



Fermi energy heavy-ion reaction studies with the compact spectrometer for heavy-ion experiment (CSHINE)

speaker : Yijie Wang (王轶杰)

coauthor : Zhigang Xiao



清华大学
Tsinghua University

■ Content

- Research background

- CSHINE detector system

- Recent studies:

 - 1, Isospin Chronology

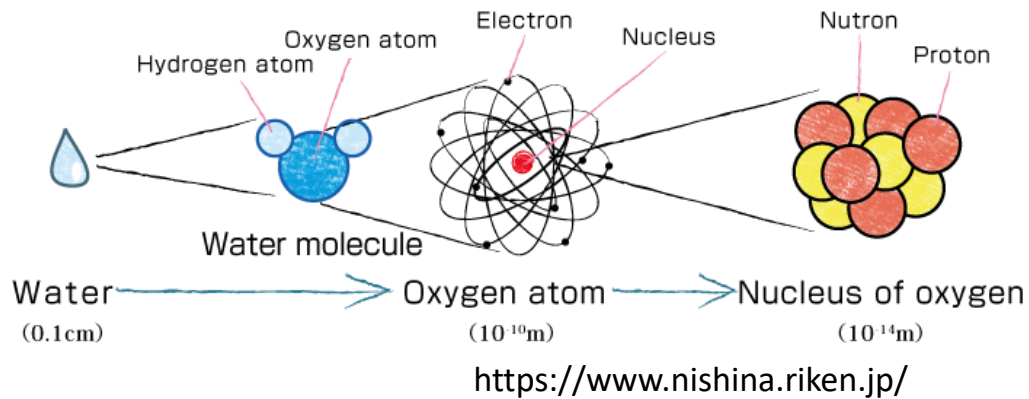
 - 2, Isospin “ping-pang” emission

 - 3, n-p Bremsstrahlung gamma in HIR

- Summary

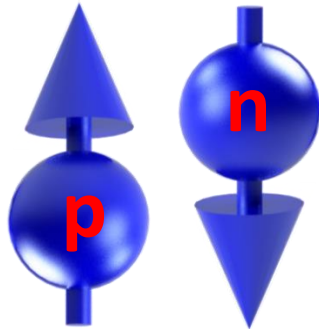
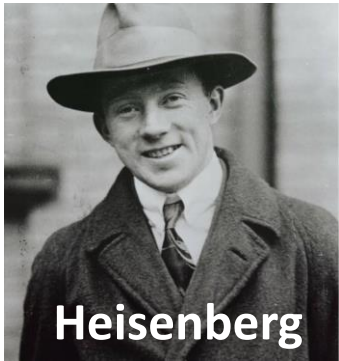
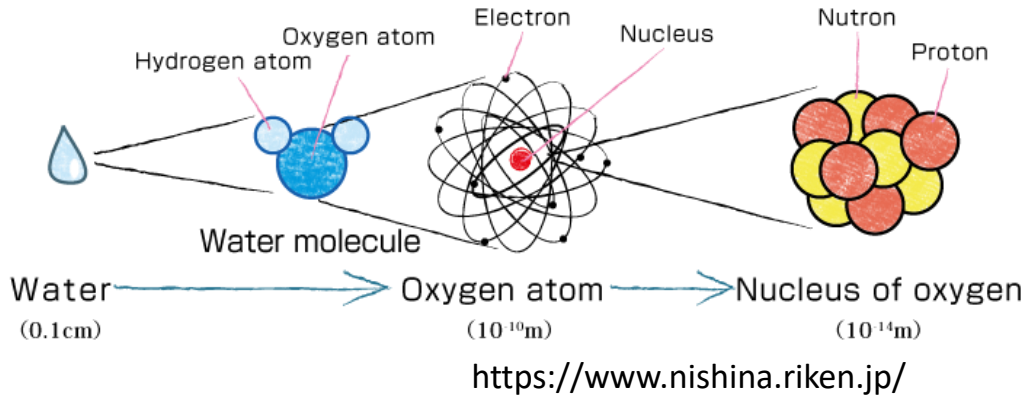
■ Nucleus, Isospin, Symmetry Energy

Molecule – Atom – Nucleus



■ Nucleus, Isospin, Symmetry Energy

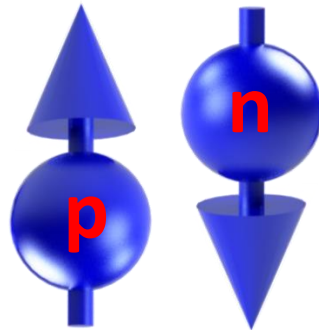
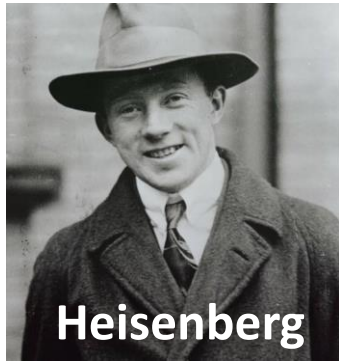
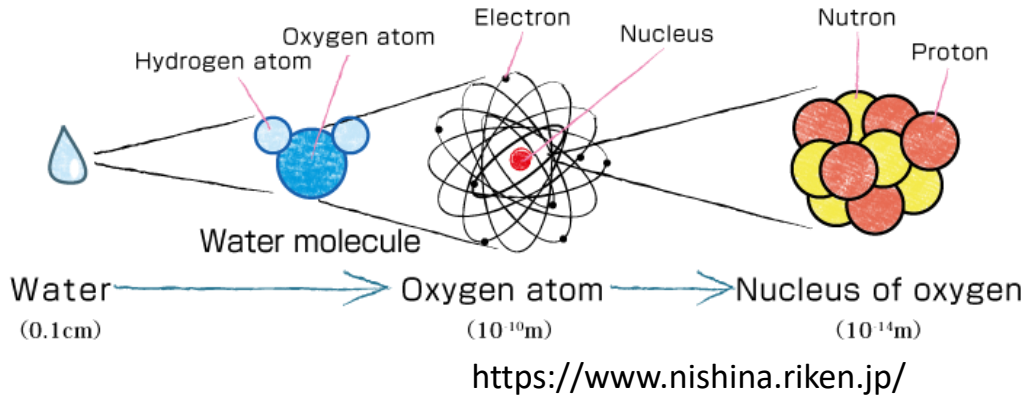
Molecule – Atom – Nucleus



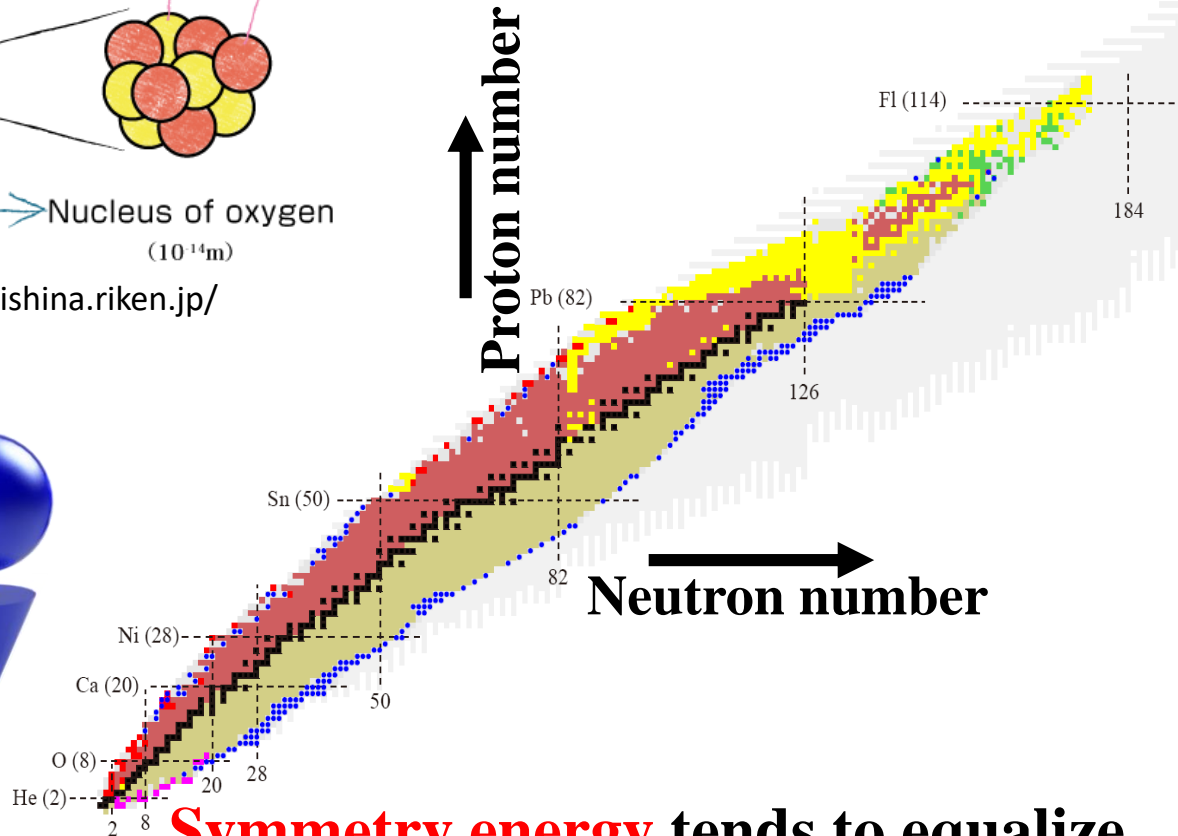
Isospin distinguishes
proton and neutron

■ Nucleus, Isospin, Symmetry Energy

Molecule – Atom – Nucleus



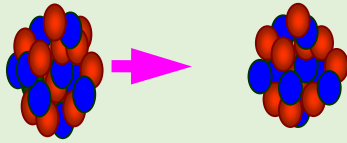
Isospin distinguishes
proton and neutron



Symmetry energy tends to equalize
the number of neutrons and protons
cf. [Yingxun Zhang, Akira Ono's talk]

■ Heavy Ion Reaction, Isospin dynamic in zeptosecond scale

Heavy Ion Reaction~ 10^{-22} s



30MeV/u ^{40}Ar

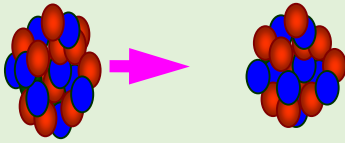
^{197}Au

Velocity: $\sim 0.25c$

Scale: $\sim 10^{-14}\text{m}$

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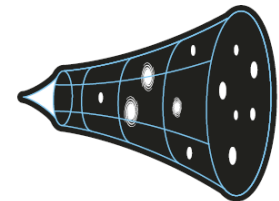
Heavy Ion Reaction
 $\sim 10^{-22}\text{s}$



ATTOSECOND
 $\sim 10^{-18}\text{s}$



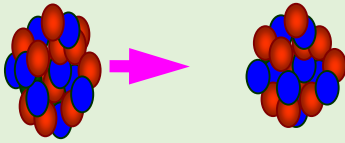
HEARTBEAT
 $\sim 1\text{s}$



AGE OF THE UNIVERSE
 $\sim 10^{18}\text{s}$

■ Heavy Ion Reaction, Isospin dynamic in zeptosecond scale

Heavy Ion Reaction $\sim 10^{-22}\text{s}$

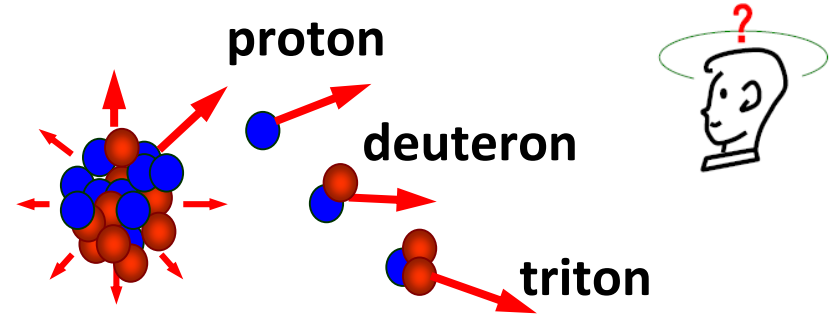


30 MeV/u ^{40}Ar

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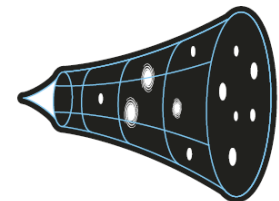
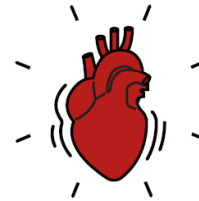
Question: How to measure isospin dynamic evolution in ultra-fast process?

Heavy Ion Reaction
 $\sim 10^{-22}\text{s}$

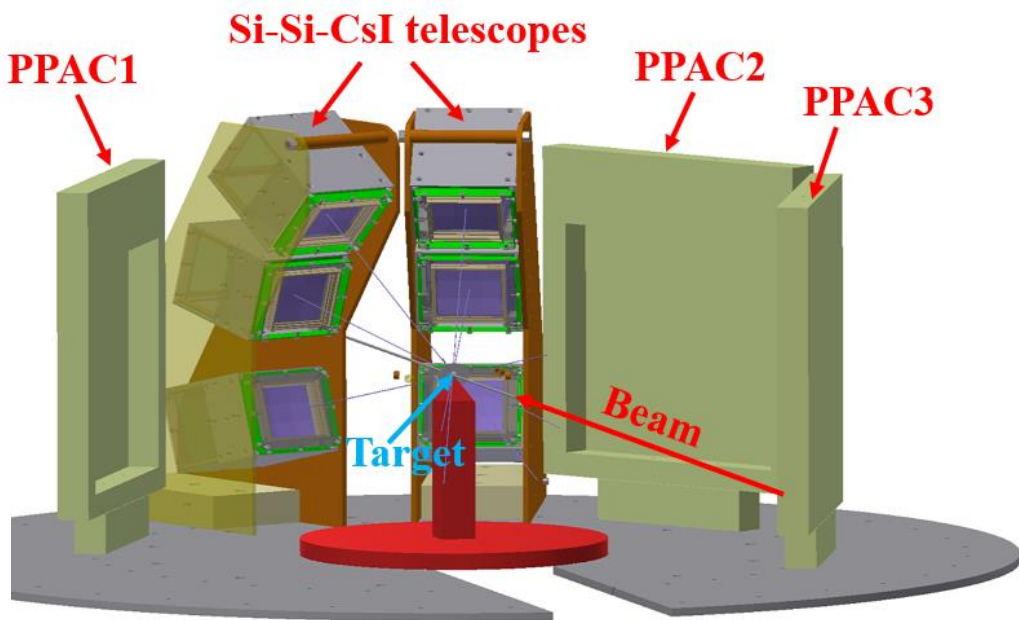
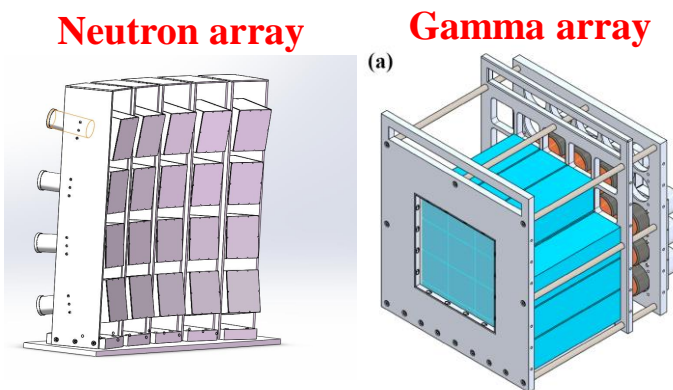
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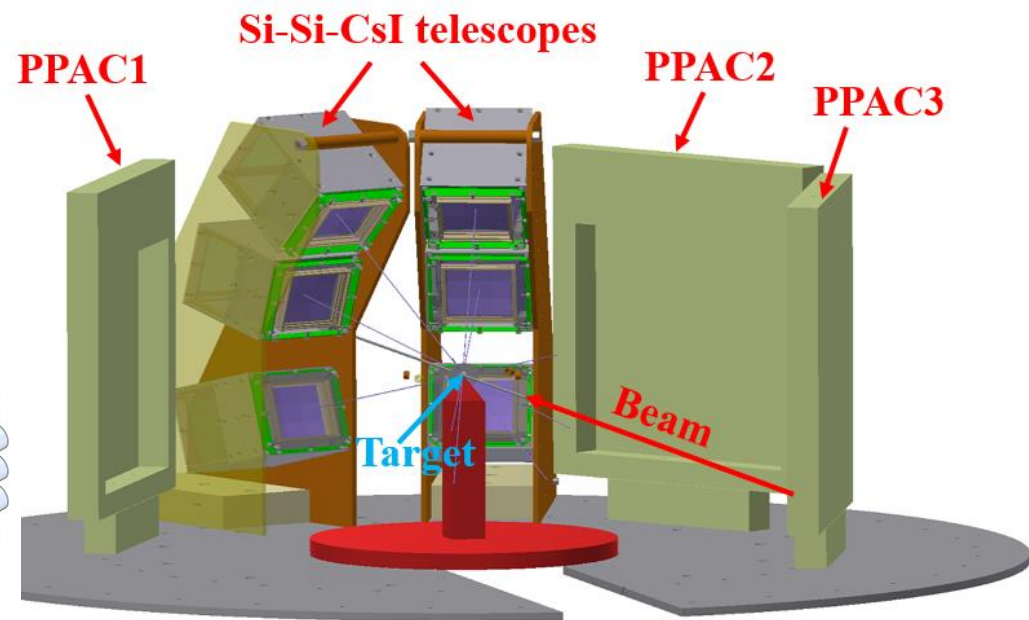
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■ Compact Spectrometer for Heavy Ion Experiment(CSHINE)

