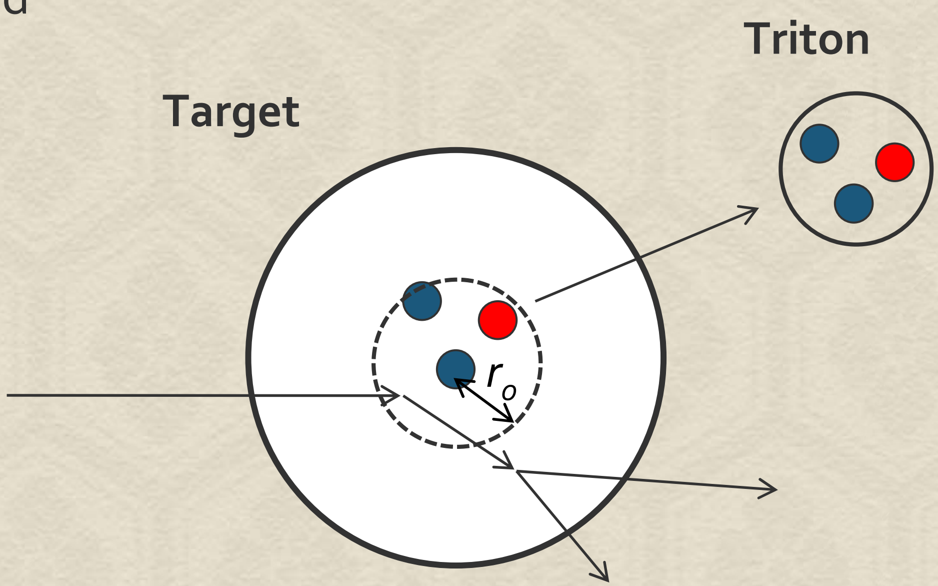
Mechanism of Cluster Productions (2)

☐ Knockout

If there are nucleons near the bombarded nucleon, the scattering is regarded as ***nucleon-cluster elastic scattering***.

