Study symmetry energy by light-ion induced reactions

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Collaborator

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Outline

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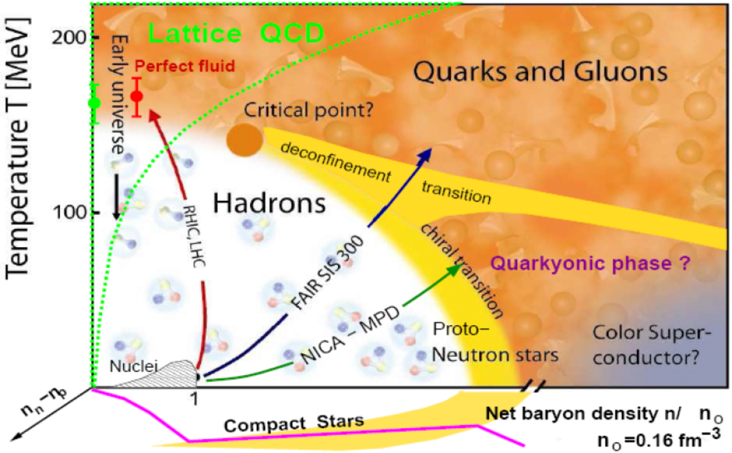
Motivation

Equation of State(EOS)

The energy of per nucleon in a nuclear matter $E(\rho, \delta, T)$.

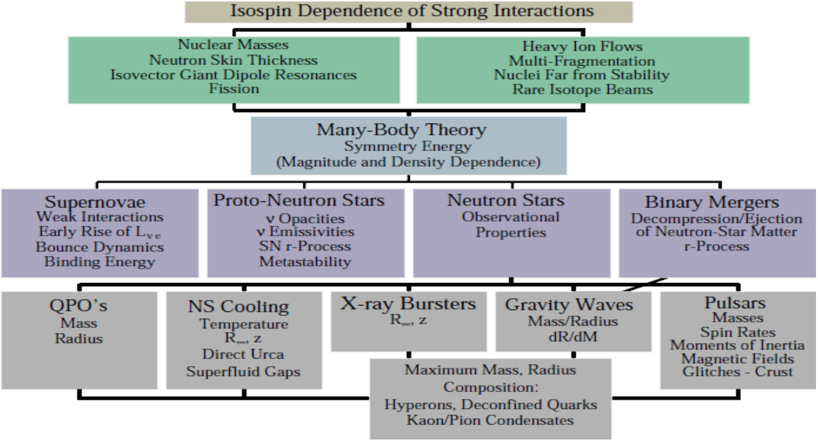


What & Why Symmetry Energy

Symmetry Energy

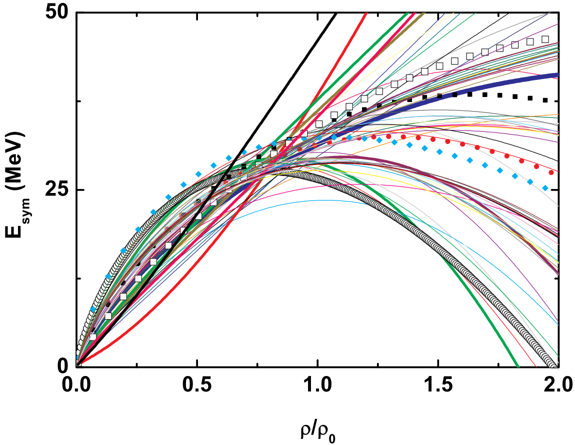
$$E(\rho,\delta) = E(\rho,0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

$$E_{\text{sym}}(\rho) = E(\rho,\delta=1) - E(\rho,\delta=0)$$



A. Steiner, M. Prakash, J. Lattimer and P. Ellis, Phys. Rep. 411, 325 (2005).

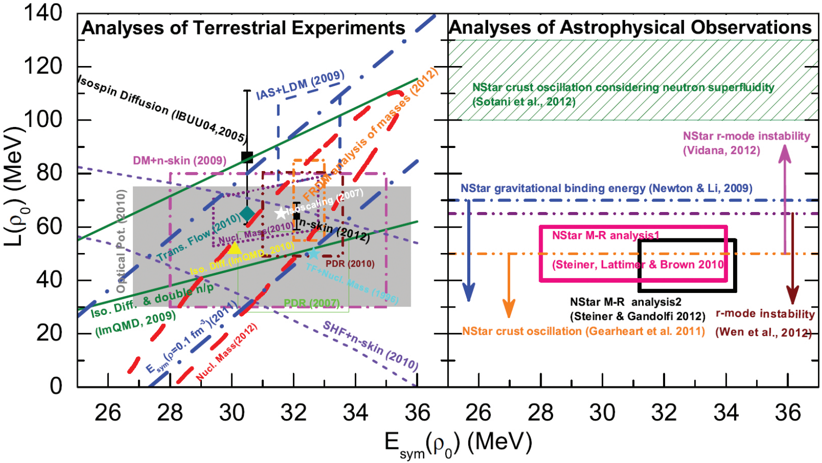
E_{sym} vs ρ is unclear



There is great uncertainty at super-high and sub-saturation density.

Need to be constrained by experiment!

Current constraints on $E_{\rm sym}(\rho)$

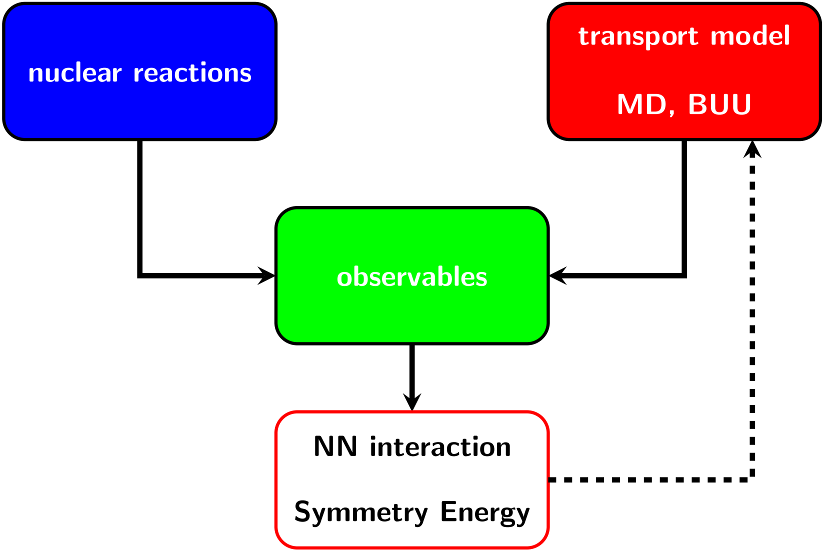


B.A. Li, L.W. Chen, F.J. Fattoyev, W.G. Newton, and C. Xu, arXiv:1212.1178

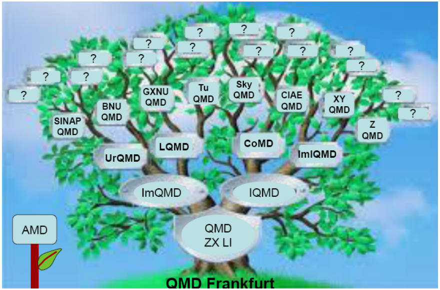
$E_{\rm sym}(\rho_0) = 32.5 \pm 2.5$ MeV $\quad L = 55 \pm 25$ MeV