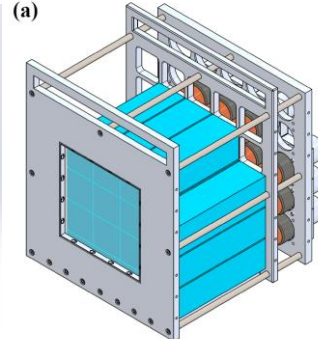
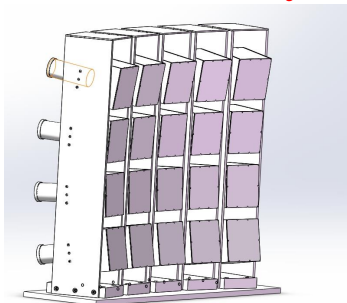


■ Compact Spectrometer for Heavy Ion Experiment(CSHINE)



Neutron array

Gamma array



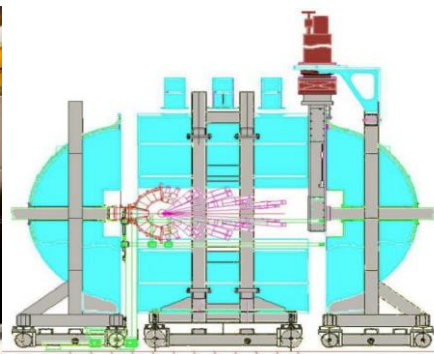
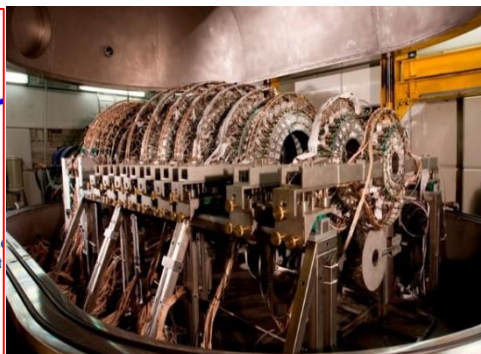
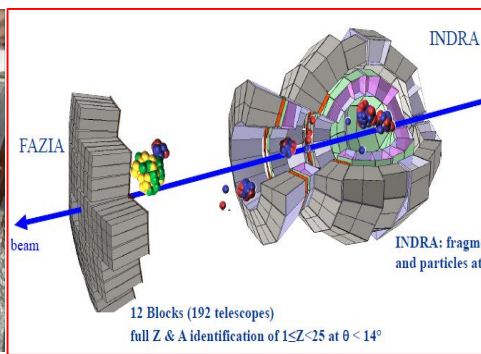
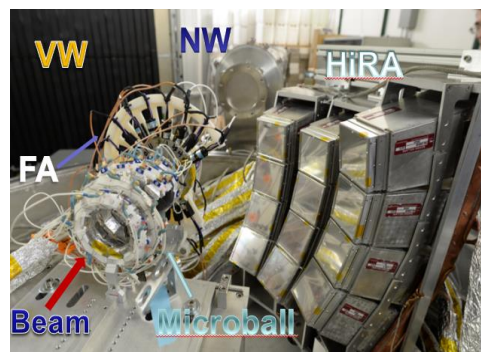
Compared with the large detector system in the world, CSHINE is relatively compact.

HiRA@FRIB

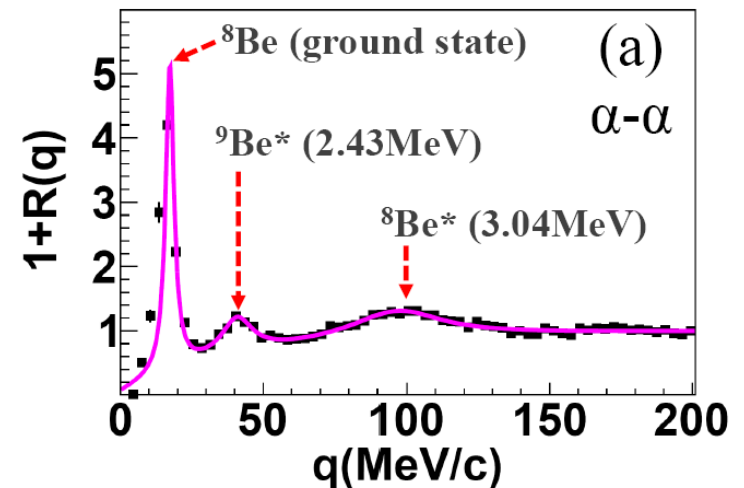
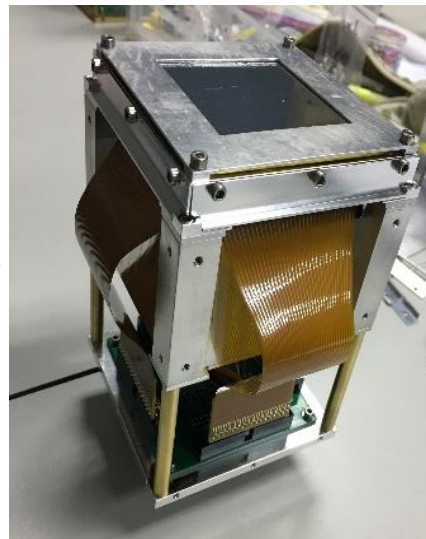
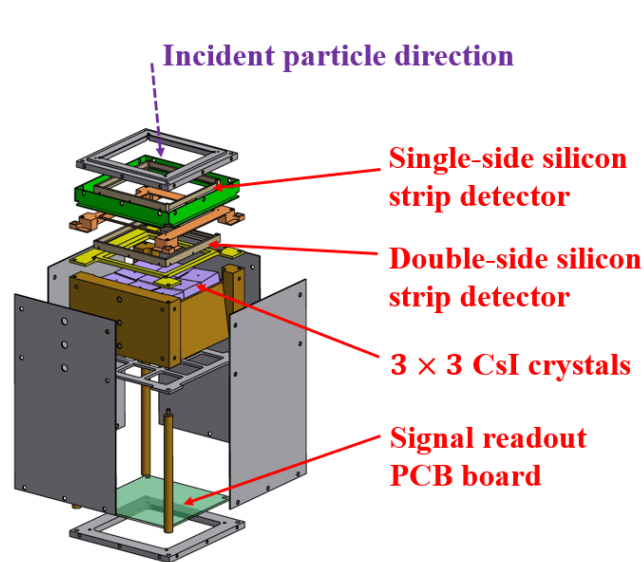
INDRA@GANIL

CHIMERA @ INFN

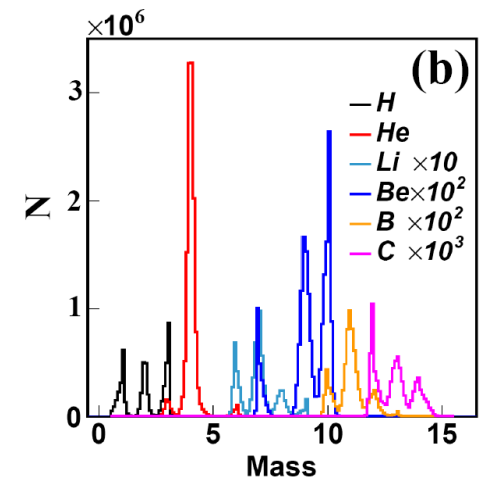
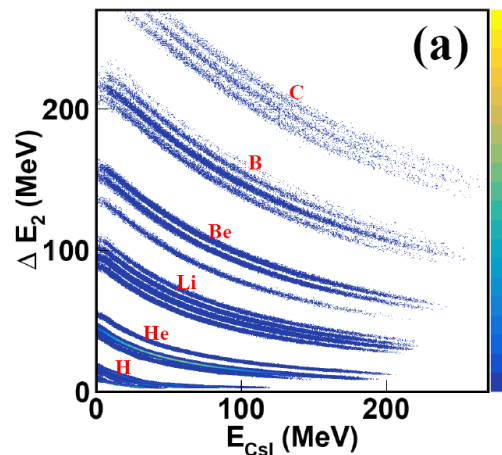
NIMROD@TAMU



■ Silicon Strip Detector Telescope (SSDT)



Silicon strip width: 2mm
Good isotopic resolution
For **light charge particles**



Nucl. Sci. Tech. 32, 4 (2021)

Nucl. Inst. Meth. A, 1011, 165592 (2021)

■ Parallel Plate Avalanche Chamber (PPAC)

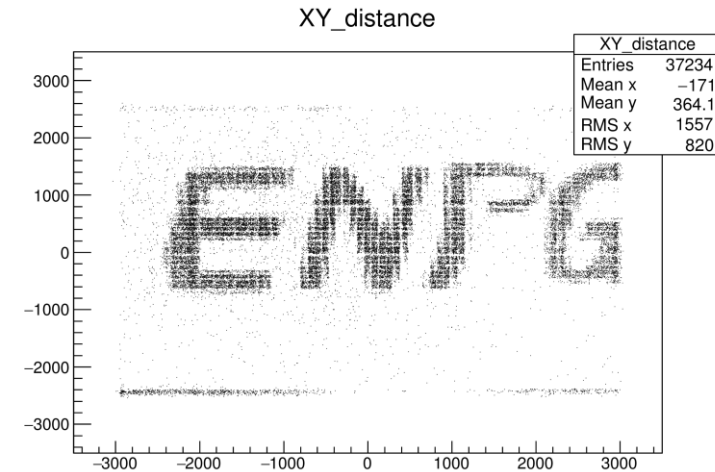
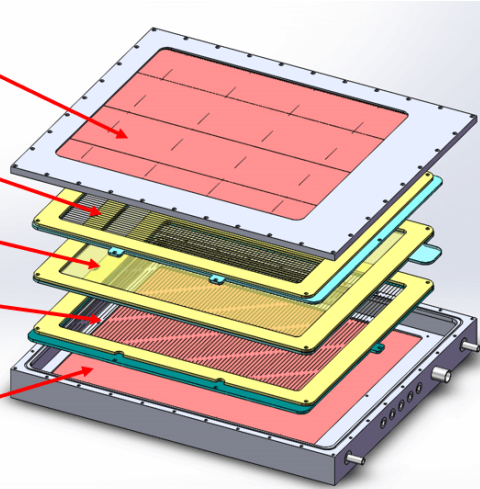
Exit window

X anode
wires plane

Cathode plane

Y anode
wires plane

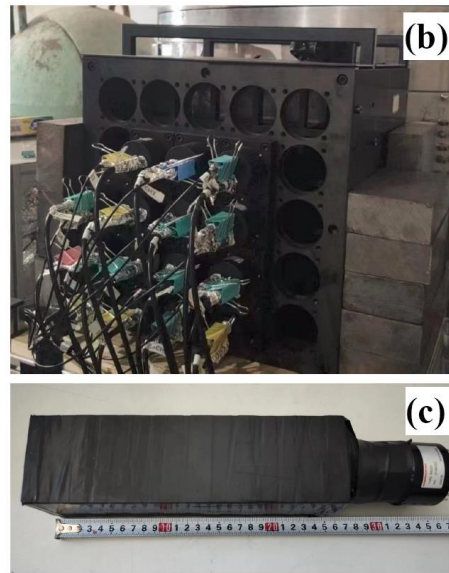
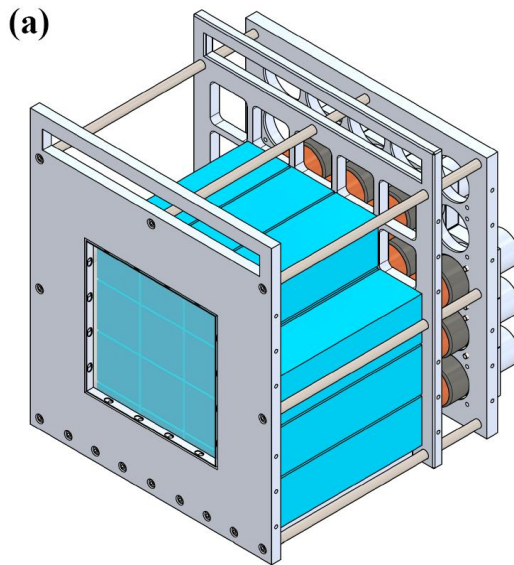
Entrance
window



Time resolution: 260ps
Position resolution: 1.4mm
Sensitive area: 240mm*280mm
For **fission fragments**

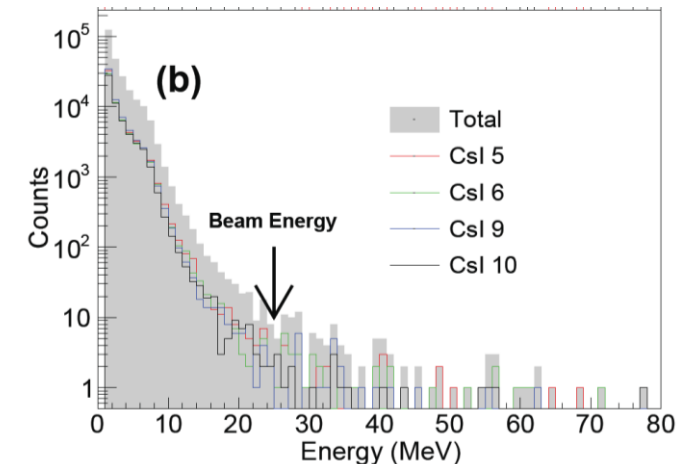
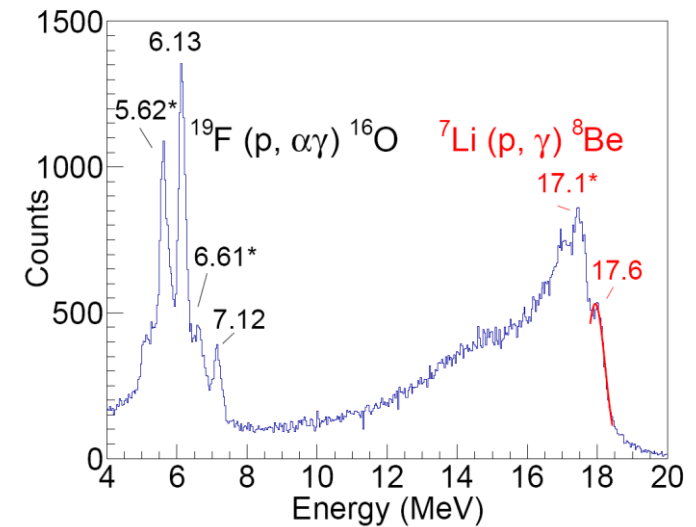
Nuclear Engineering and Technology 52,3 (2019)

■ High Energy Gamma Array



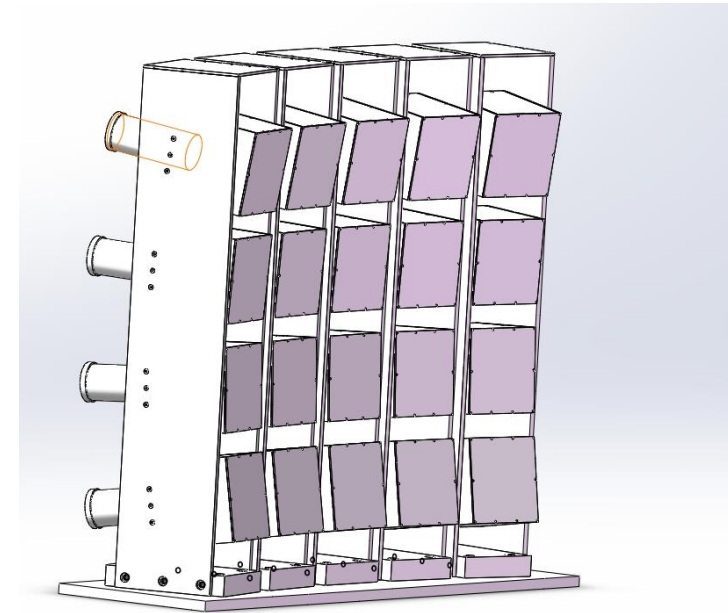
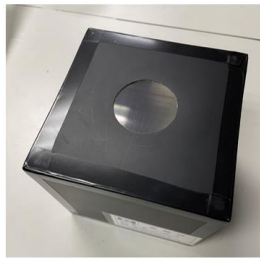
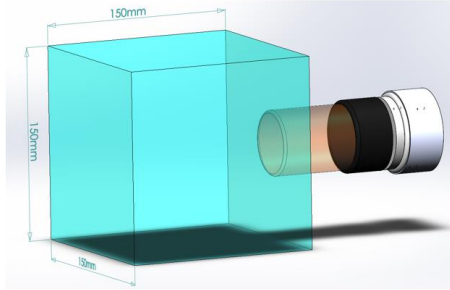
Energy resolution: 3%
Energy range: 10-80MeV
For **high energy gamma**

Nucl. Inst. Meth. A, 1053, 168330 (2023)



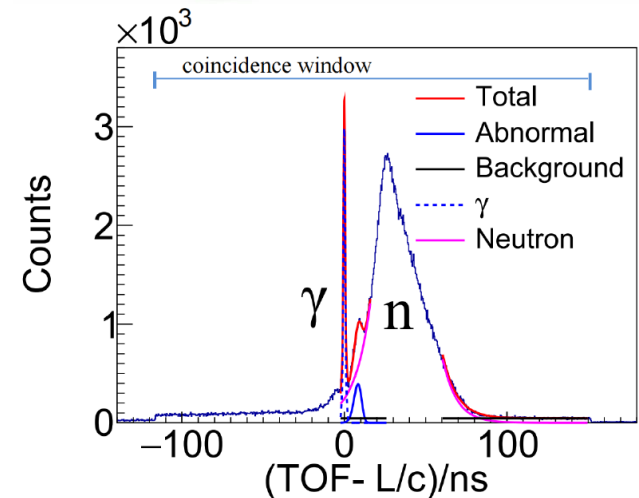
■ Neutron detector Array

Heavy ion reAction Neutron MEasurement detector (HANMER)



Plastic scintillator + PMT
15cm * 15cm * 15cm; 4 * 5 units
For **neutron**

ArXiv:2406.18605



■ Physics studies at CSHINE:

① Light charge particles

- a, Isospin relaxation
- b, E_{sym} in nEoS
- c, HBT correlation
- d, Yield Ratio

...