✓Conditional expression

$$r_{ij} < r_0, \quad (r_0 = 1.2 \text{ fm})$$

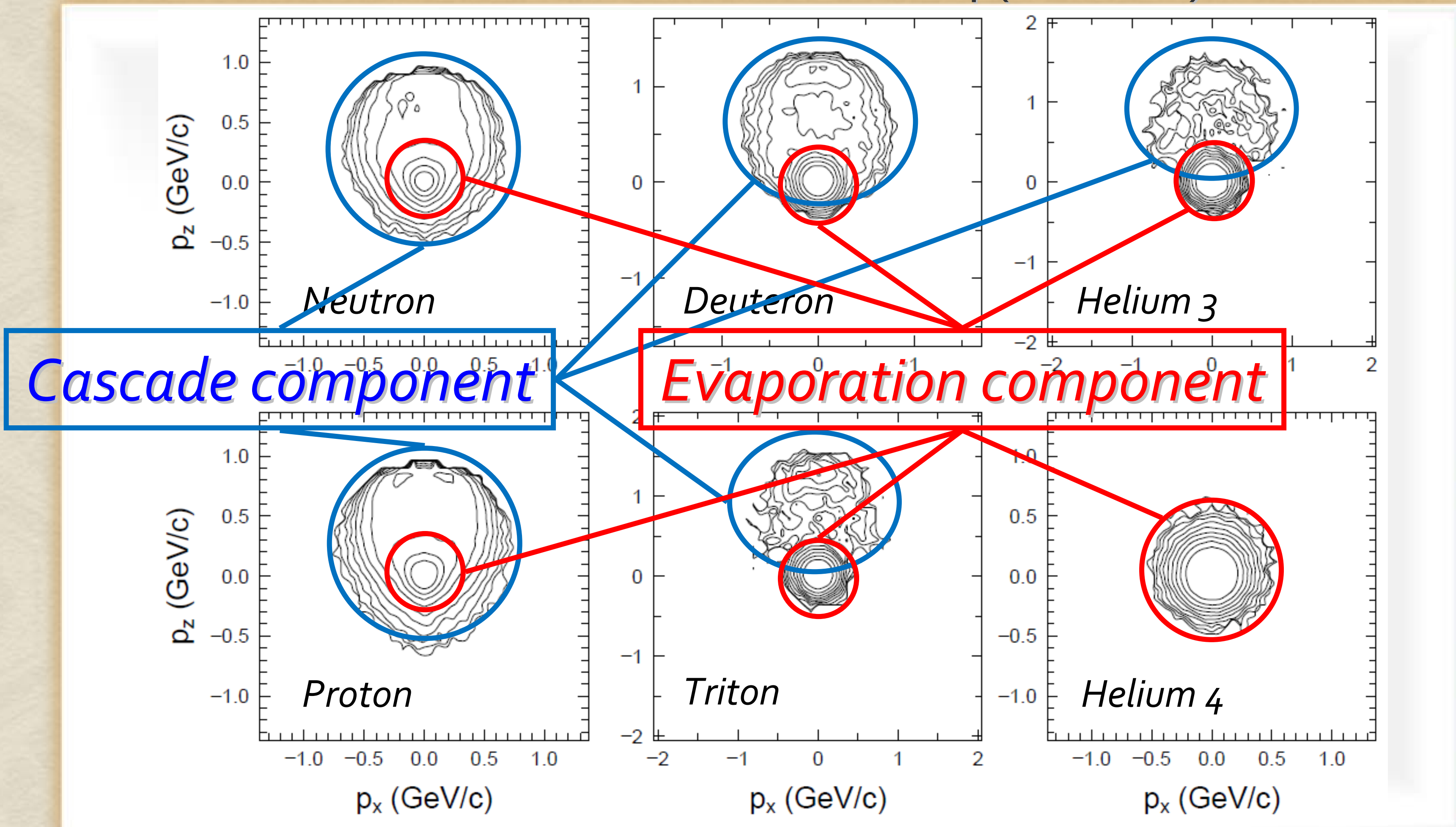


Schematic representation of