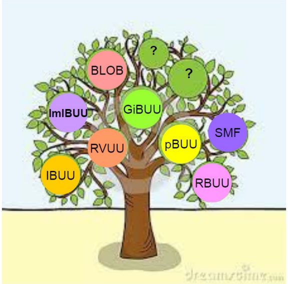
$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0)\,(\rho/\rho_0)^\gamma$ with $\gamma = 0.9 \pm 0.4$

Transport Model



Effect of isovector potential is very weak, and will be smeared by so many factors, such as NN collision, variety of system density · · · . Isovector effects on the observables are only 20%.





Taken from presentation of Hermann Wolter

The uncertainty from various transport models is also about 20% even under controlled conditions. Jun Xu, et al, PRC93, 044609(2016)

Important to reduce the uncertainty, to reliably describe HIC.

That is a long way to go!!

Another way: find observables

more sensitive to E_{sym}

but

unsensitive to transport model

Reaction induced by intermediate energy light-ion

Advantage

1. There is not compression and expansion;
2. less collision;
3. Easy to model the reaction and reduce the model dependence.

Outline

ImQMD Model

$$\dot{\vec{r}}_i = \frac{\partial H}{\partial \vec{p}_i}, \quad \dot{\vec{p}}_i = -\frac{\partial H}{\partial \vec{r}_i}$$

$$H = T + U_{\rm loc} + U_{\rm Coul}$$

$$U_{\rm loc} = \int V_{\rm loc} d\vec{r}$$

2-body | 3-body | surface

$$V_{\rm loc}(\rho) = \frac{\alpha}{2}\frac{\rho^2}{\rho_0} + \frac{\beta}{\gamma+1}\frac{\rho^{\gamma+1}}{\rho_0^{\gamma}} + \frac{g_{\rm sur}}{2\rho_0}(\nabla\rho)^2$$

$$+\frac{g_{\rm sur,iso}}{\rho_0}[\nabla(\rho_{\rm n} - \rho_{\rm p})]^2 + \frac{C_{\rm s}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\rho\delta^2 + g_{\rho\tau}\frac{\rho^{8/3}}{\rho_0^{5/3}}.$$

surface symmetry | symmetry | $\rho\tau$ term

ImQMD model has been successfully applied to HICs at energies near Coulomb barries and intermediate energies

Benchmark calculations

ImQMD+Statistical decay model

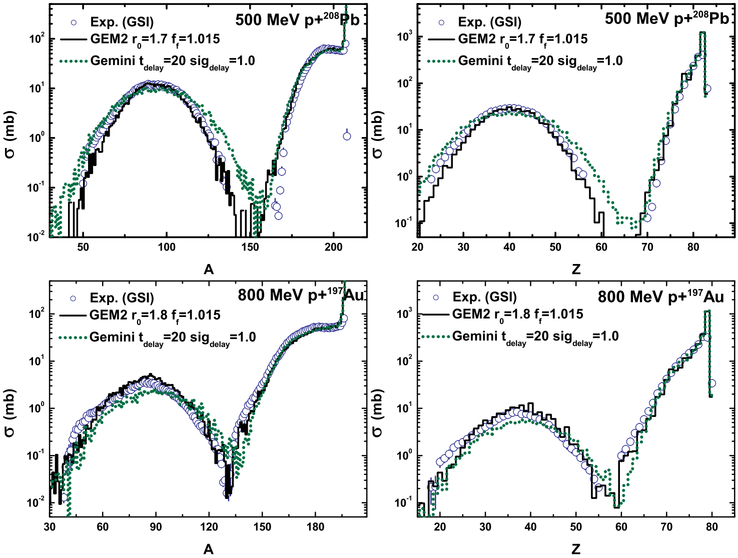
Production mass/charge/isotope distribution (GSI)
1 GeV p+^{208}Pb, ^{238}U;
800 MeV p+^{197}Au;
500 MeV p+^{208}Pb;
300, 500, 750, 1000 MeV p+^{56}Fe

Double differential cross section (DDX) of emitted neutrons and protons (Los Alamos)
113, 256, 597, 800 MeV p+A

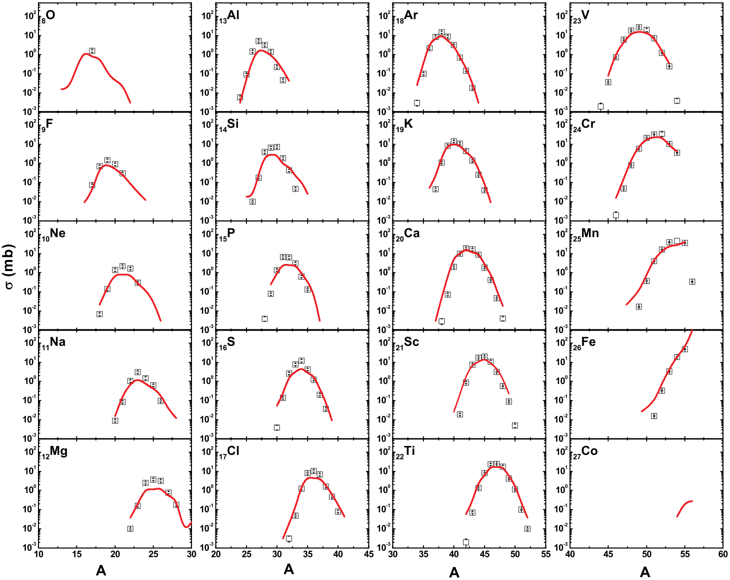
DDX of light charged particles
62, 200, 392, 1200 MeV p+A, 300-500 MeV p+Cu