② Fission fragments

- a, Fast fission
- b, Fission dynamics
- c, Folding angle
- d, Neck emission

...

③ High energy gamma

- a, np bremsstrahlung
- b, Short Range Corr.
- c, $np \rightarrow d + \gamma$
- d, E_γ spectrum

...

④ Future plane

- a, n-n HBT correlation
- b, t and ^3He emission
- c, $\theta(n/p)$ distribution
- d, Resonance decay

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Y.J. Wang, et al., *The Emission Order of Hydrogen Isotopes via Correlation Functions in 30 MeV/u Ar+Au Reactions* (Physics Letters B, 825, 136856 (2022))

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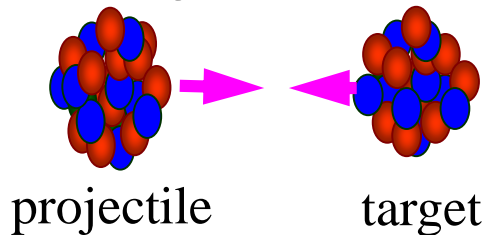
Method: HBT method (Intensity interferometer). *cf.* [^{Chuan Fu}
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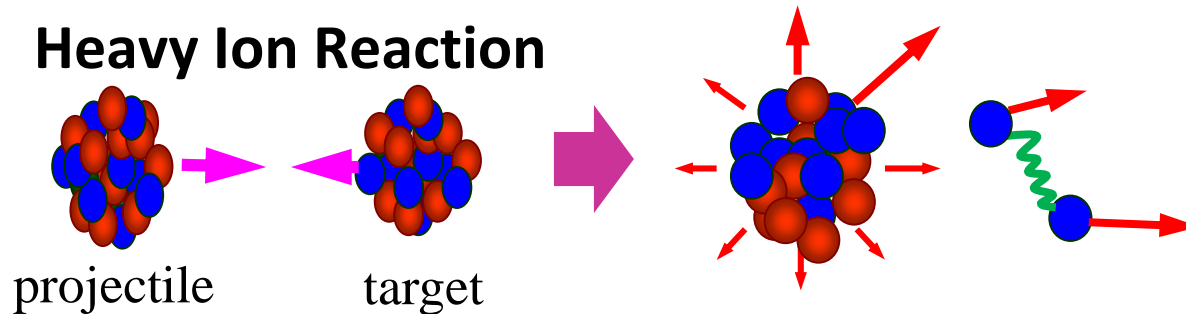
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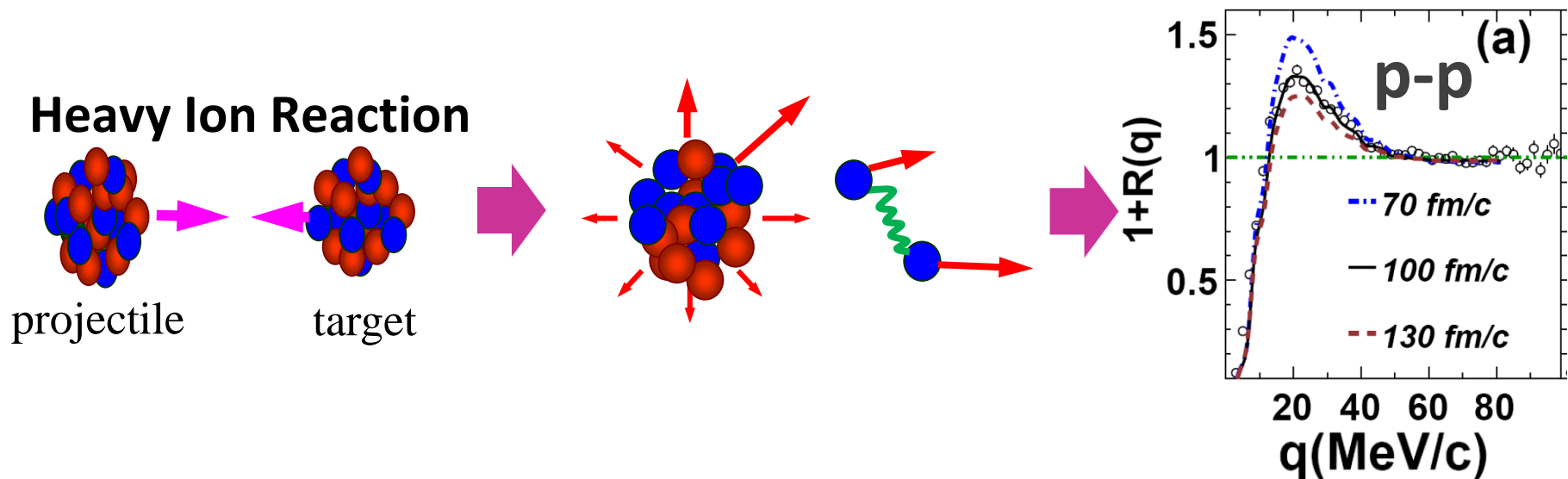
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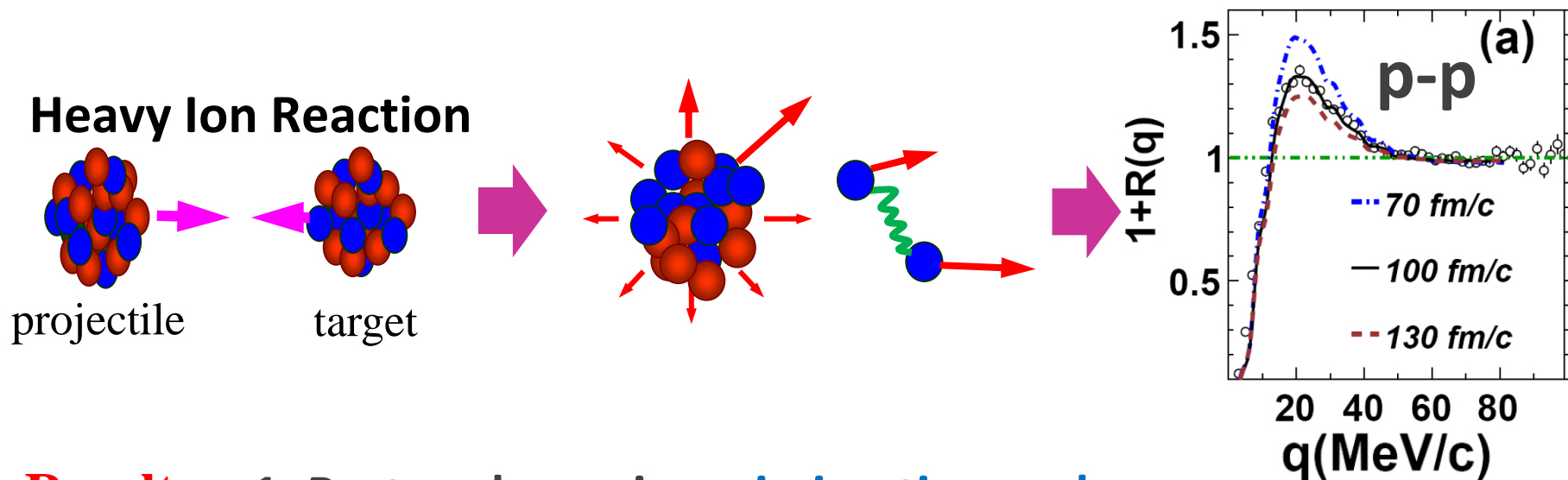
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Results: 1, Proton dynamic emission timescale:

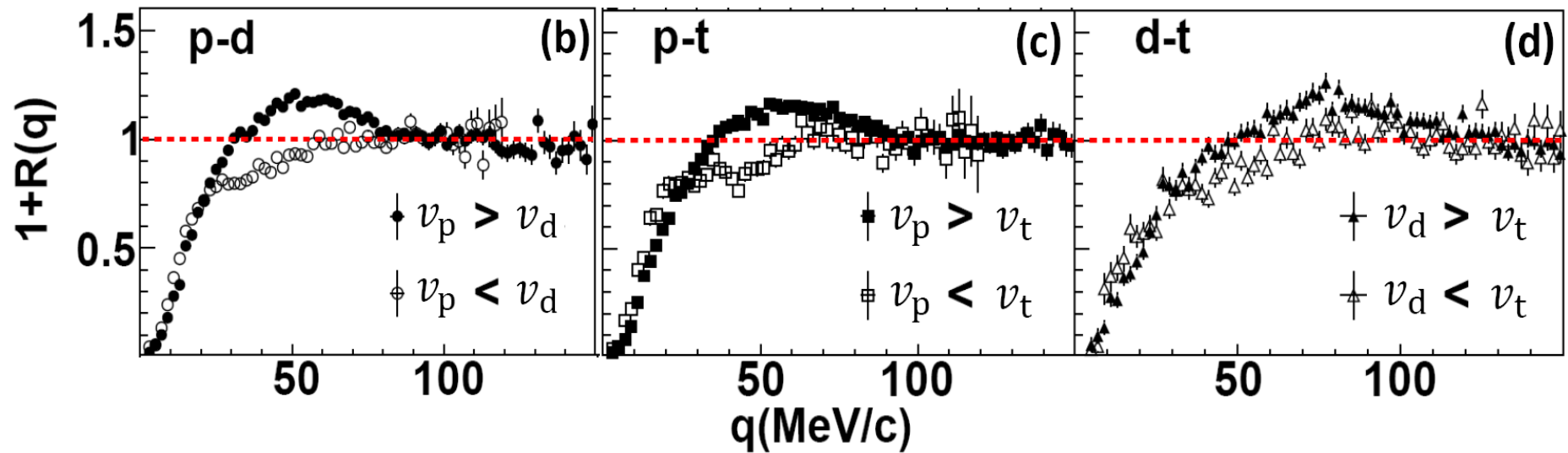
$$\tau_p \approx 100 \text{ fm}/c$$

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Method: Velocity-gated correlation function method.

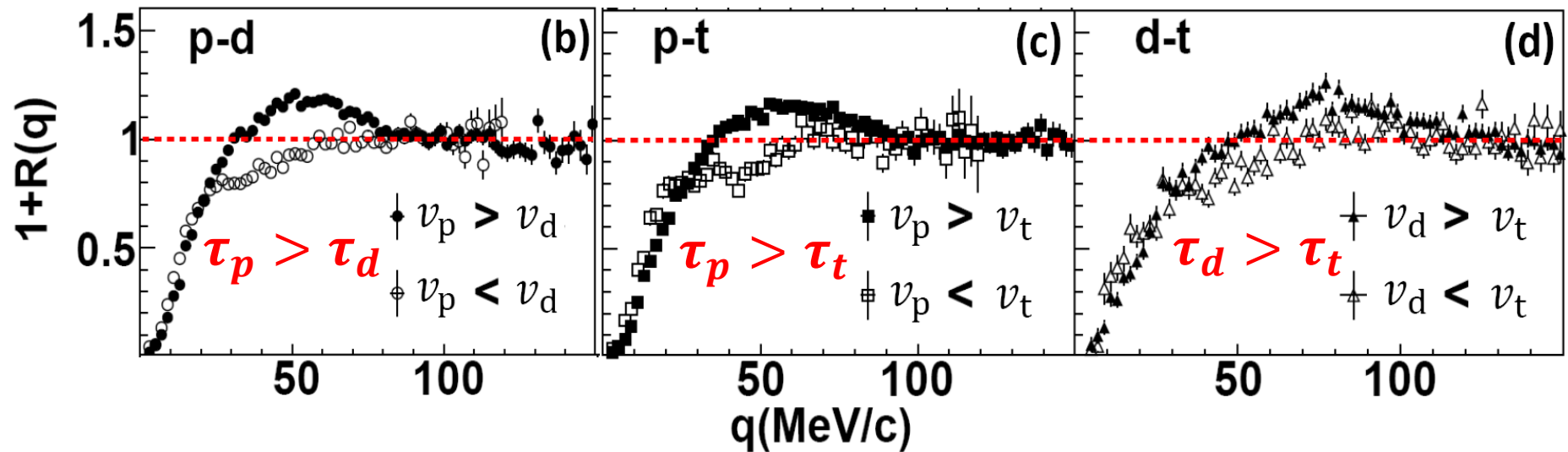
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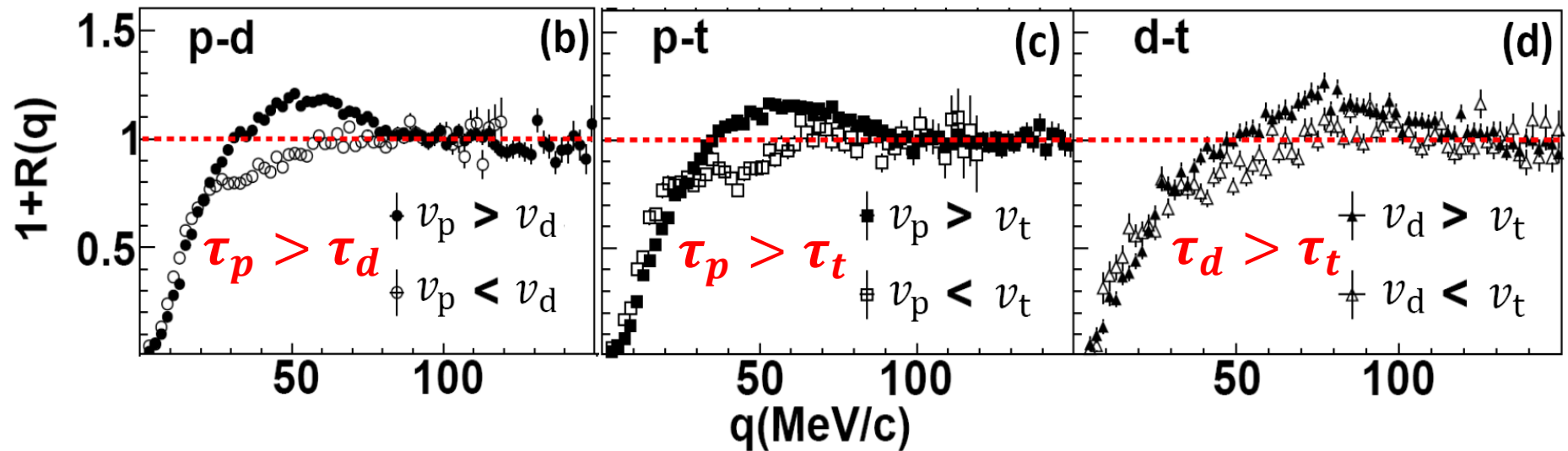
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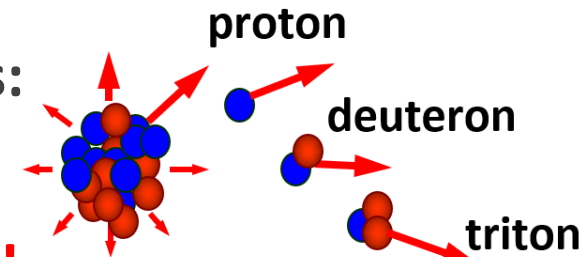
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Results: 2, Emission order of hydrogen isotopes:

$$\tau_p > \tau_d > \tau_t$$

Neutron-rich particle emitted earlier!