The knockout mechanism

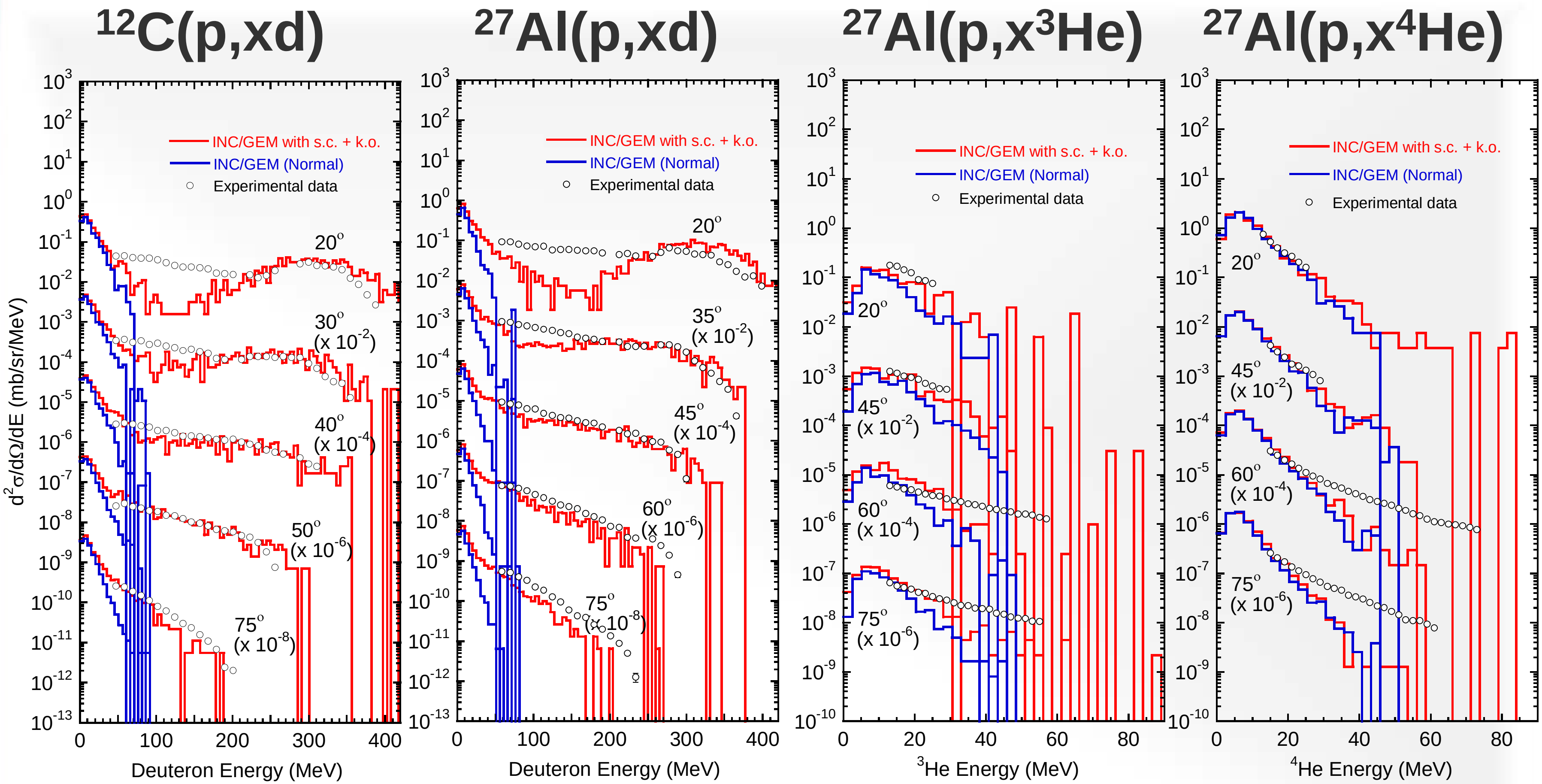
Contour Plot of Momentum distribution of Secondary Particles