Data are taken from https://www-nds.iaea.org/spallations

Some results

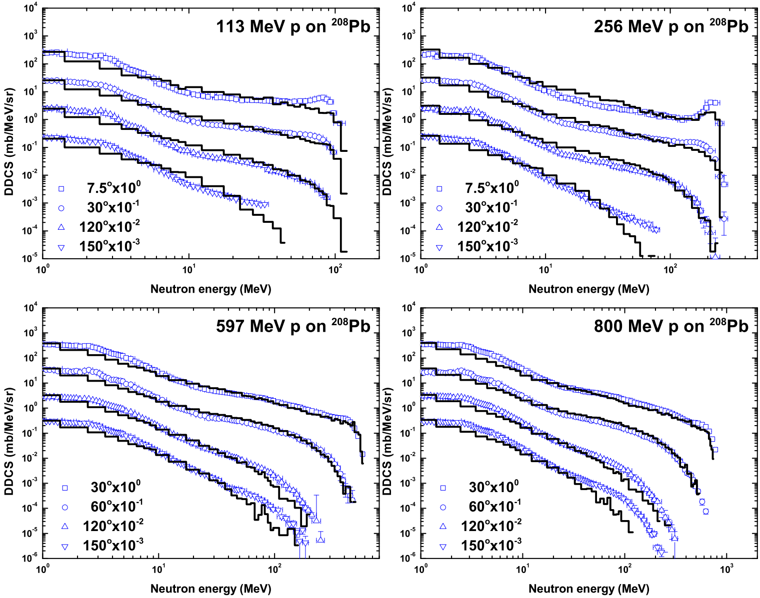


Production mass/charge distribution in 500、800 MeV $p+^{208}$Pb, ^{197}Au

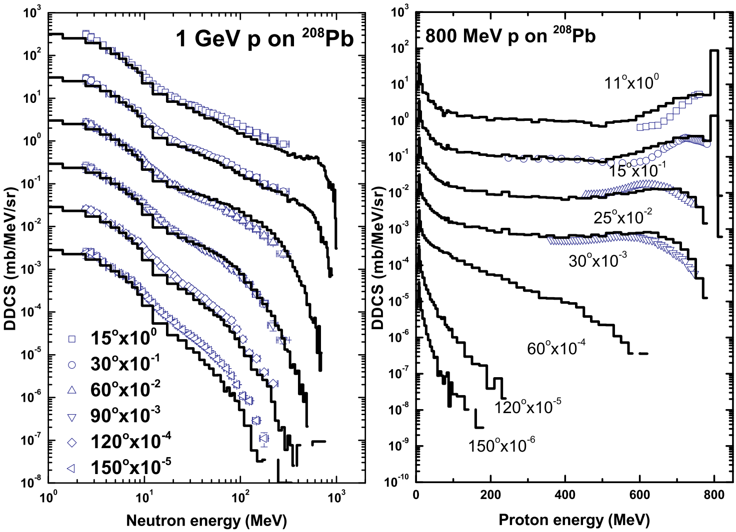


Isotope distribution in 1 GeV p+^{56}Fe

Li Ou, JPG36, 125104 (2009).

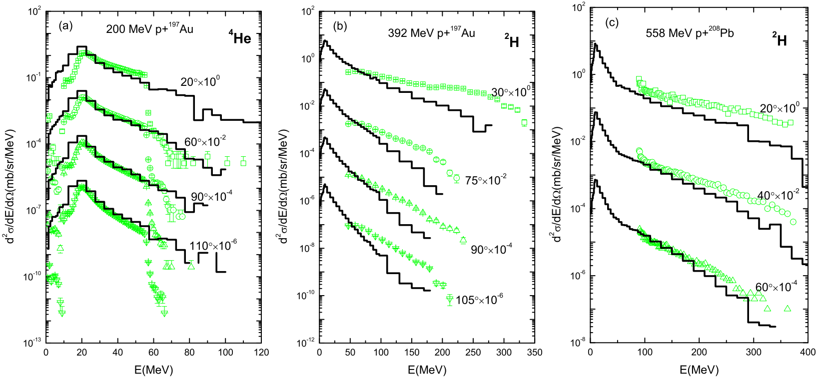


DDX of emitted neutron in 113、256、597、800 MeV $p+^{208}$Pb



DDX of emitted neutron in 1 GeV $p+^{208}$Pb
and DDX of emitted proton in 800 MeV $p+^{208}$Pb。

Li Ou, JPG35, 055101 (2008).



DDX of light charged particles

Dexian Wei, JPG41, 035104 (2014), NPA933, 114 (2015).

Outline

Character of isovector potential

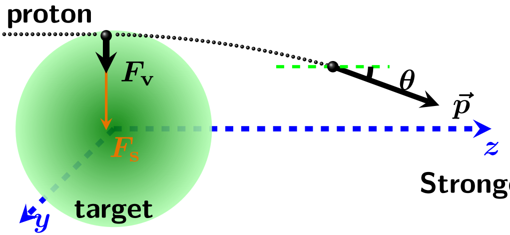
$$V(\rho, \delta) = V(\rho, 0) + V_{\mathrm{sym}}(\rho)$$

Isoscalar potential $V(\rho, 0)$: attractive for proton and neutron

Isovector potential $V_{\mathrm{sym}}(\rho)$: attractive for proton but repulsive for neutron (in neutron-rich environment)

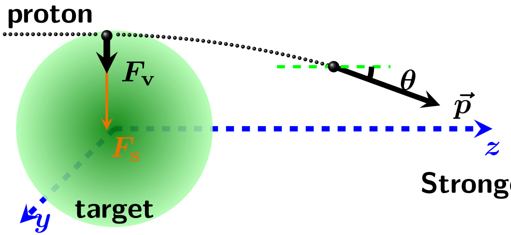
All observables sensitive to symmetry energy are based on this character!

Nucleon scattering reaction

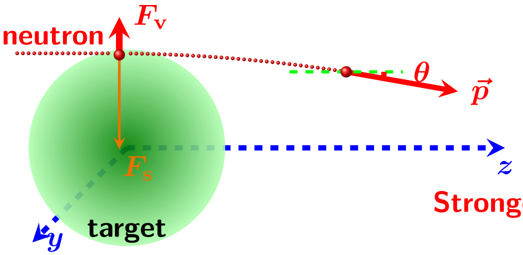


Stronger isovector potential
larger θ!