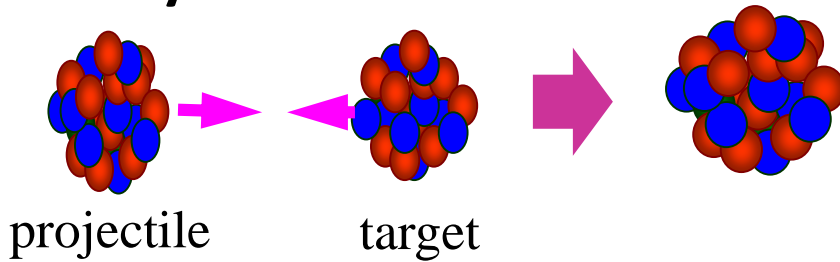


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Recent work 2: Ping-pang emission

$^{86}\text{Kr}@25\text{MeV/u} + ^{208}\text{Pb}$

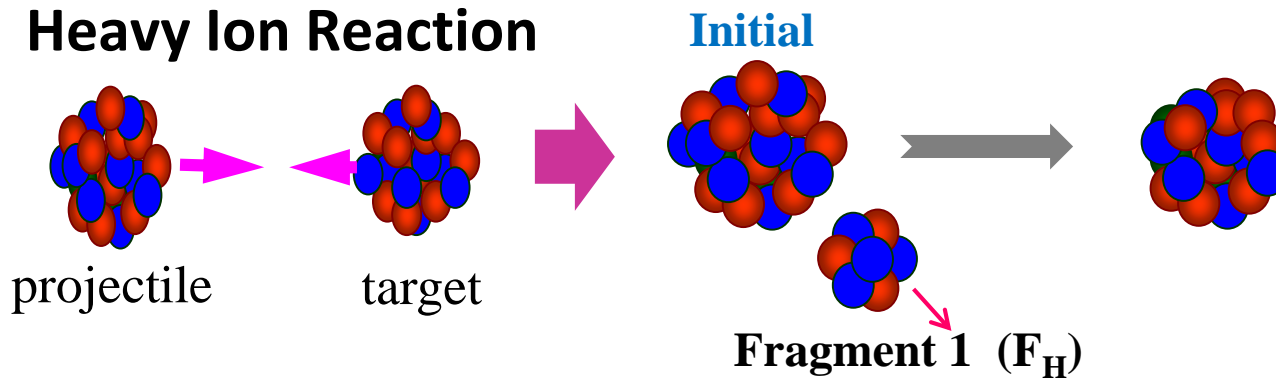
Heavy Ion Reaction



Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

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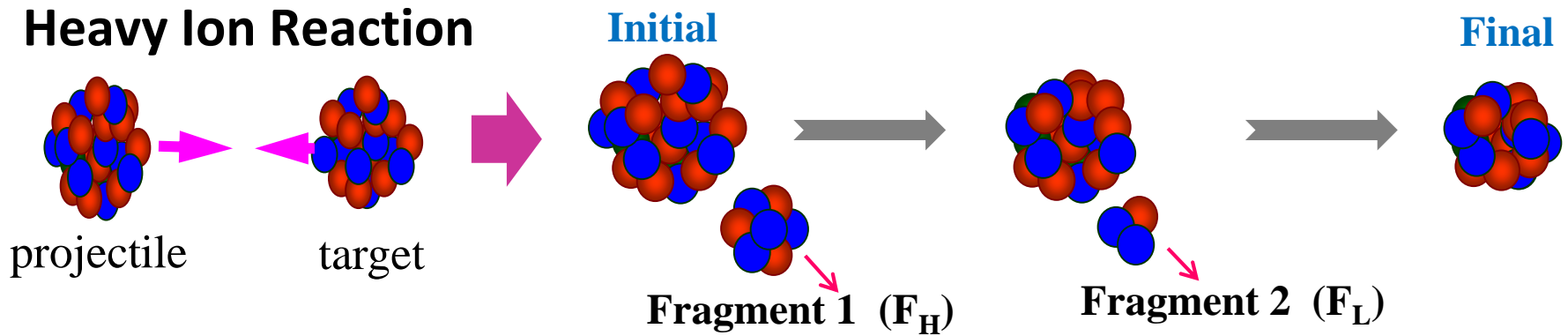
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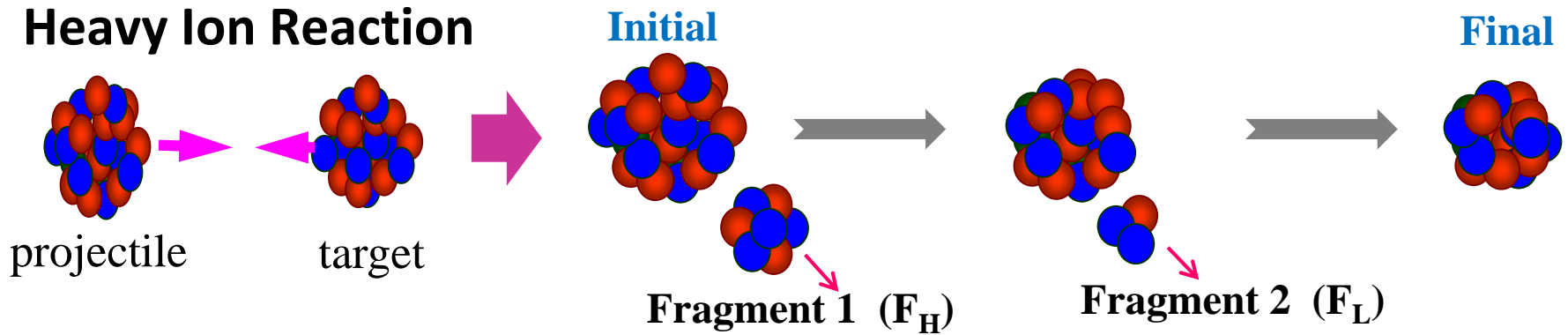
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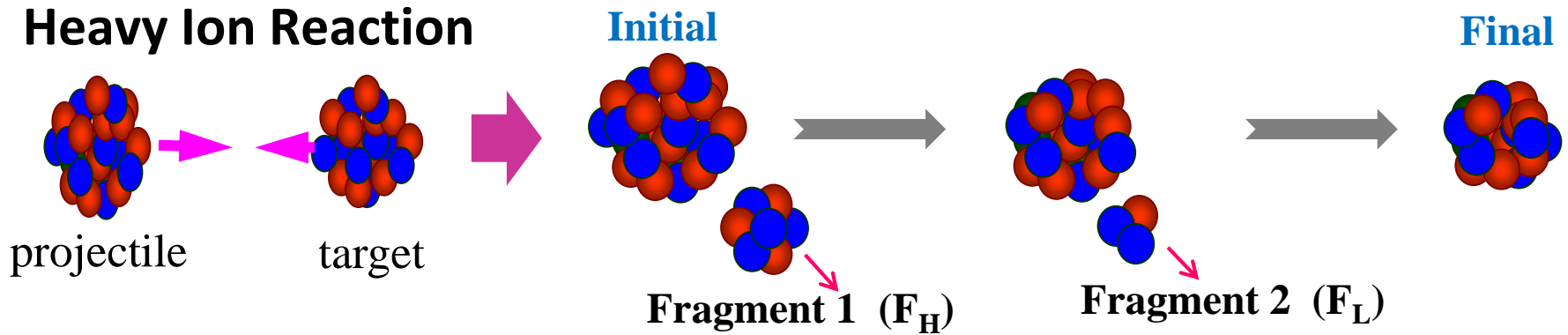


Question: Isospin correlation F_H vs. F_L in time sequence?

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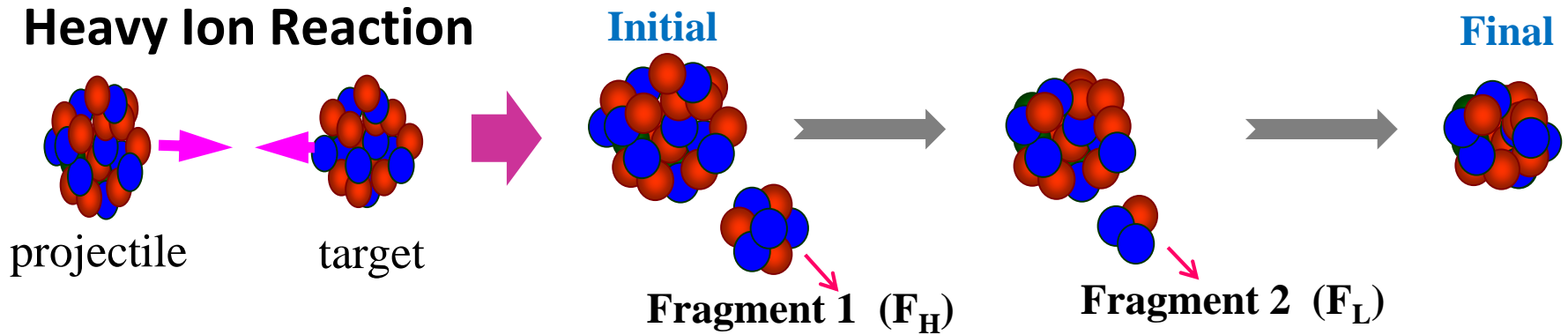
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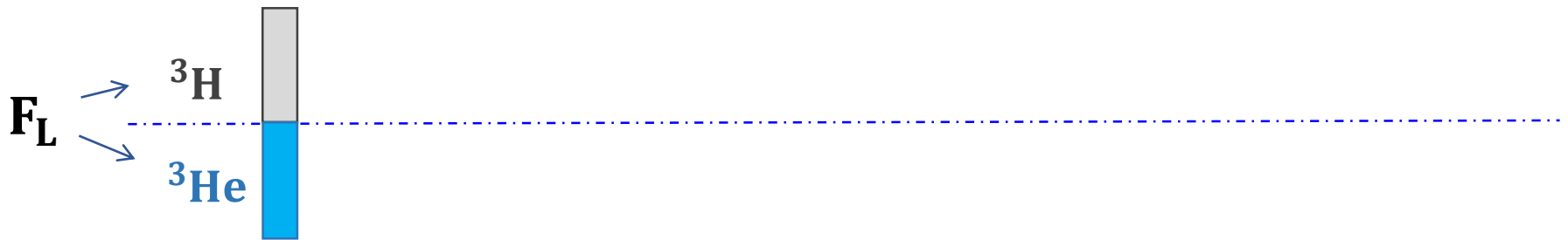
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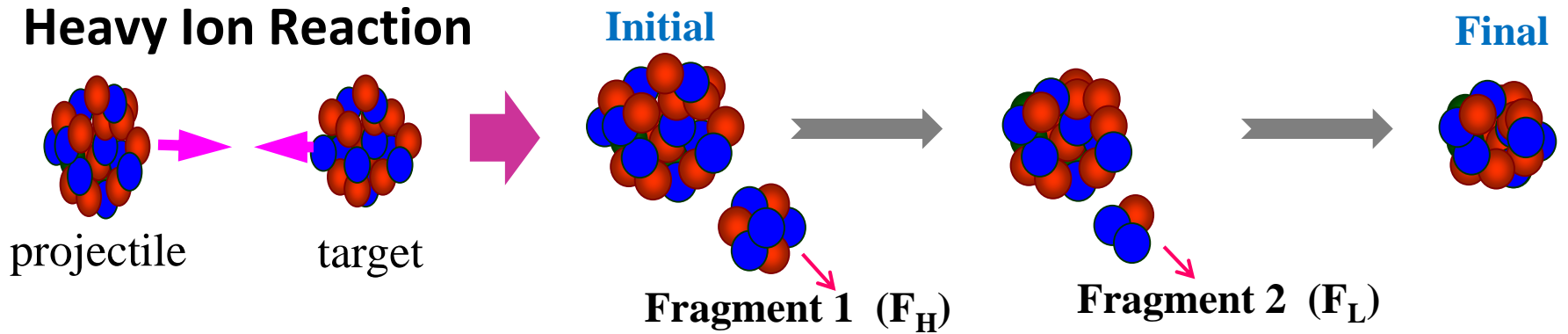
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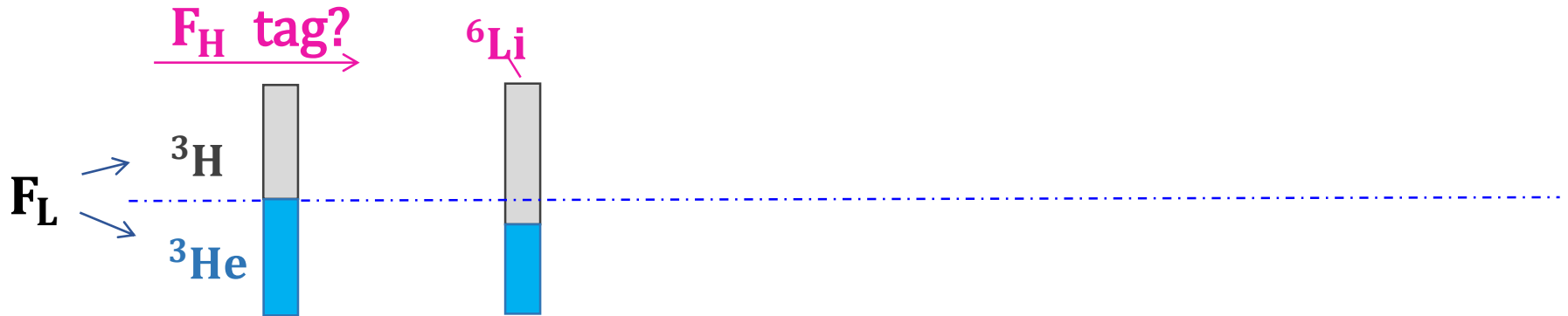
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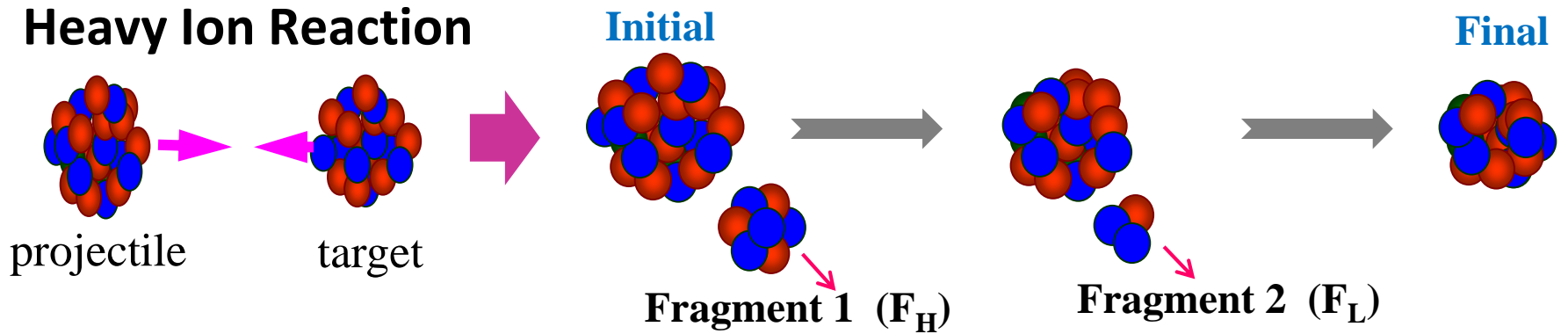
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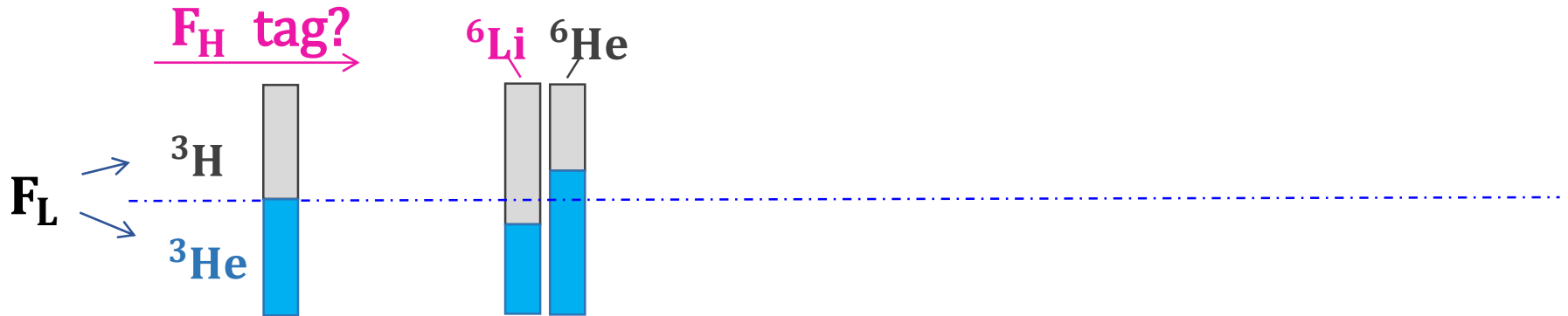
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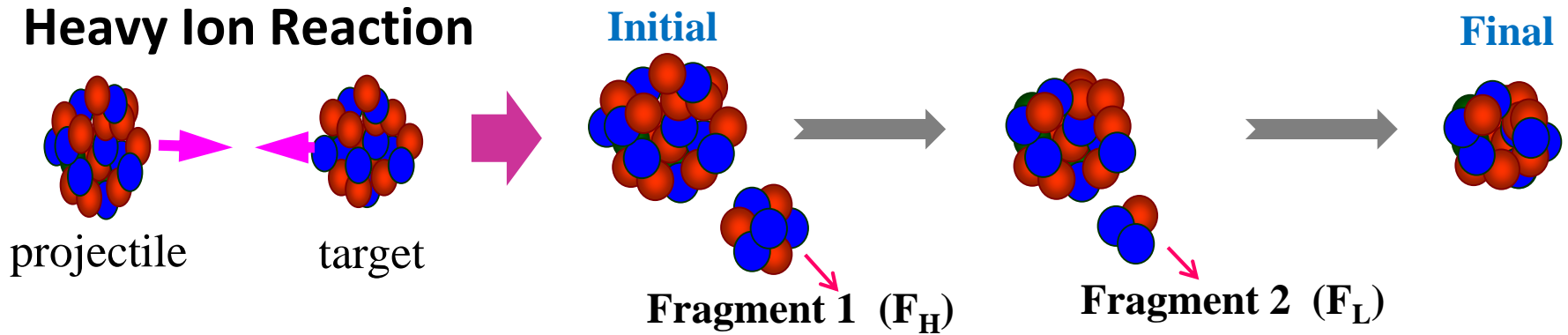
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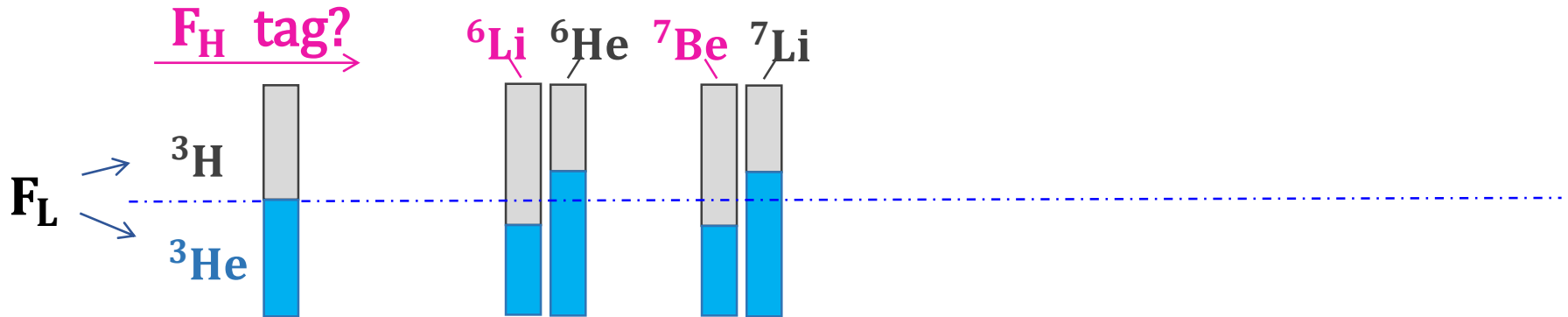
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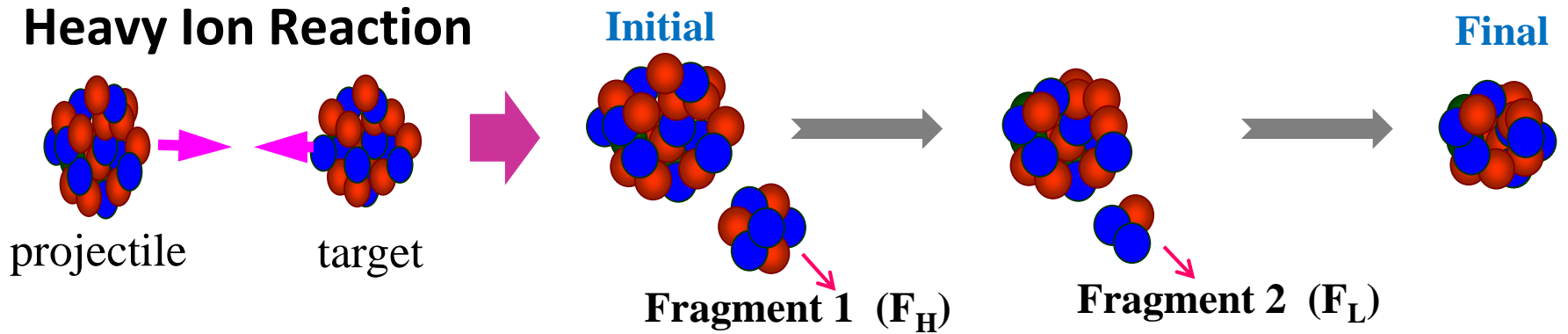
Method: Isobaric method (F_H : neutron deficient, neutron rich)



Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

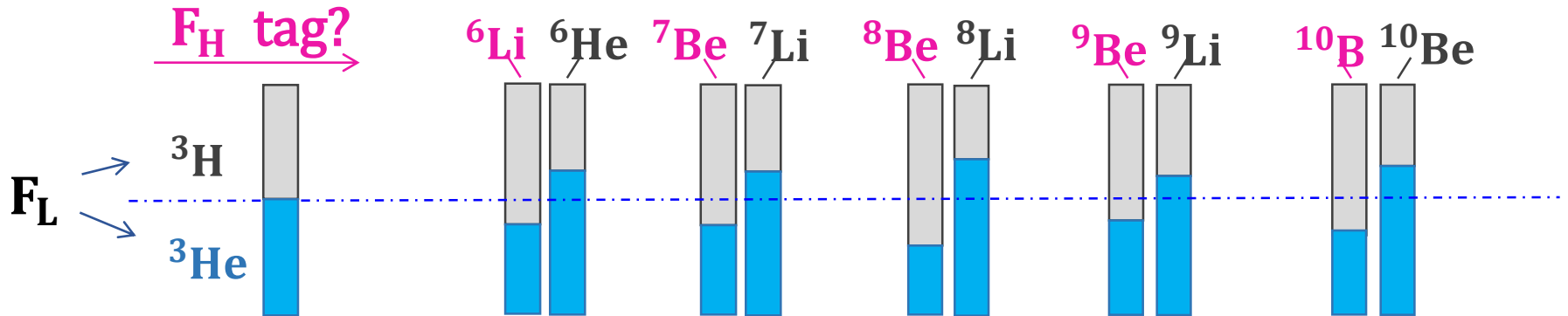
Recent work 2: Ping-pang emission

$^{86}\text{Kr}@25\text{MeV/u} + ^{208}\text{Pb}$



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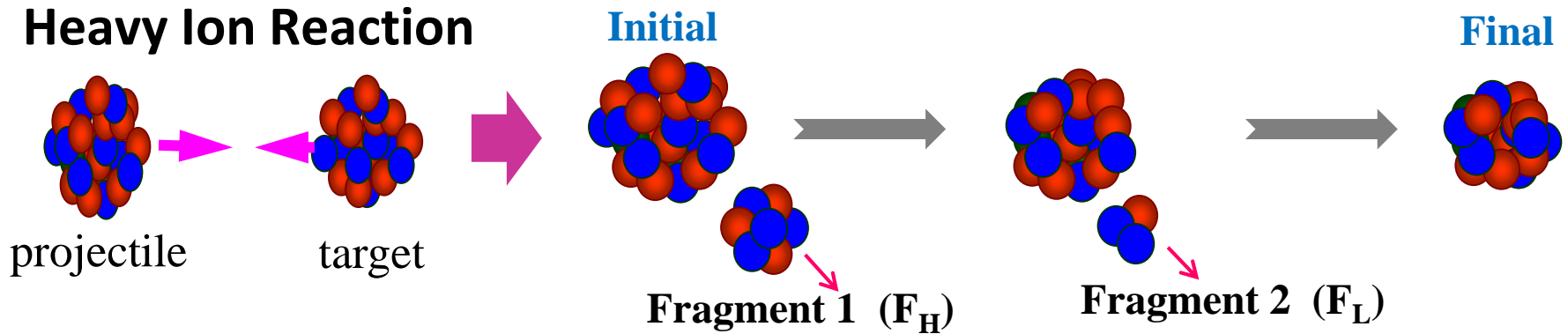
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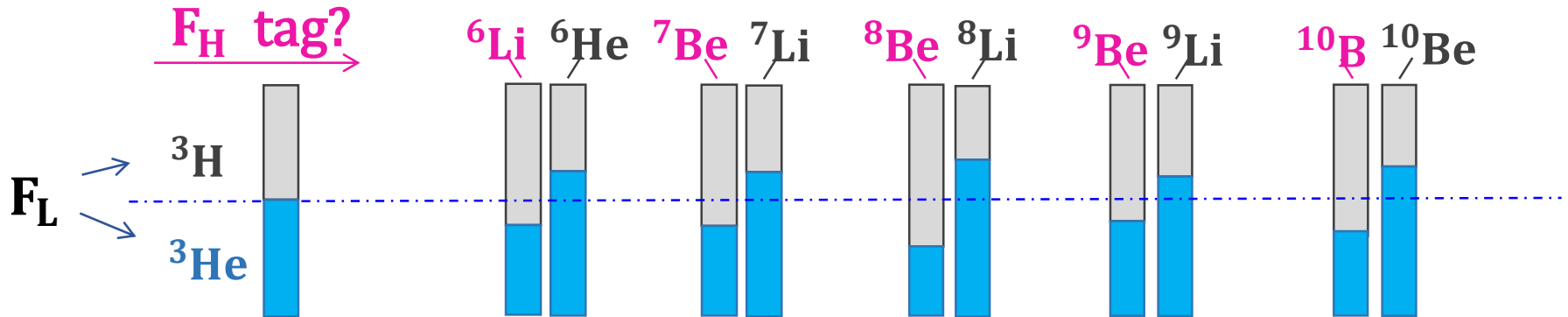
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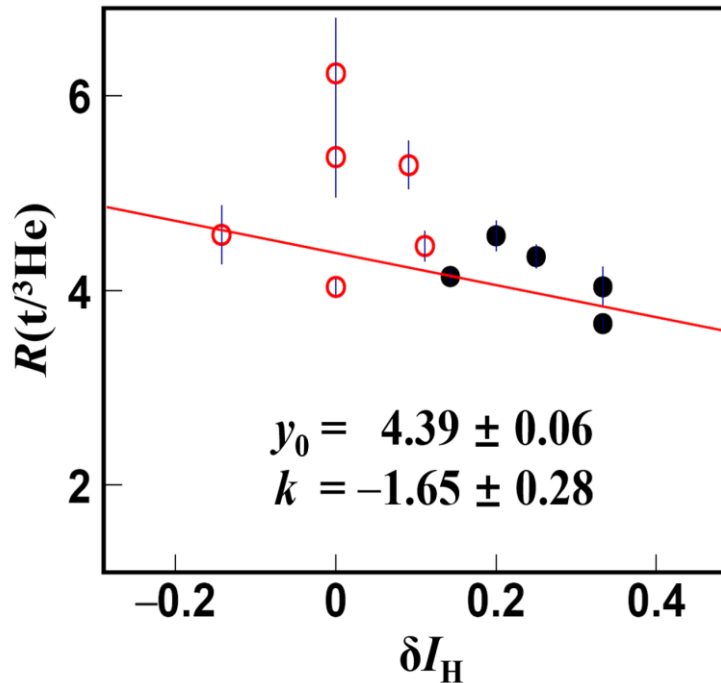
Results: Neutron rich and deficient particle emitted alternatively!

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

**Isospin relation
between F_H vs. F_L**

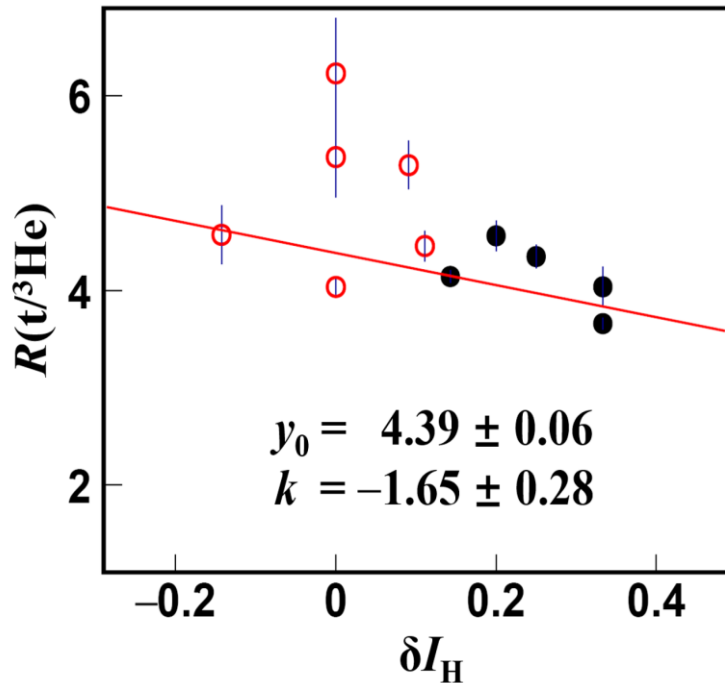
Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

Isospin relation between F_H vs. F_L



Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

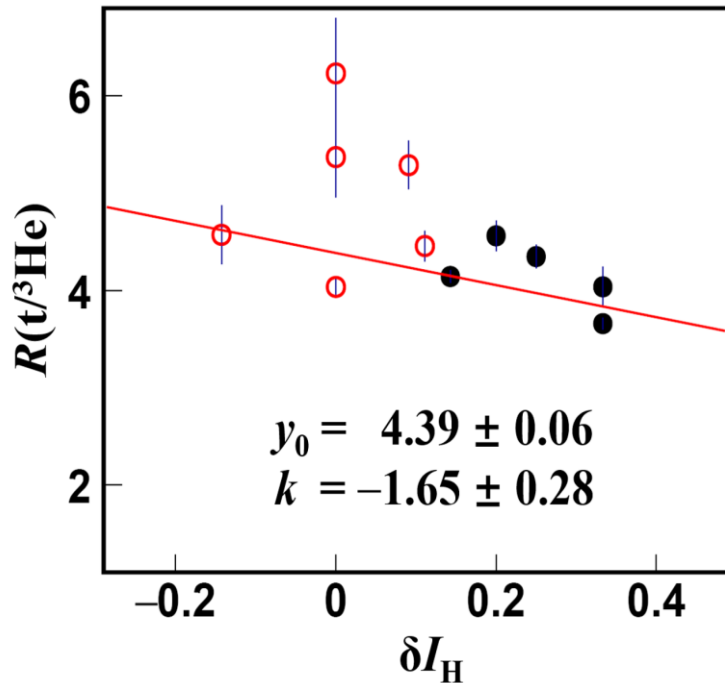
Isospin relation between F_H vs. F_L



1, **Isospin anti-correlation.**

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

Isospin relation between F_H vs. F_L

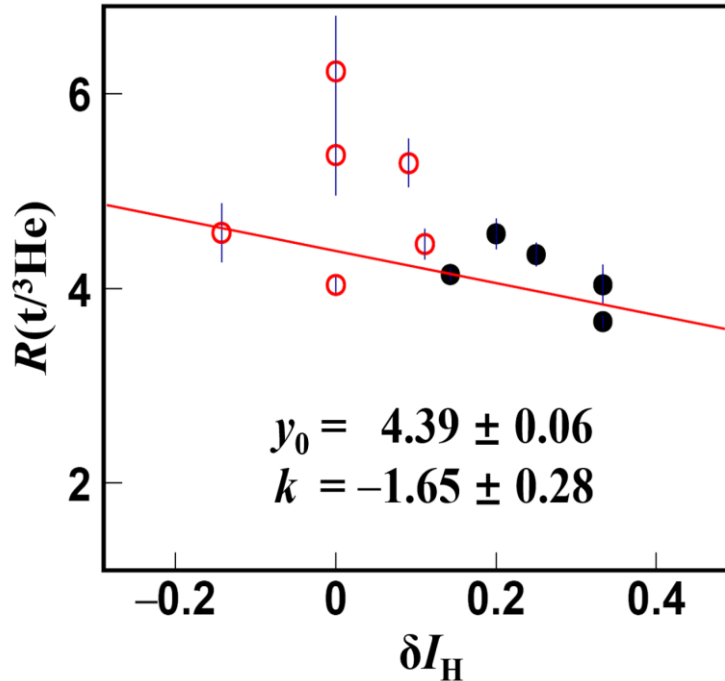


1, **Isospin anti-correlation.**

N/Z property of residue and initial system

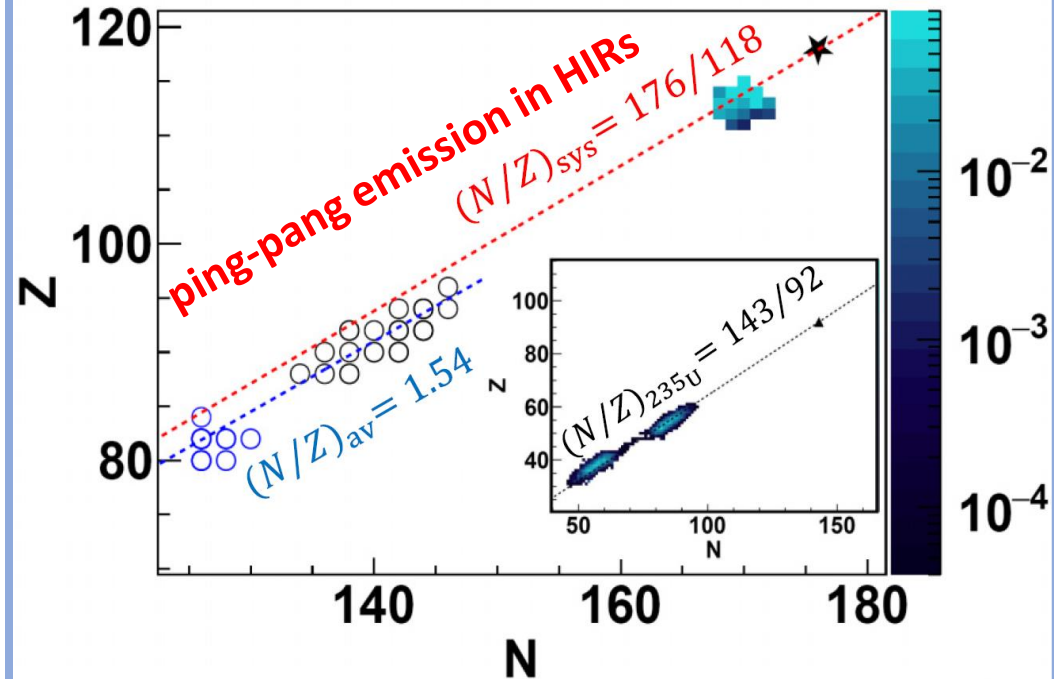
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Isospin relation between F_H vs. F_L



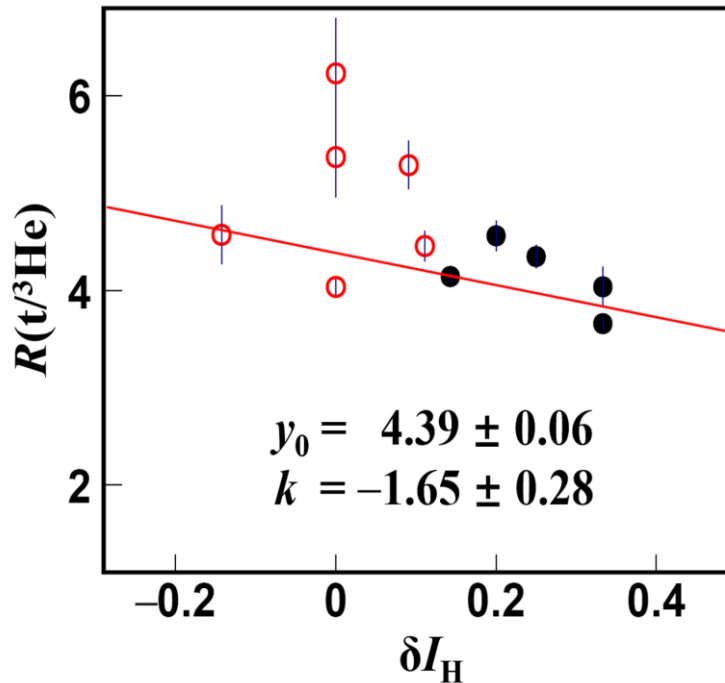
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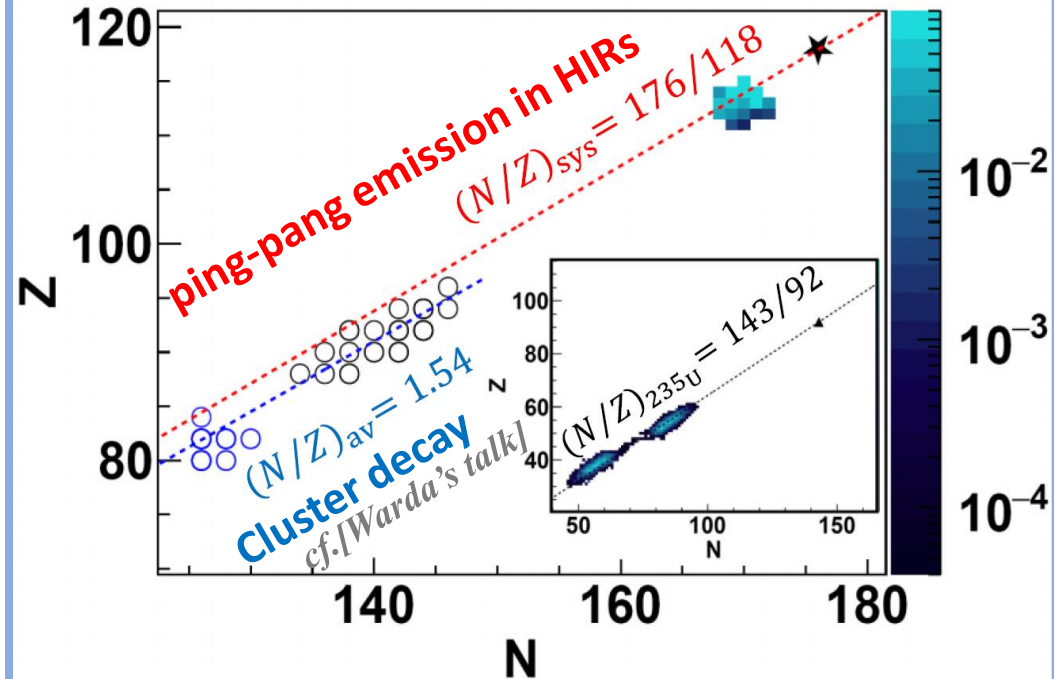
Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