INC with Knockout + GEM

p(392 MeV) + ^{27}Al reaction



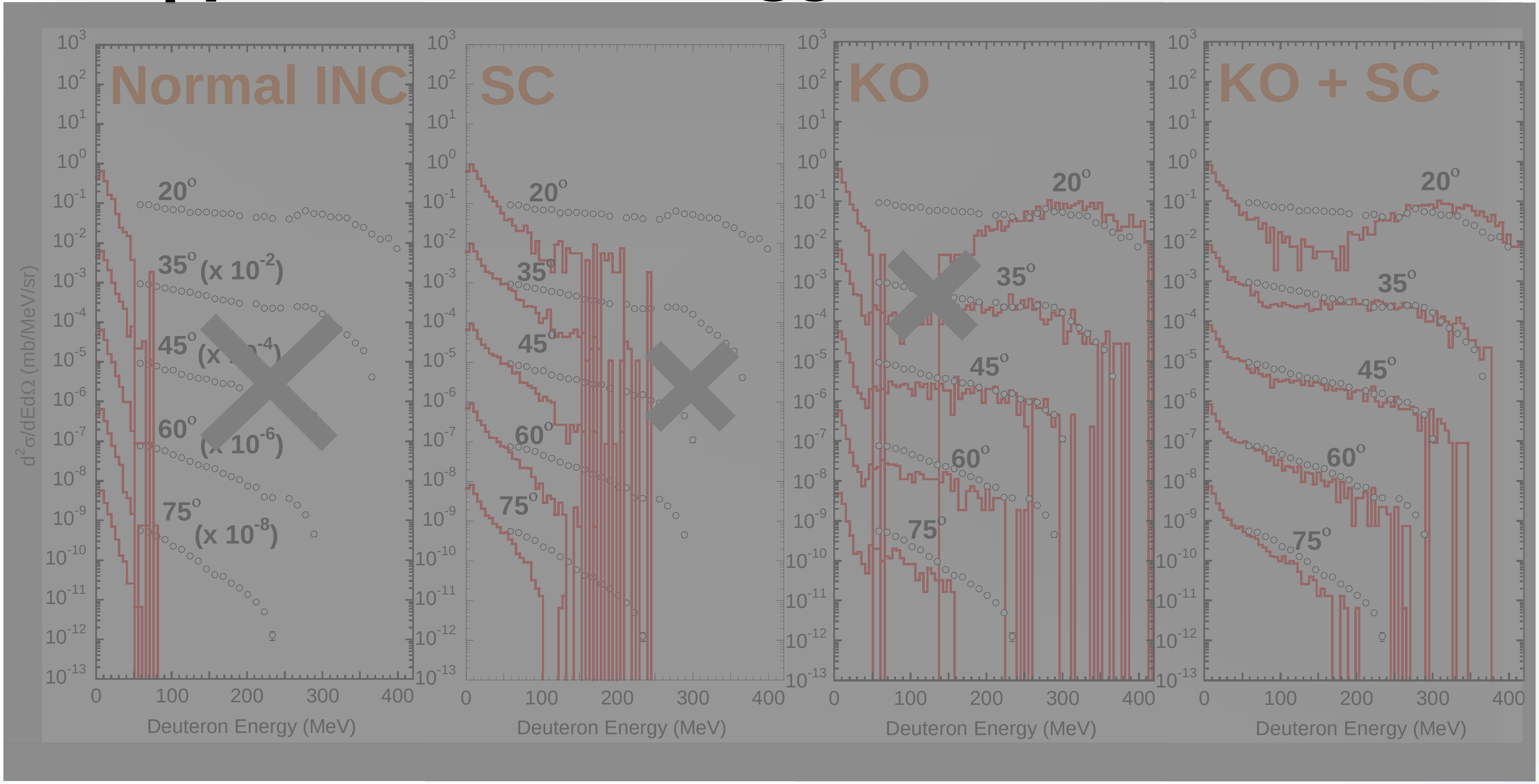
Comparison with Experimental Data (3)



392 MeV proton induced **CLUSTER** production double-differential cross sections

Contribution of Each Mechanism

$^{27}Al(p,xd)$ reaction at 392 MeV



Summary and Conclusion

- We developed a nuclear reaction code based on the intranuclear cascade (INC) model which describe not only nucleon productions but also cluster productions.

- It was found that combination of ***surface coalescence(pickup)*** plus ***knockout*** is effective to describe cluster productions .