Nucleon scattering reaction

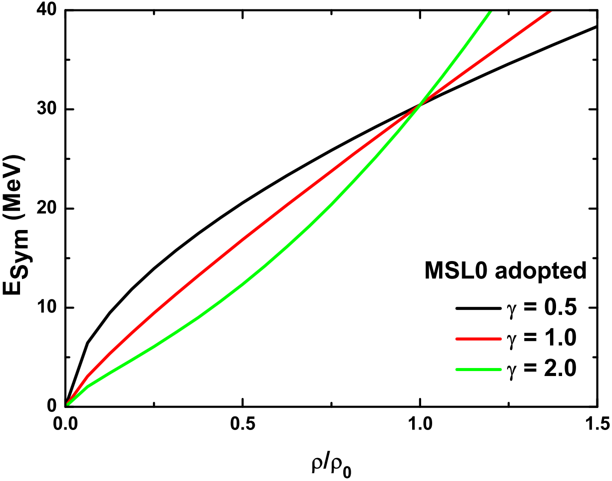


Stronger isovector potential larger θ!

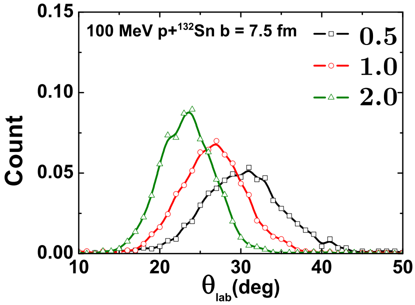


Stronger isovector potential smaller θ!

$E_{\rm sym}$ in ImQMD

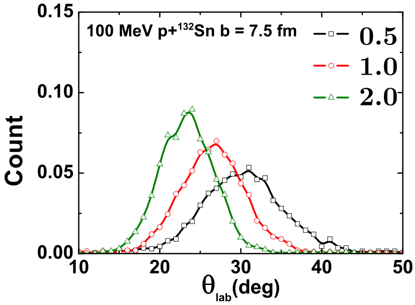


$$E_{\rm sym}(\rho) = \frac{C_{\rm s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{\rm s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

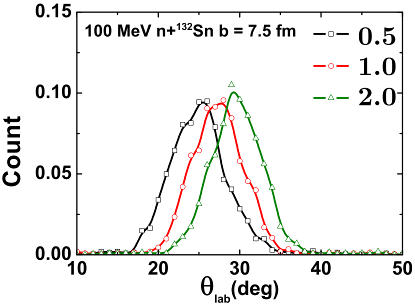


p+^{132}Sn.

Li Ou *et.al* PRC78, 044609 (2008)

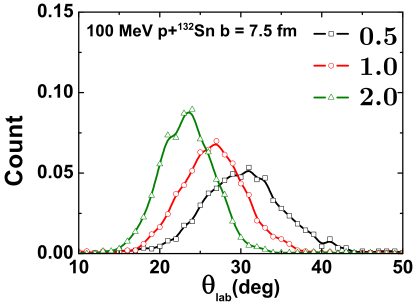


$p+^{132}Sn.$

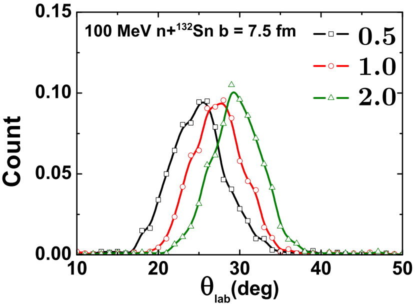


$n+^{132}Sn.$

Li Ou ***et.al*** **PRC78, 044609 (2008)**



p+^{132}Sn.

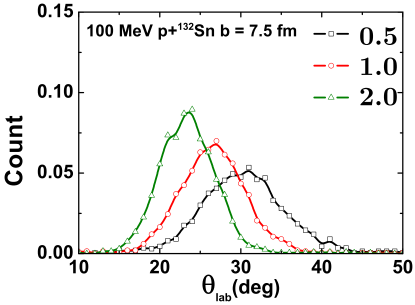


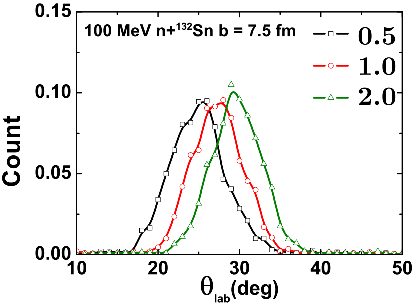
n+^{132}Sn.

$$\Delta\theta = \theta_p - \theta_n = \begin{cases} 5.5^\circ, & \gamma = 0.5, \quad \text{soft} \\ 0.5^\circ, & \gamma = 1.0, \quad \text{linear} \\ -6.6^\circ, & \gamma = 2.0, \quad \text{stiff} \end{cases}$$

Can possibly provide very clear constraint for $E_{\text{sym}}(\rho)$.

Li Ou *et.al* PRC78, 044609 (2008)





p+^{132}Sn. **n+^{132}Sn.**

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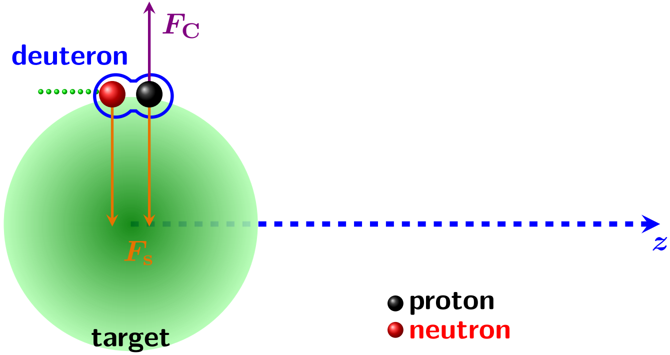
Can possibly provide very clear constraint for $E_{\rm sym}(\rho)$.

Difficult to be proved by experiment.

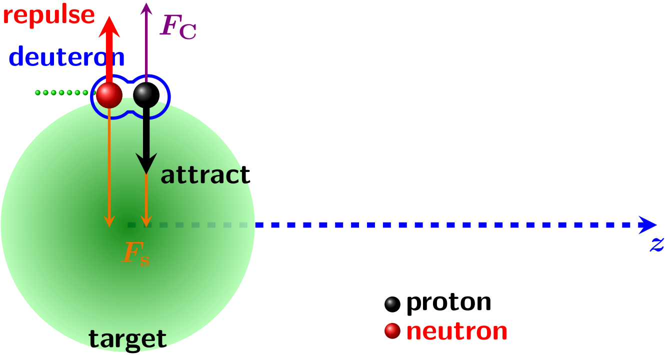
No good monochromatic neutron beam around 100 MeV!