Isospin relation between F_H vs. F_L



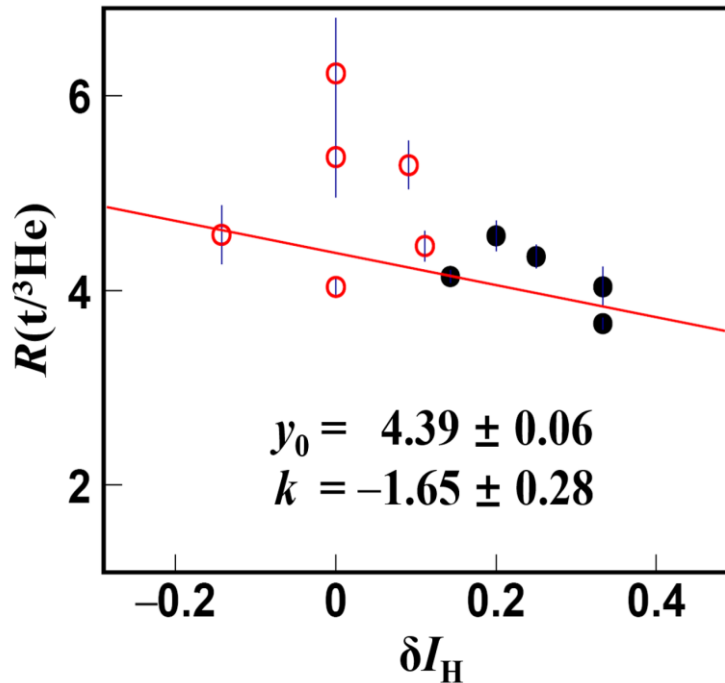
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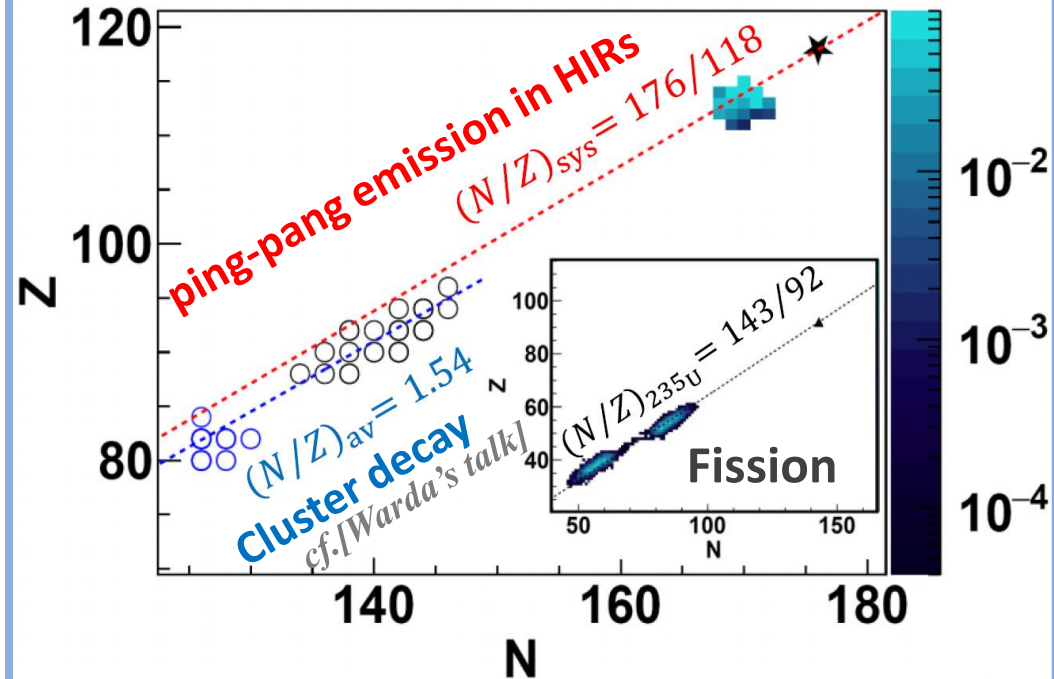
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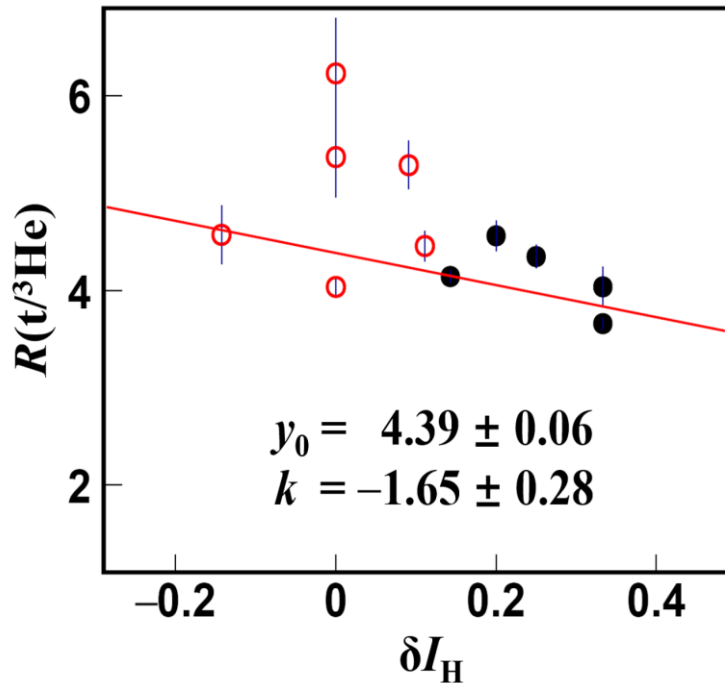
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N/Z property of residue and initial system



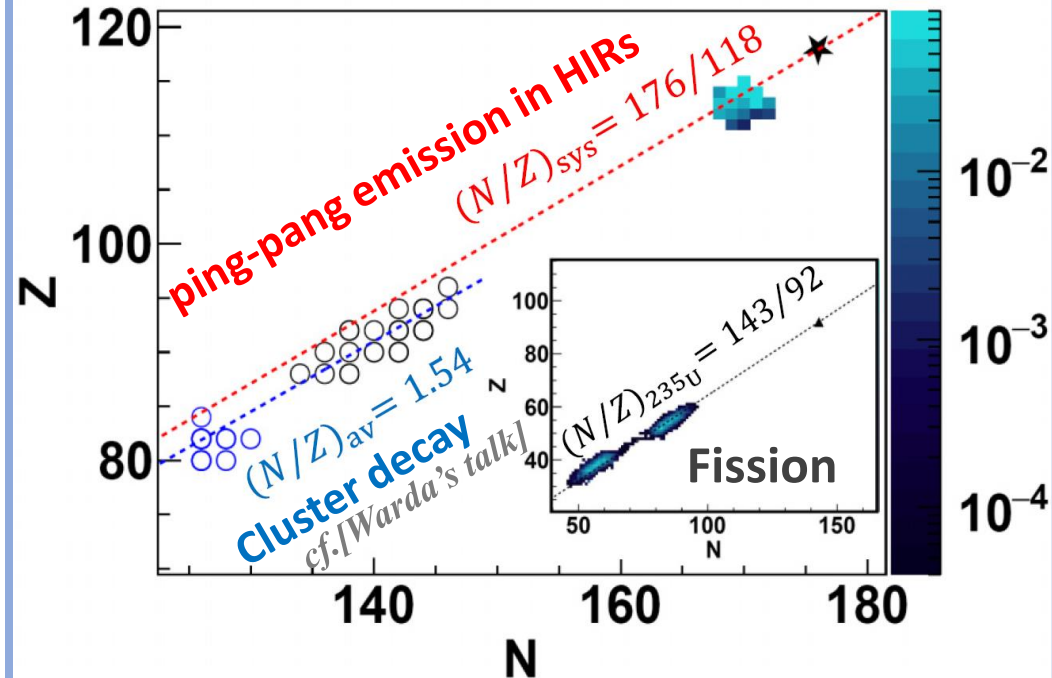
Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

Isospin relation between F_H vs. F_L



1, Isospin anti-correlation.

N/Z property of residue and initial system



2, Isospin balance effect in HIRs.

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

■ Recent work 3: n-p Bremsstrahlung γ $^{86}\text{Kr}@25\text{MeV/u} + ^{124}\text{Sn}$

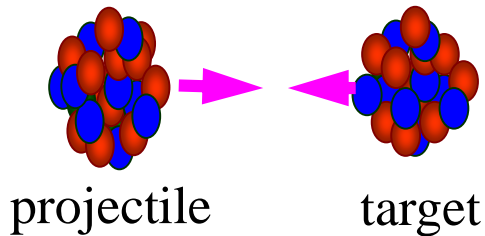
Motivation: Origin of high energy γ from HIR?

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

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Heavy Ion Reaction

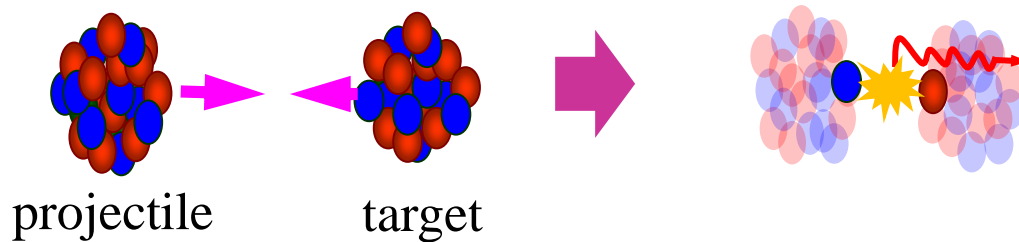


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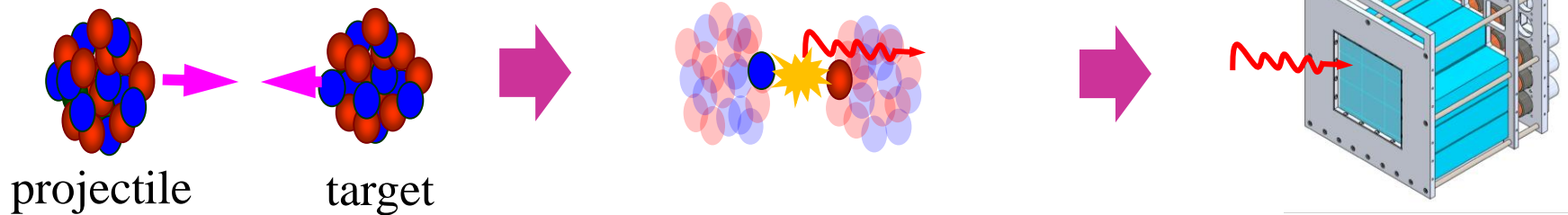
Process: n-p Bremsstrahlung γ

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

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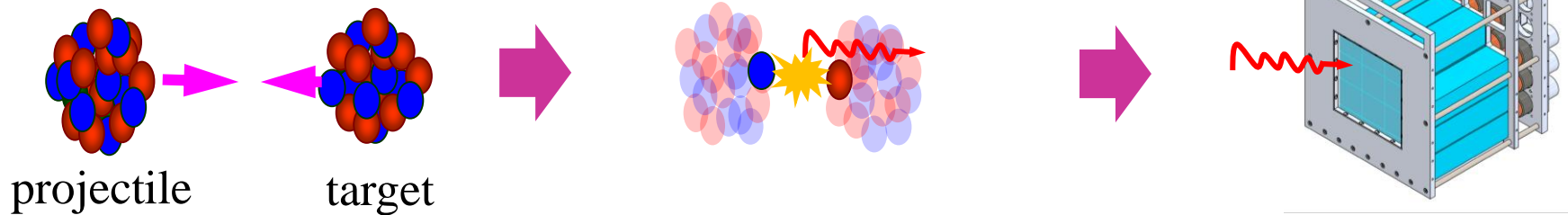
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Process: n-p Bremsstrahlung γ

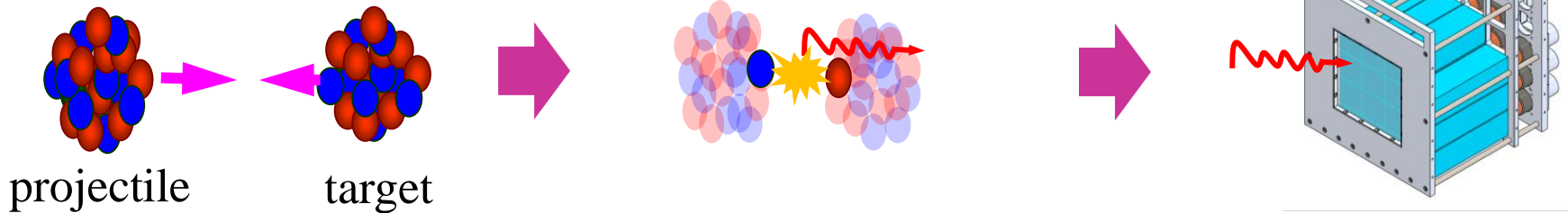
Advantage : Clean electromagnetic probe

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

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Motivation: Origin of high energy γ from HIR?

Heavy Ion Reaction

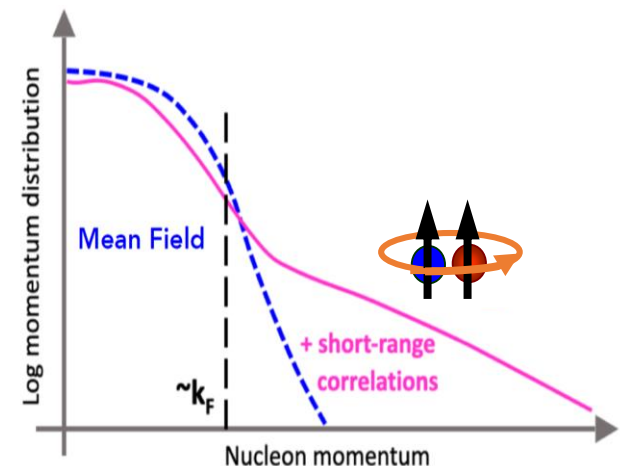


Process: n-p Bremsstrahlung γ

Advantage : Clean electromagnetic probe

Bremsstrahlung γ spectrum is related to the **high-momentum component** in nucleon momentum distribution (SRC)

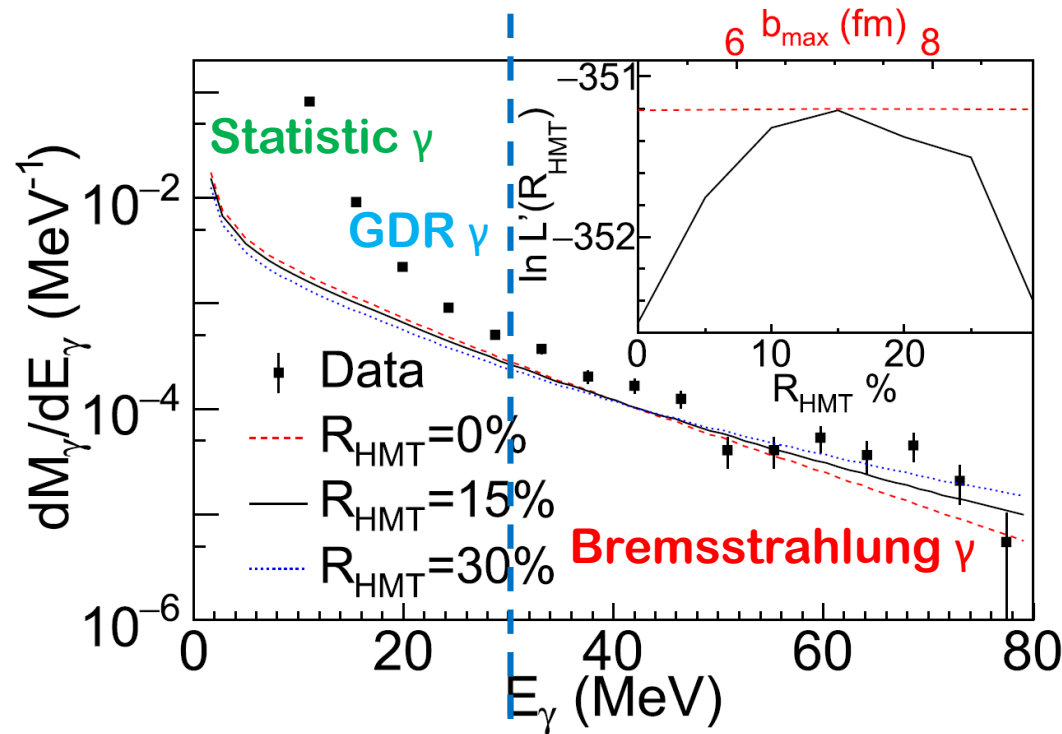
cf. [Bao-Jun Cai' talk]