Outline

- Motivation & Background

    Early studies and technical issues

- Theory & our code

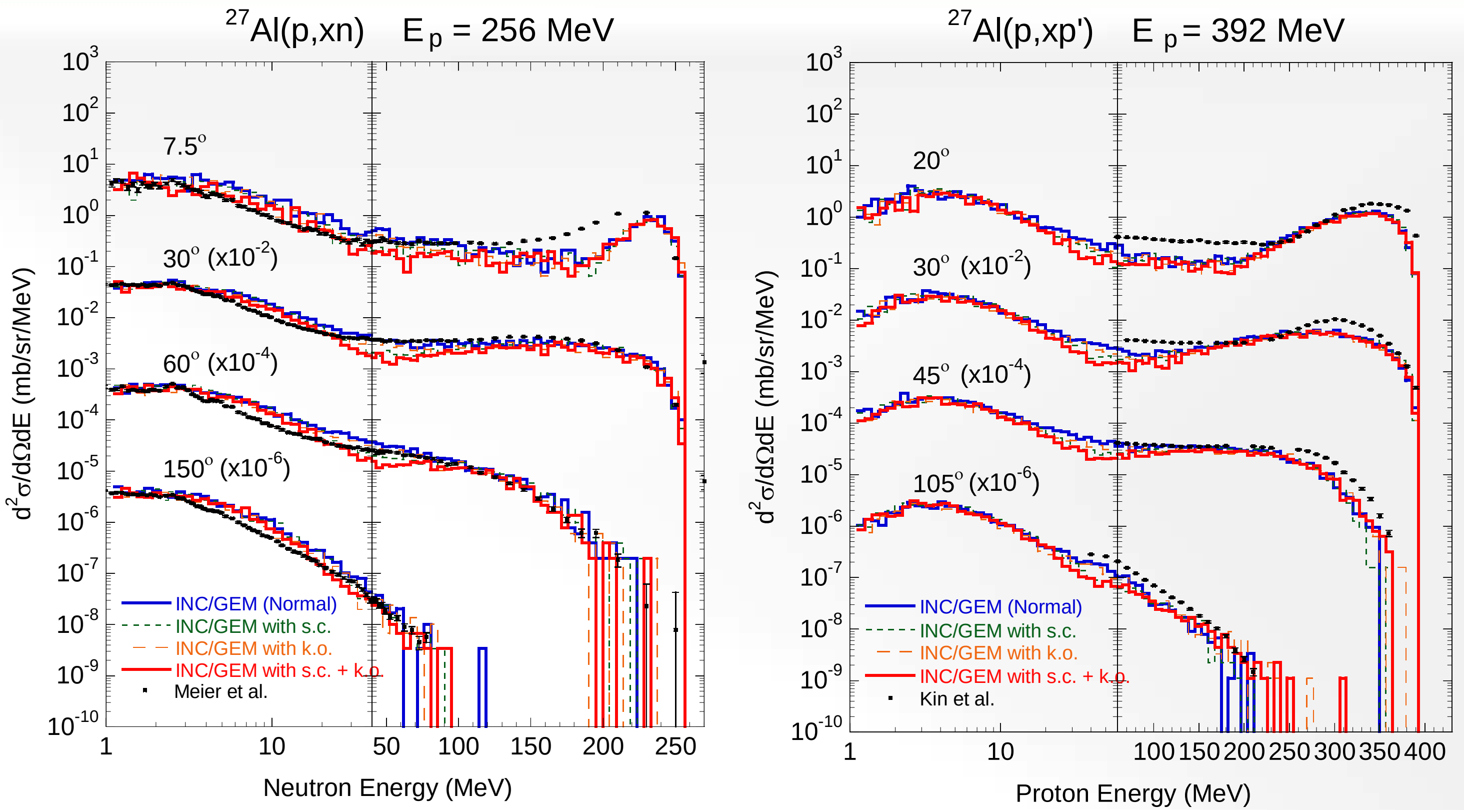
    Description of our intranuclear cascade model
    and cluster production mechanism