Li Ou *et.al* PRC78, 044609 (2008)

Deuteron breakup reaction

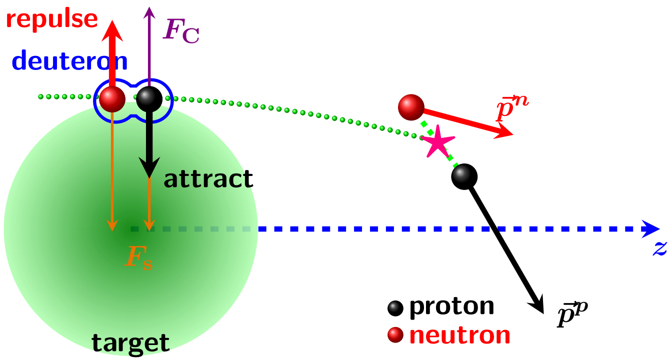


Deuteron breakup reaction



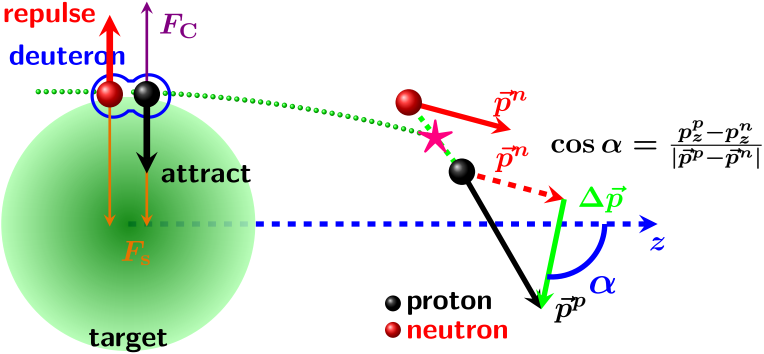
- **Deuteron rotates under torque.**

Deuteron breakup reaction



- Deuteron rotates under torque.
- Proton and neutron move freely after deuteron breaks.

Deuteron breakup reaction



- **Deuteron rotates under torque.**
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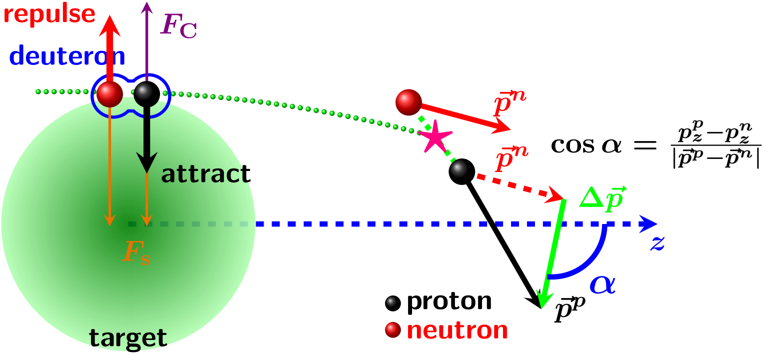
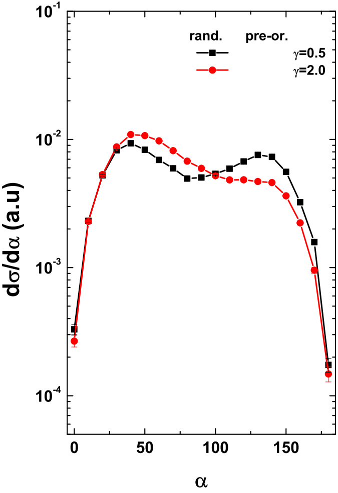
Deuteron breakup reaction



- **Deuteron rotates under torque.**
- **Proton and neutron move freely after deuteron breaks.**
- **Larger correlation angle with stronger isovector potential!**

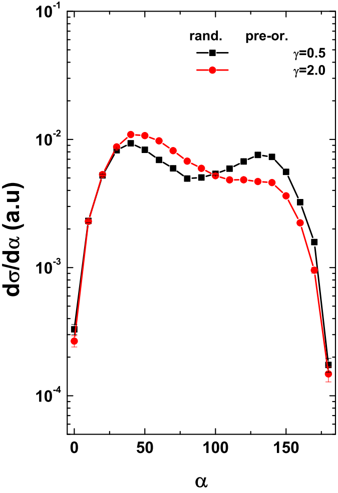
Isospin effect on reorientation of deuteron



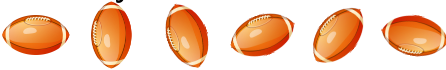
100 MeV/u $d+^{124}$Sn @ b=7 fm

- **Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.**

Isospin effect on reorientation of deuteron



100 MeV/u
d+^{124}Sn @ b=7 fm
Randomly oriented deuteron



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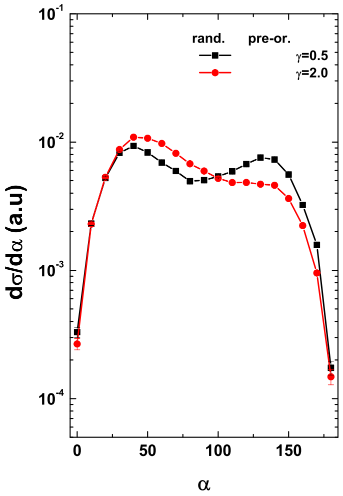
Isospin effect on reorientation of deuteron



100 MeV/u
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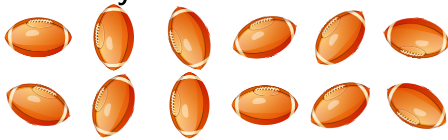
Randomly oriented deuteron



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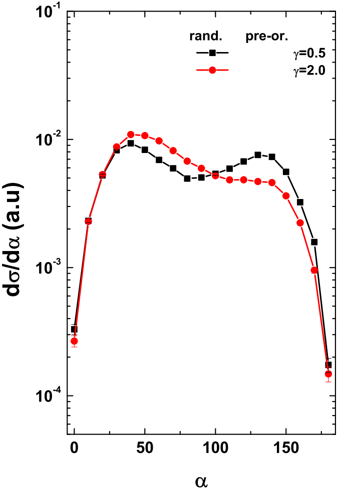
Isospin effect on reorientation of deuteron