O. Hen et al. (CLAS Collaboration), Science, 346 (6209):614, 2014.

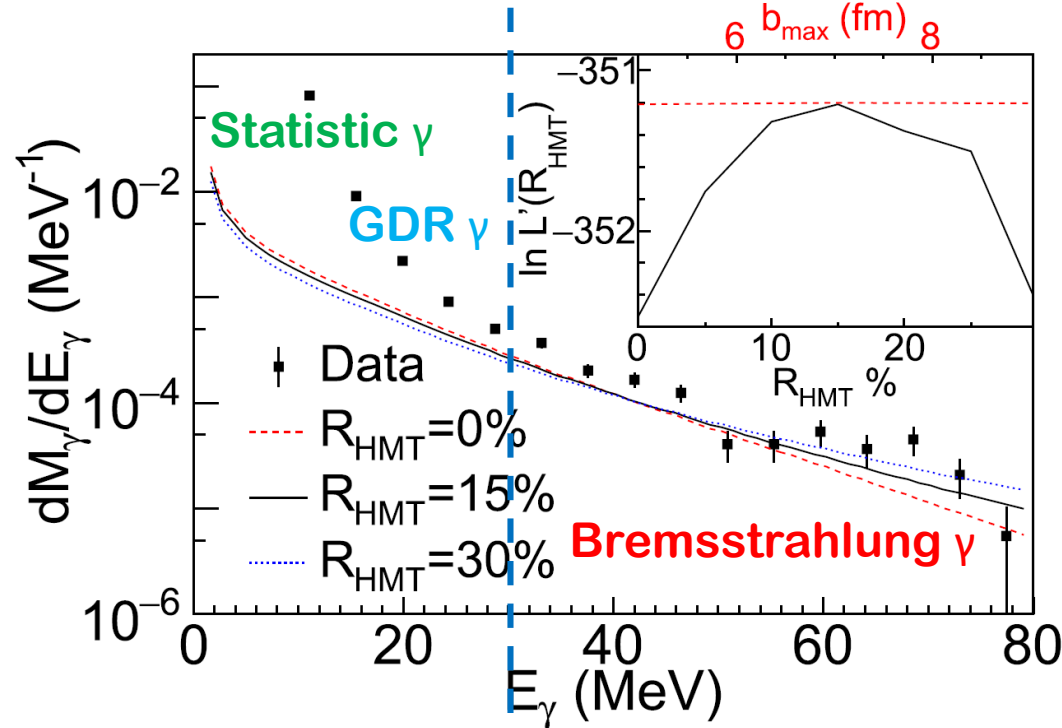
Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

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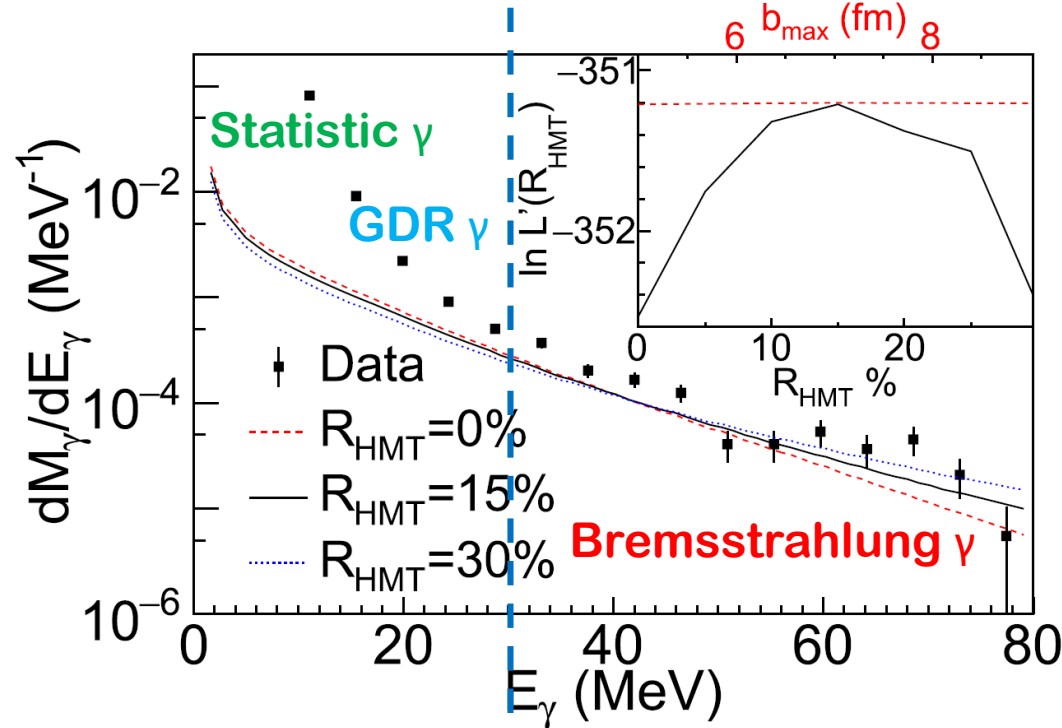
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Theory: IBUU model (includes np Bremsstrahlung process)

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

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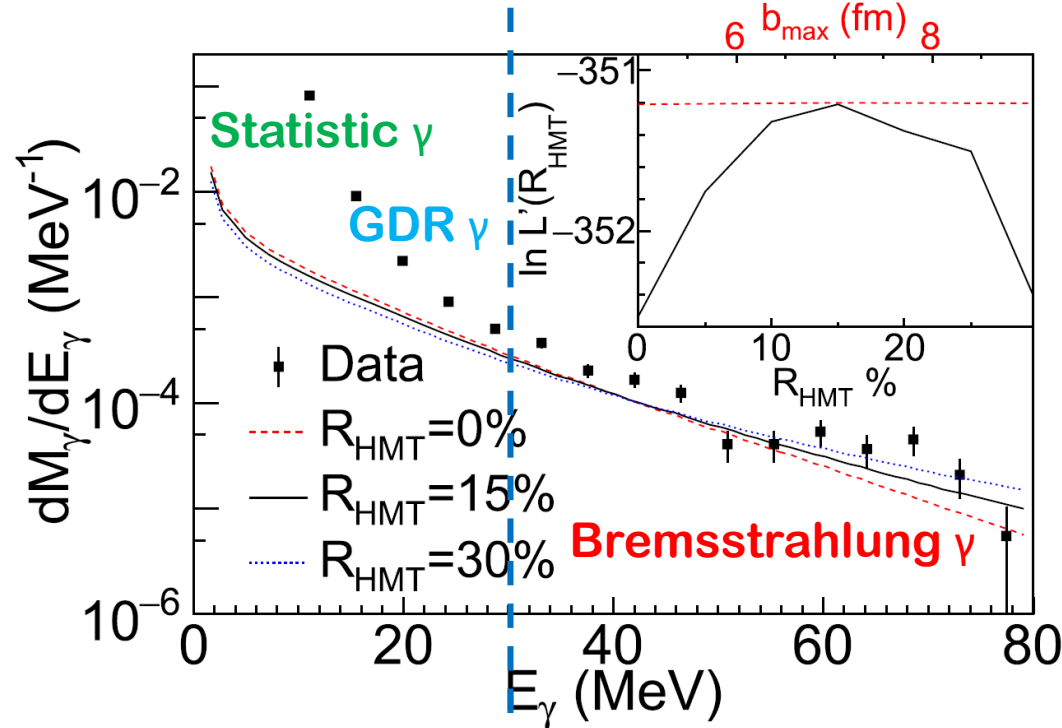


Theory: IBUU model (includes np Bremsstrahlung process)

Method: Likelihood fit from 35MeV to 80MeV

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

Recent work 3: n-p Bremsstrahlung γ $^{86}\text{Kr}@25\text{MeV/u} + ^{124}\text{Sn}$



Theory: IBUU model (includes np Bremsstrahlung process)

Method: Likelihood fit from 35MeV to 80MeV

Result: 15% high-momentum component is favored.

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))

Summary

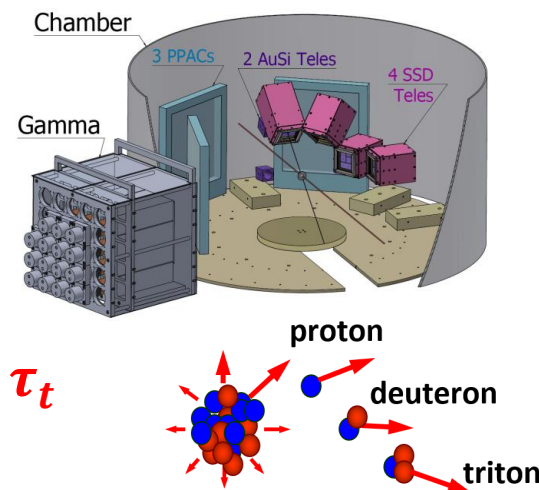
① CSHINE system,
HIRs in RIBLL1, IMP, Lanzhou, China

② Isospin chronology:

Proton emission timescale: $\tau_p \approx 100 \text{ fm}/c$

Emission order of hydrogen isotopes: $\tau_p > \tau_d > \tau_t$

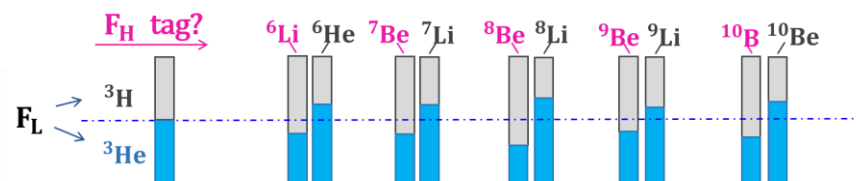
Neutron-rich particle emitted earlier



③ Isospin ping-pang emission:

Isospin alternative emission

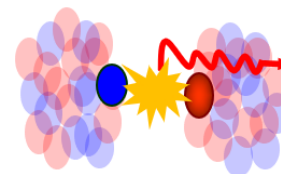
Isospin balance effect in HIRs



④ n-p Bremsstrahlung γ in HIR:

Bremsstrahlung γ spectrum in HIR

High-momentum component in nucleon



Future plan: a, n-n HBT correlation; b, Resonance decay ...

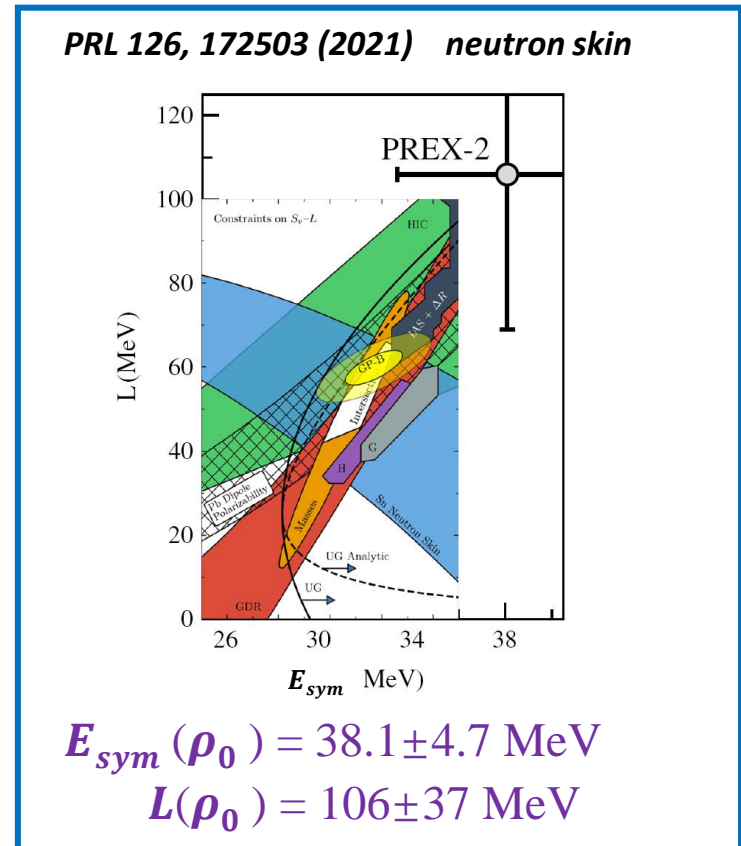
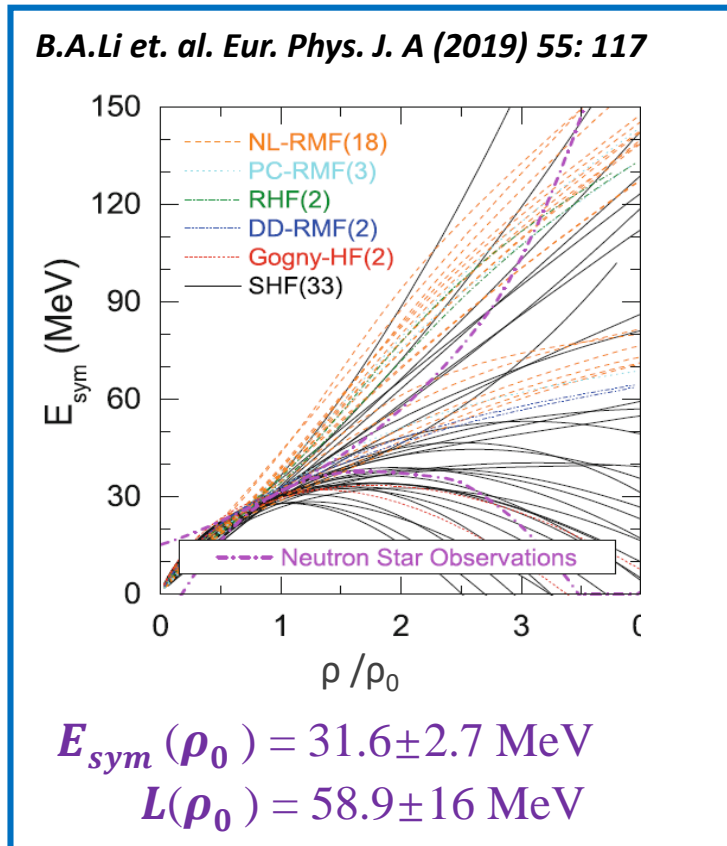


■ backup

■ backup



■ Current situation of Esym



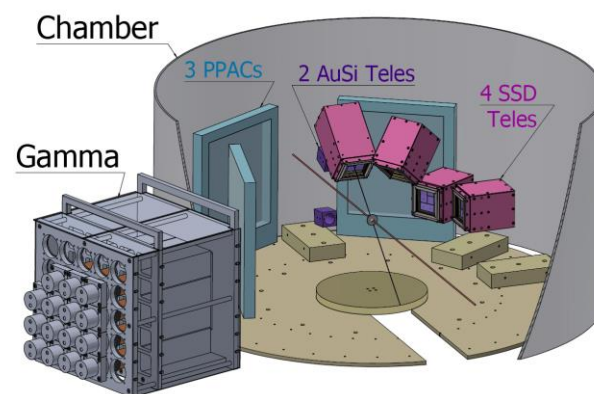
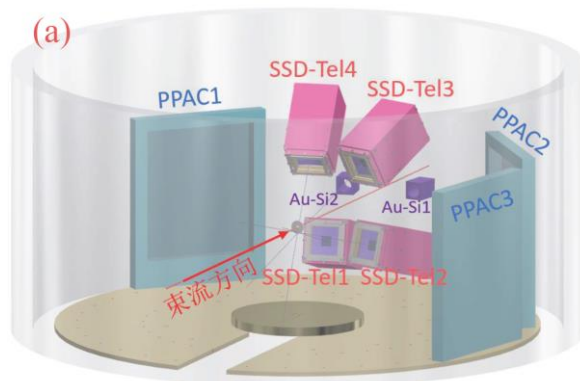
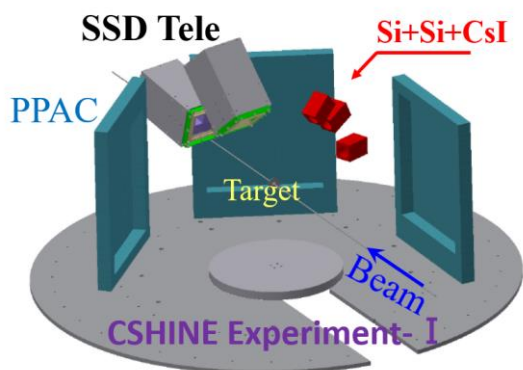
■ Experiments on CSHINE