- Results

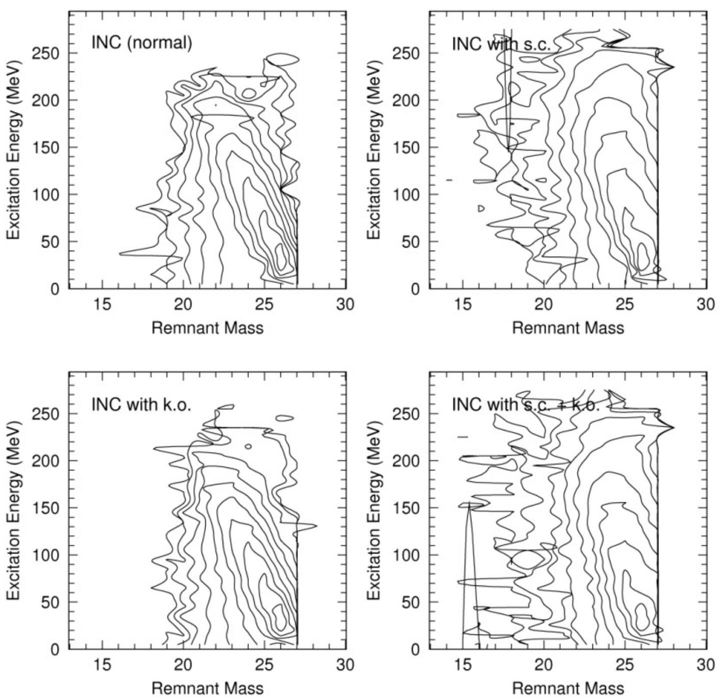
    Comparison with experimental data

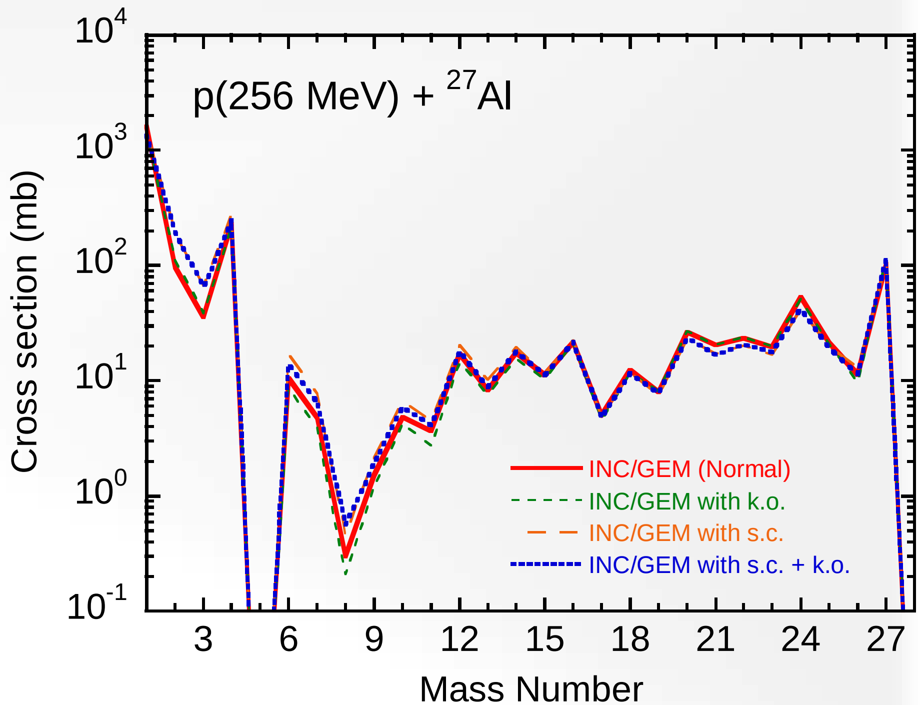
- Summary

Influence upon Nucleon Production Spectra



Introduction of cluster production mechanism does not affect nucleon production spectra.





Remnant mass-excitation energy distribution

Mass distribution of residual nuclei

Kinematics of the Knockout

N-AN elastic scattering

Relative momentum in the center-of-momentum system

$$\mathbf{p}_{\mathrm{cm}} = \mathbf{p}_{\mathrm{proj}} + \beta T \qquad \text{with} \qquad T = \gamma\left(\gamma \frac{\mathbf{p}_{\mathrm{proj}} \cdot \beta}{\gamma + 1} - E_{\mathrm{proj}}\right)$$

where

$$\beta = \frac{\mathbf{p}_{\mathrm{proj}} + \mathbf{p}_{\mathrm{clust}}}{E_{\mathrm{proj}} + E_{\mathrm{clust}}}, \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}},$$

$$\mathbf{p}_{\mathrm{clust}} = \sum_{i=1}^{A_{\mathrm{clust}}} \mathbf{p}_i \qquad E_{\mathrm{clust}} = \sqrt{p_{\mathrm{clust}}^2 + \left(A_{\mathrm{clust}} m\right)^2},$$