100 MeV/u
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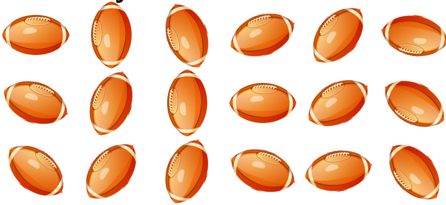
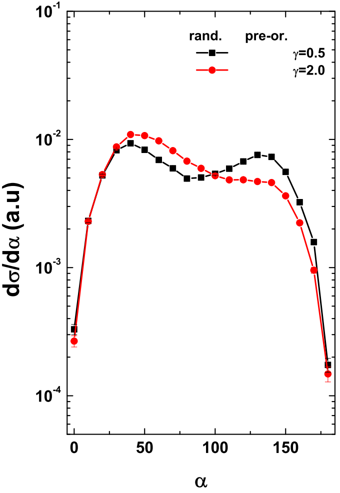
Randomly oriented deuteron



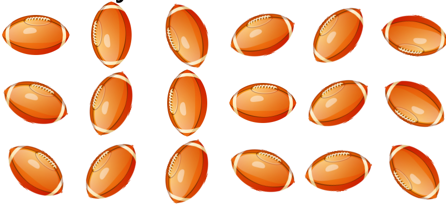
- **Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.**

Isospin effect on reorientation of deuteron



100 MeV/u $d+^{124}$Sn @ b=7 fm

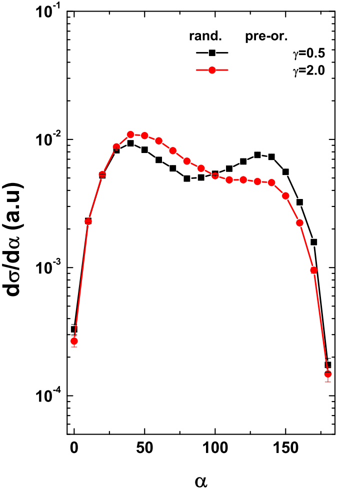
Randomly oriented deuteron



Pre-oriented deuteron

- **Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.**

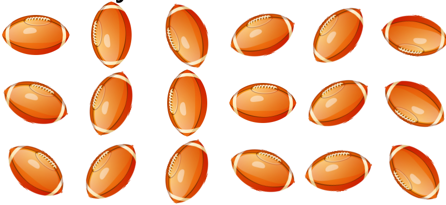
Isospin effect on reorientation of deuteron



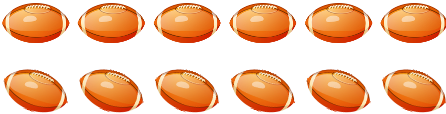
100 MeV/u

$d+^{124}$Sn @ b=7 fm

Randomly oriented deuteron

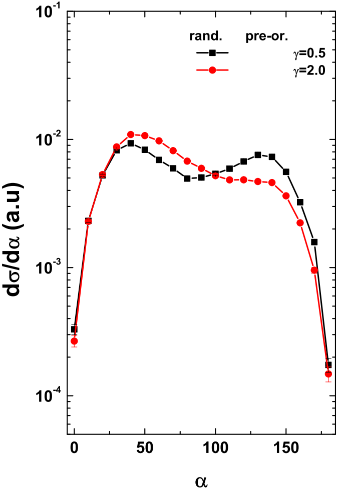


Pre-oriented deuteron



- Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.

Isospin effect on reorientation of deuteron



100 MeV/u
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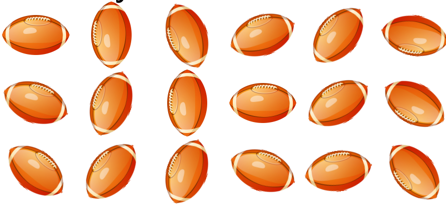
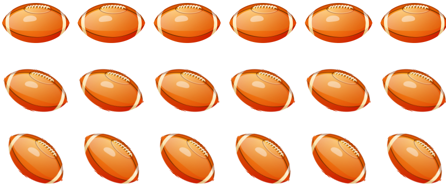
Randomly oriented deuteron

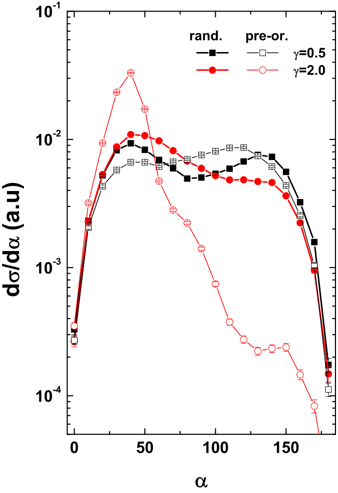


Pre-oriented deuteron



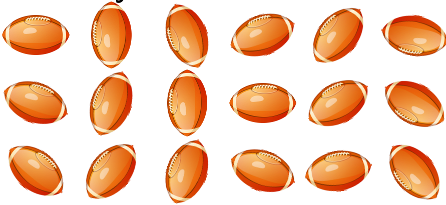
- **Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.**

Isospin effect on reorientation of deuteron

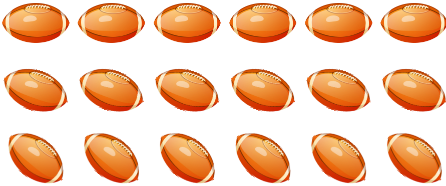


100 MeV/u $d+^{124}$Sn @ b=7 fm

Randomly oriented deuteron

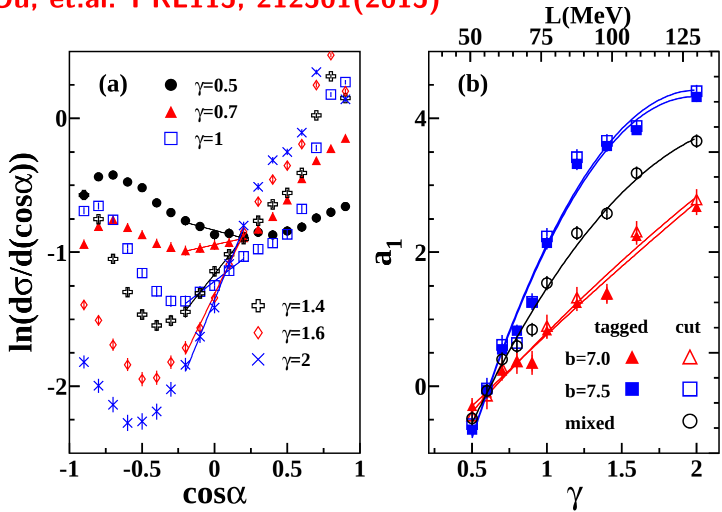


Pre-oriented deuteron



- **Effect of the symmetry potential is largely smeared by the random initial orientation of the incident deuteron.**
- **Effect is more clear with polarized deuteron.**

Li Ou, et.al. PRL115, 212501(2015)



$$\ln\left[d\sigma/d\left(\cos\alpha\right)\right] = a_0 + a_1 \cos\alpha$$

Slope coefficient a_1 increases significantly with γ, can be a sensitive observable to constrain E_{sym}.