Sum of momenta of constituent nucleons

Kinetic energy of the cluster

$$T_{\mathrm{clust}} = -A_{\mathrm{clust}} m + \sqrt{p_{\mathrm{clust}}^2 + \left(A_{\mathrm{clust}} m\right)^2} + V_0$$

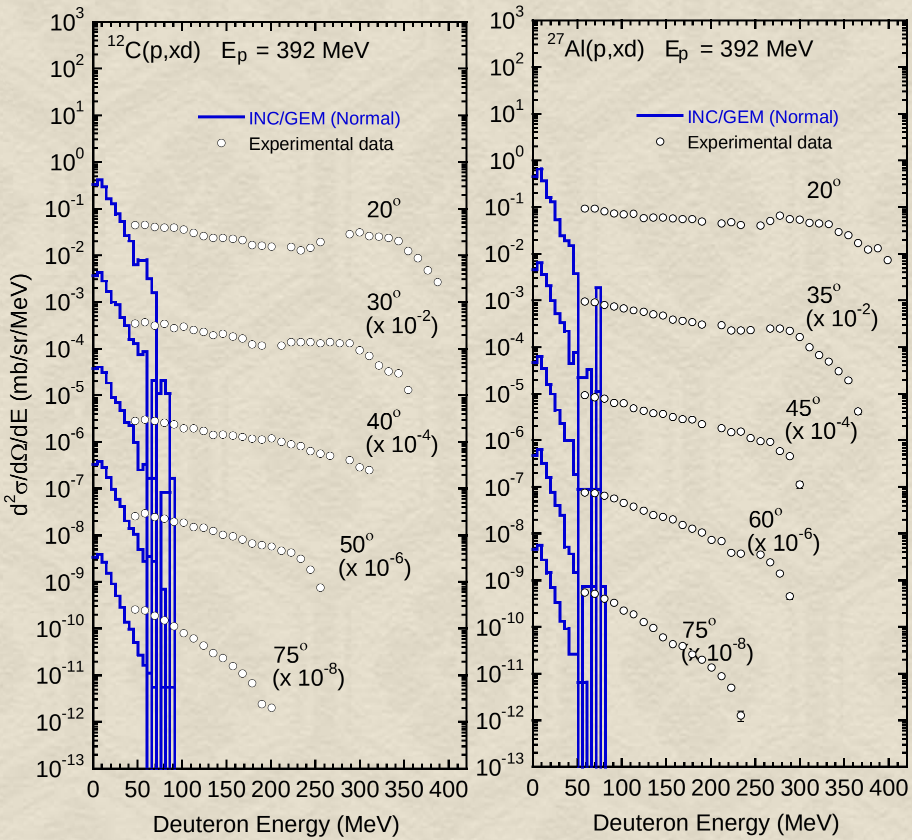
Kinematics of the Surface Coalescence

Kinetic energy of the cluster outside the target nucleus

$$T_{\mathrm{clust}} = -A_{\mathrm{clust}} m + \sqrt{p_{\mathrm{clust}}^2 + \left(A_{\mathrm{clust}} m\right)^2} + A_{\mathrm{clust}} V_0$$ **+ binding energy?**

with

$$\mathbf{p}_{\mathrm{clust}} = \sum_{i=1}^{A_{\mathrm{clust}}} \mathbf{p}_i$$ **+ intrinsic momentum?**



^{12}C(p,xd) E_p = 392 MeV
^{27}Al(p,xd) E_p = 392 MeV
INC/GEM (Normal)
Experimental data
20°
30° (x 10^{-2})
40° (x 10^{-4})
50° (x 10^{-6})
75° (x 10^{-8})
35° (x 10^{-2})
45° (x 10^{-4})
60° (x 10^{-6})
d^{2}σ/dΩ/dE (mb/sr/MeV)
Deuteron Energy (MeV)