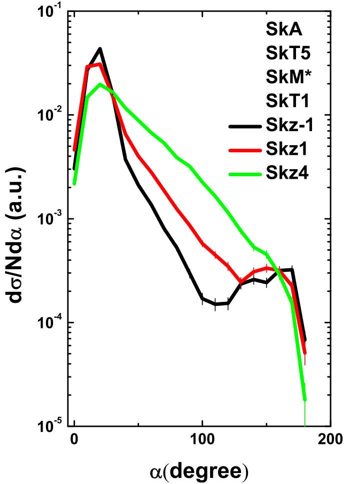
Outline

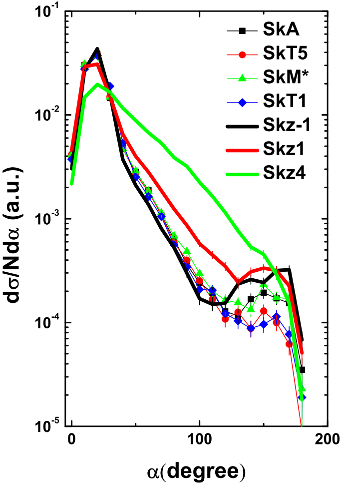
Summary

- **Within ImQMD framework, the reorientation effect of deuteron attributed to isovector interaction in the nuclear field of heavy target nuclei has been investigated for the first time.**
- **The correlation angle of nucleons from breakup polarized deuteron, depends sensitively on the isovector potential but insensitively on the isoscaler potential.**
- **In terms of sensitivity and cleanness, the breakup reactions induced by polarized deuteron beam at about 100 MeV/u provide a more stringent constraint to the symmetry energy at subsaturation densities.**

Thank you for your attention!

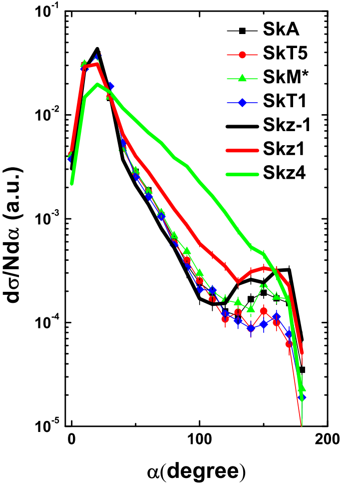
Skz series:
same $E(\rho, 0)$, various $E_{\rm sym}(\rho)$





Skz series:
same $E(\rho, 0)$, various $E_{\mathrm{sym}}(\rho)$

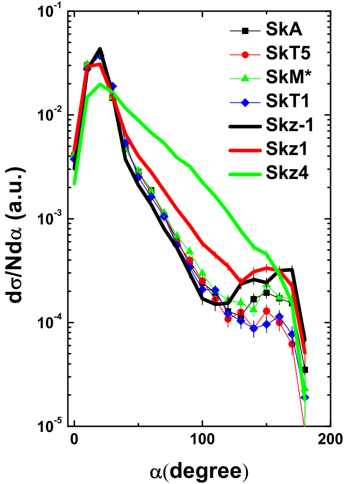
SkA, SkT5, SkT1, Skz-1:
same $E_{\mathrm{sym}}(\rho)$, various $E(\rho, 0)$



Skz series:
same $E(\rho, 0)$, various $E_{\mathrm{sym}}(\rho)$

SkA, SkT5, SkT1, Skz-1:
same $E_{\mathrm{sym}}(\rho)$, various $E(\rho, 0)$

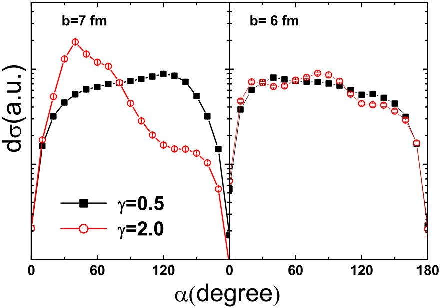
Sensitive to $E_{\mathrm{sym}}(\rho)$, robust to $E(\rho, 0)$!



Skz series:
same $E(\rho, 0)$, various $E_{\rm sym}(\rho)$

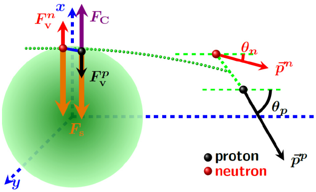
SkA, SkT5, SkT1, Skz-1:
same $E_{\rm sym}(\rho)$, various $E(\rho, 0)$

Sensitive to $E_{\rm sym}(\rho)$, robust to $E(\rho, 0)$!

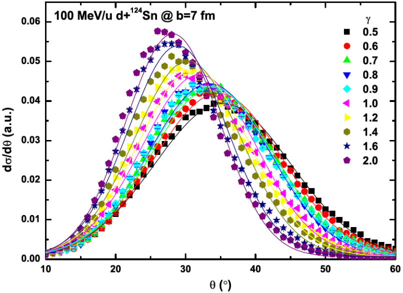


To exclude events with small impact parameter.

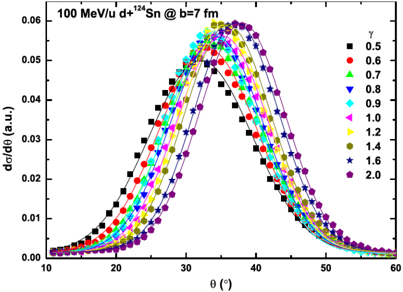
p,n elastic scattering angle



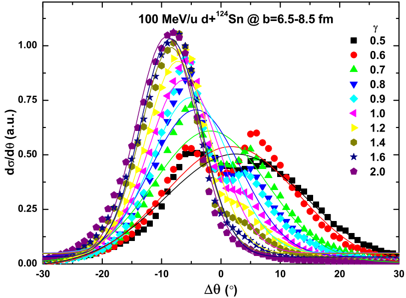
$$\sigma = \sigma_0 + \frac{A}{W\sqrt{\pi/2}} e^{-\frac{2(\theta-\theta_c)^2}{W^2}}$$



proton



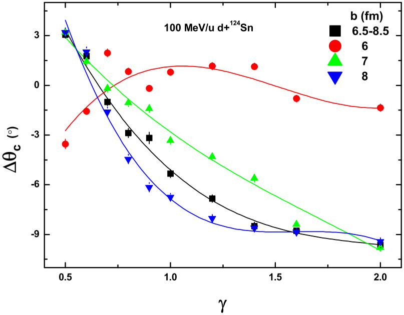
neutron

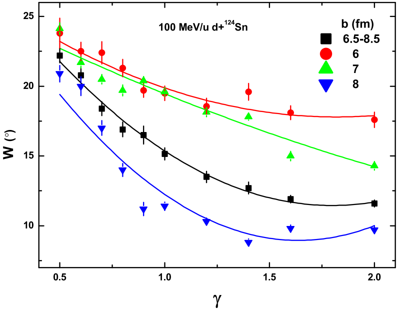


$$\Delta\theta = \theta_p - \theta_n$$

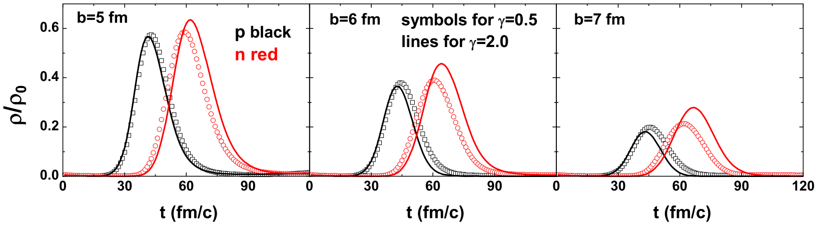
$$\sigma = \sigma_0 + \frac{A}{W\sqrt{\pi/2}} e^{-\frac{2(\Delta\theta - \Delta\theta_c)^2}{W^2}}$$

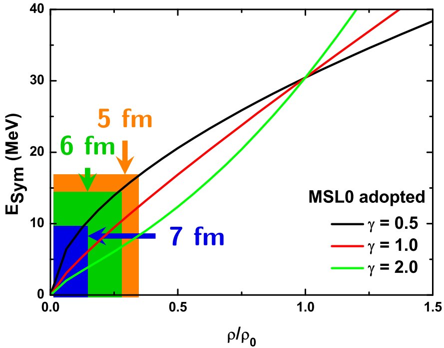
$\Delta\theta_c$ and W are also good probe to study E_{sym}.





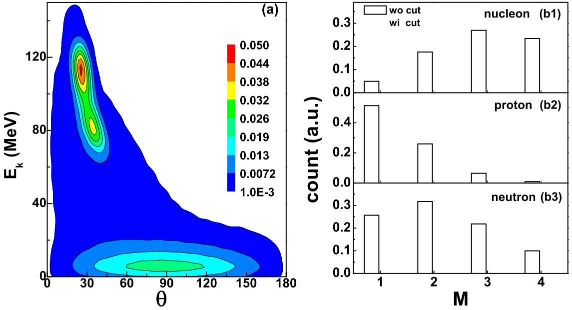
Character





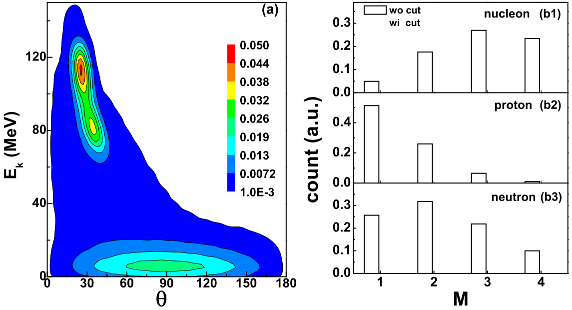
- E_{sym} below $0.5\rho_0$ can be obtained by this method.
- More sensitive and clear than HIC observables because the influence of collision can be easily excluded.

Experimental identification



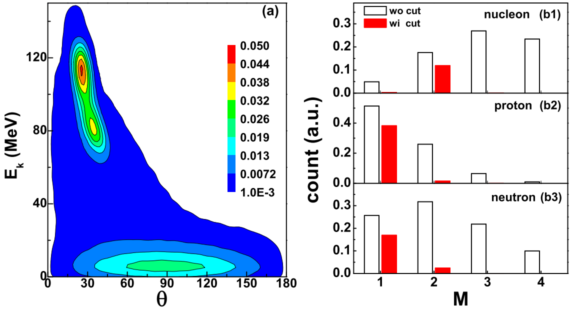
- **Nucleons from projectile or target can be distinguished by θ-E_k correlation. Two components are evidently separated.**

Experimental identification

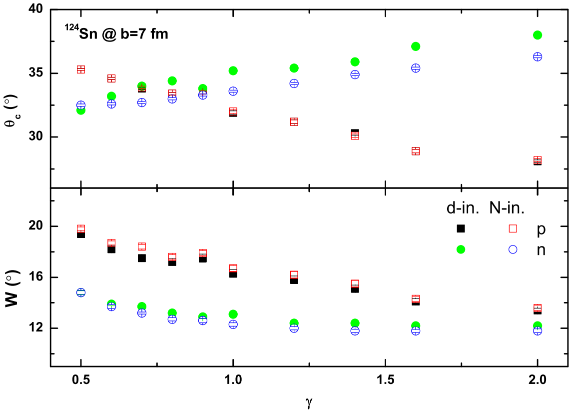


- **Nucleons from projectile or target can be distinguished by θ-$E_{\rm k}$ correlation. Two components are evidently separated.**
- $M_{\rm p} = M_{\rm n} = 1$. **Most of spallation events can be excluded.**

Experimental identification



- **Nucleons from projectile or target can be distinguished by θ-E_k correlation. Two components are evidently separated.**
- **$M_\mathrm{p} = M_\mathrm{n} = 1$. Most of spallation events can be excluded.**
- **With energy cut $E_\mathrm{k} \geqslant 50$ MeV, breakup events caused by collision can be excluded.**



Scattering angle distributions for elastic scattering are close to each other in deuteron-induced and nucleon-induced.