At RIBLL1, HIRFL, IMP, Lanzhou

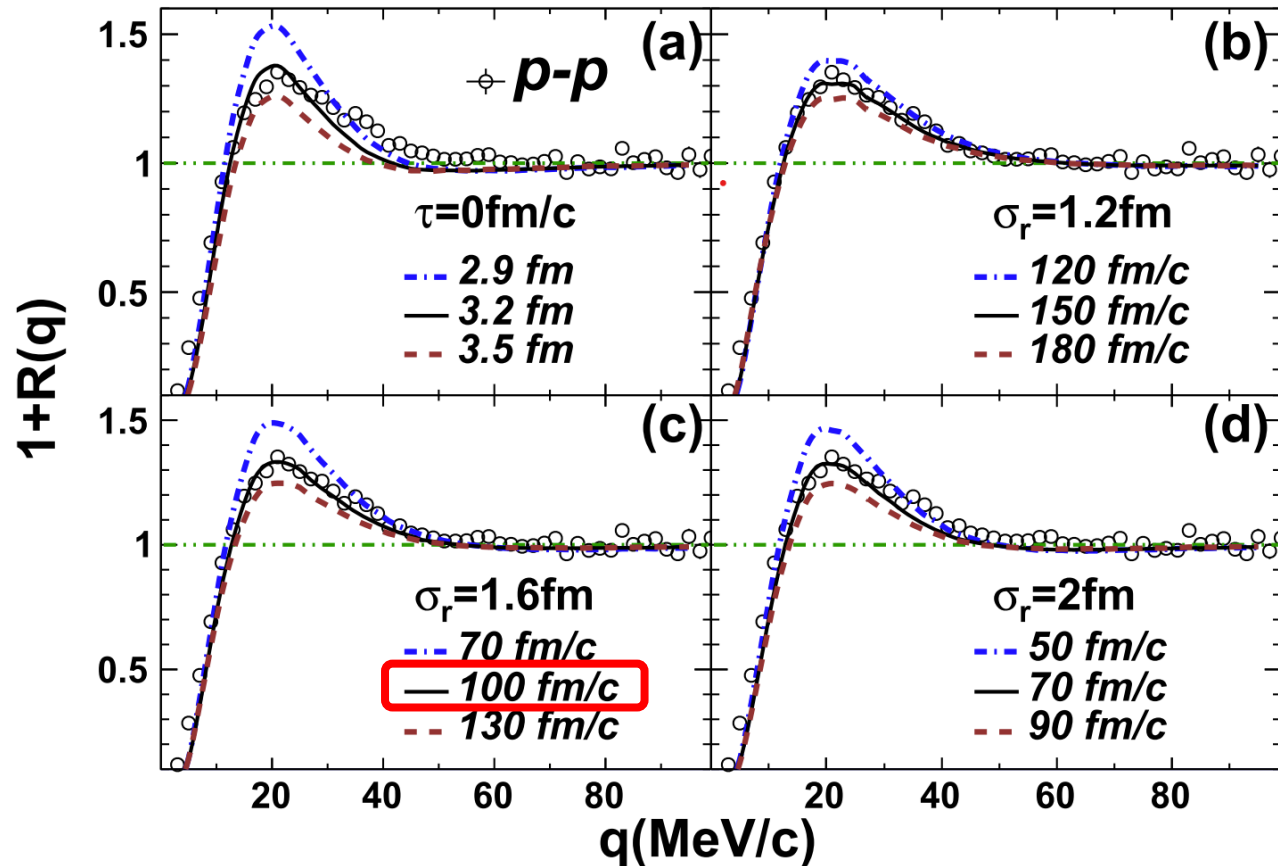
2018, $^{40}\text{Ar}@30\text{MeV/u} + ^{197}\text{Au}$
2*SSDT + 3*PPAC

2019, $^{86}\text{Kr}@25\text{MeV/u} + ^{208}\text{Pb}$
4*SSDT + 3*PPAC

2022, $^{86}\text{Kr}@25\text{MeV/u} + ^{124}\text{Sn}$
4*SSDT + 3*PPAC + Gamma array



Proton correlation function compared with CRAB calculation:

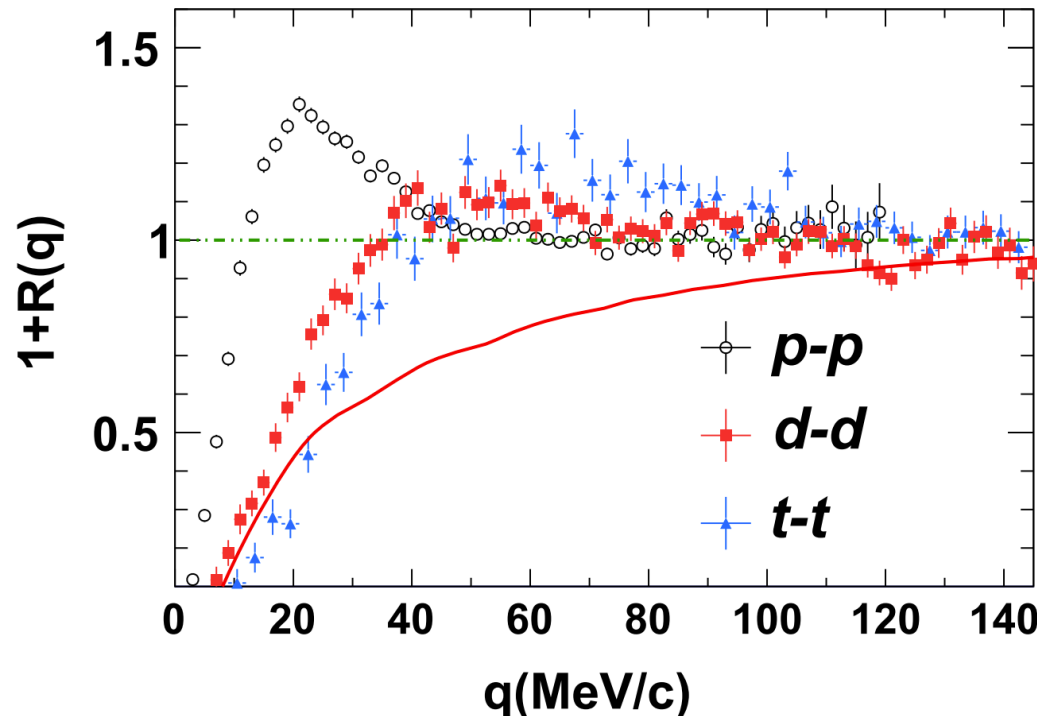


Best fit, Proton emission timescale: $\tau_p \approx 100\text{fm/c}$

Physics Letters B, 825, 136856 (2022)

CRAB: S. Pratt, CRAB version 3, <https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html>

Deuteron-deuteron and triton-triton correlation function:



Original plan: Get the p,d,t timescale with CRAB,
and determine the emission order directly.

Situation: With Woods-Saxon potential, CRAB can't reproduce the d-d CF.

Question: How to determine the emission order of p,d,t?

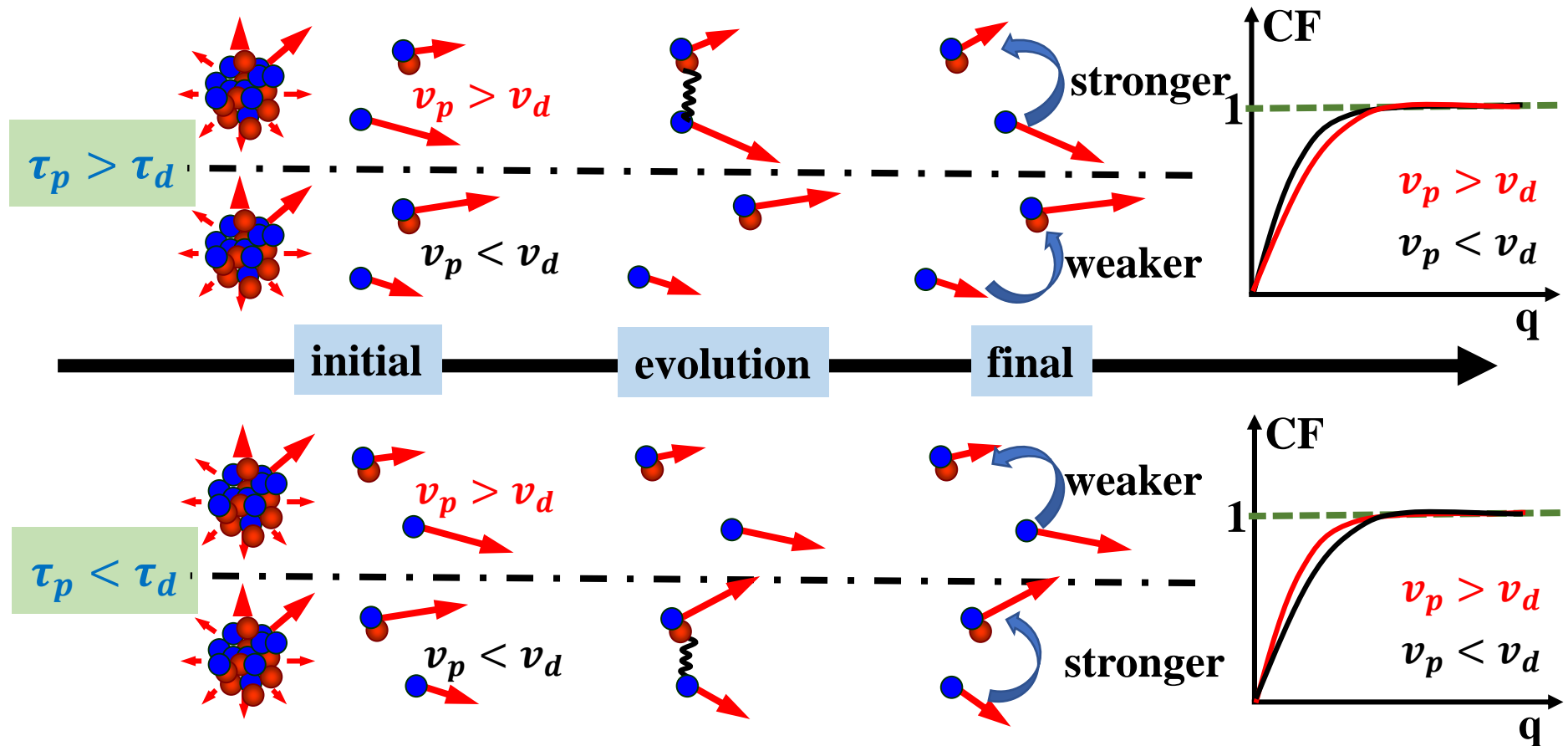
Physics Letters B, 825, 136856 (2022)

CRAB: S. Pratt, CRAB version 3, <https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html>

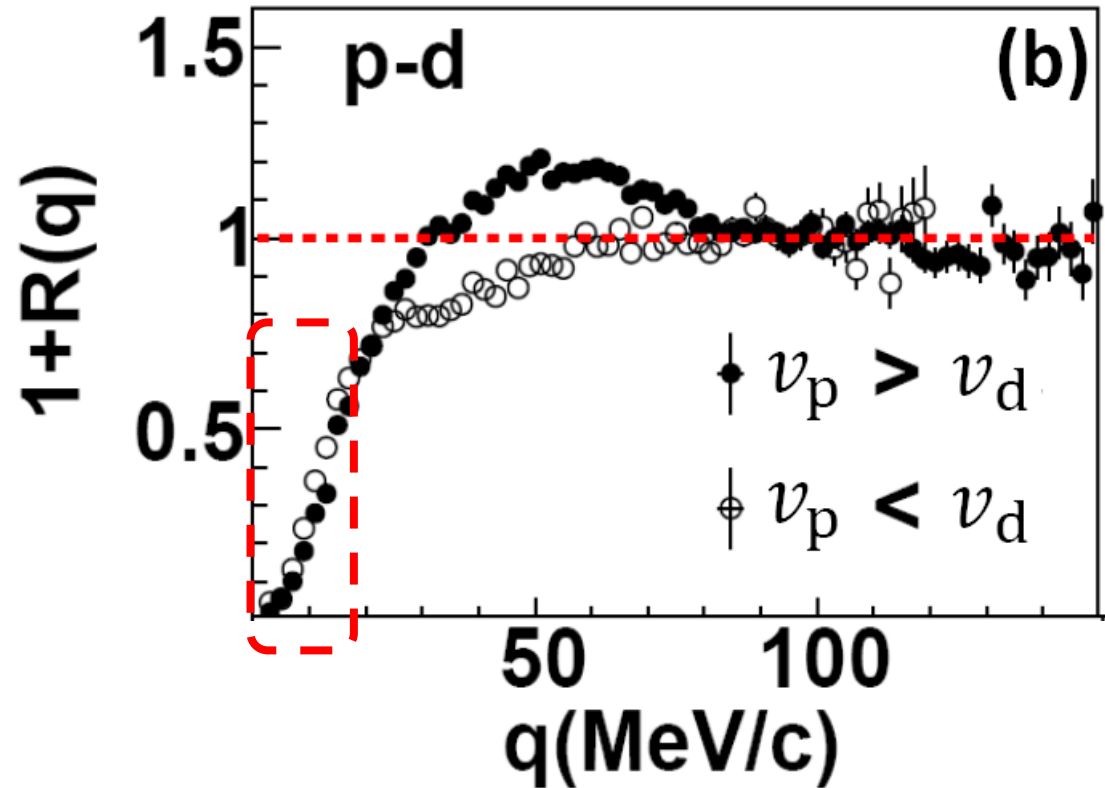
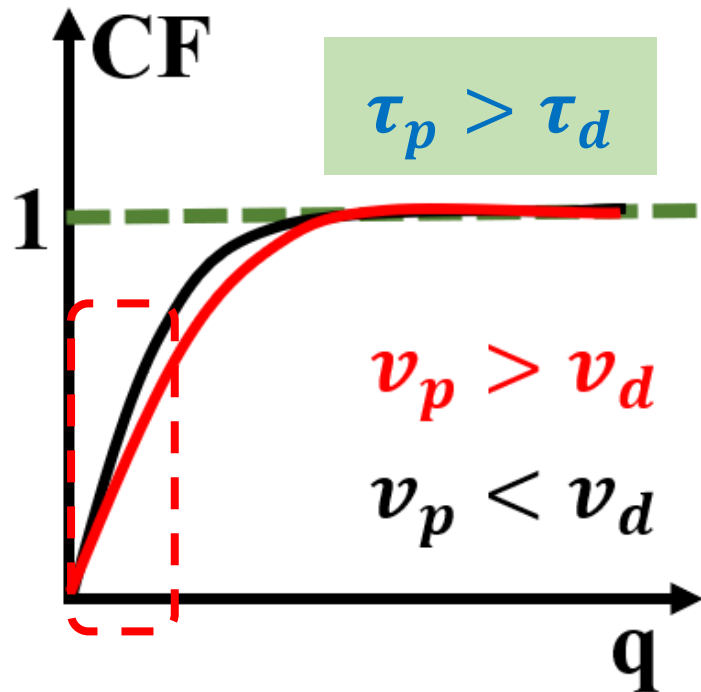
Particle emission order

Velocity-gated correlation function method [*PhysRevLett.91.092701* *PhysRevC.35.1695*]

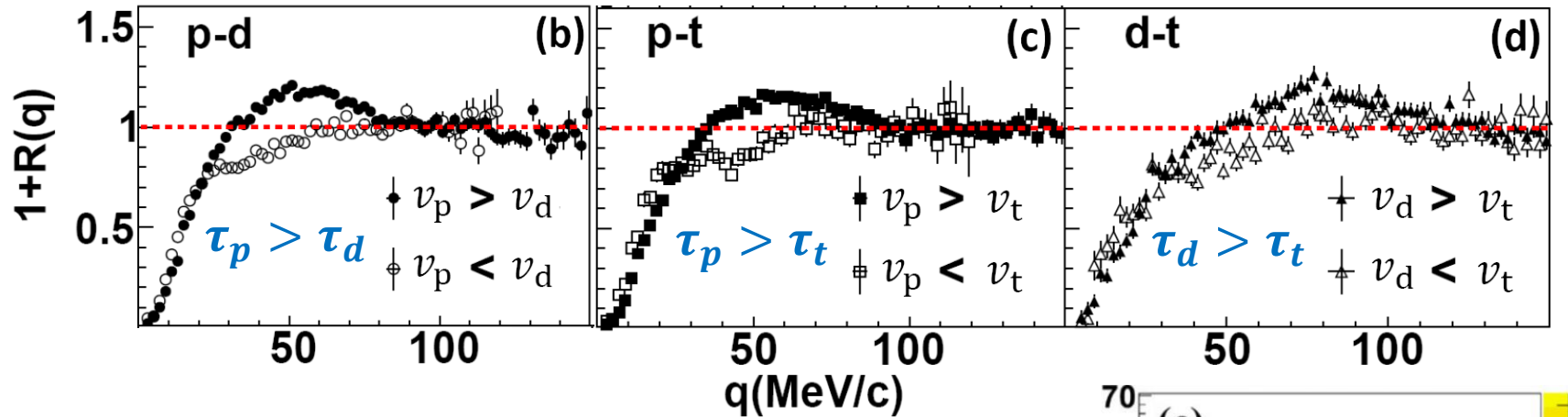
Taking proton and deuteron as example:



Particle with higher velocity showing strong anti-correlation means this particle is emitted later!



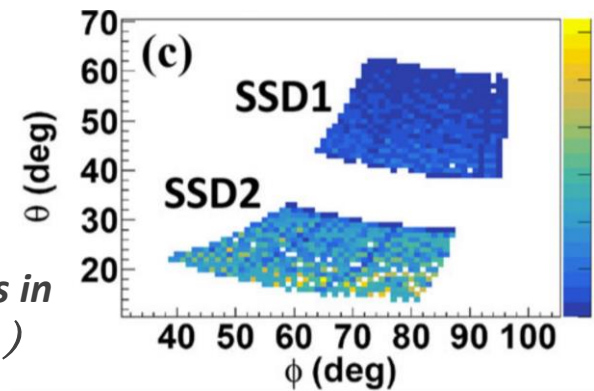
Deuteron is emitted earlier than proton! $\tau_p > \tau_d$



$$\tau_p > \tau_d > \tau_t$$

Neutron rich particles emitted earlier !

The Emission Order of Hydrogen Isotopes via Correlation Functions in 30 MeV/u Ar+Au Reactions (Physics Letters B, 825, 136856 (2022))

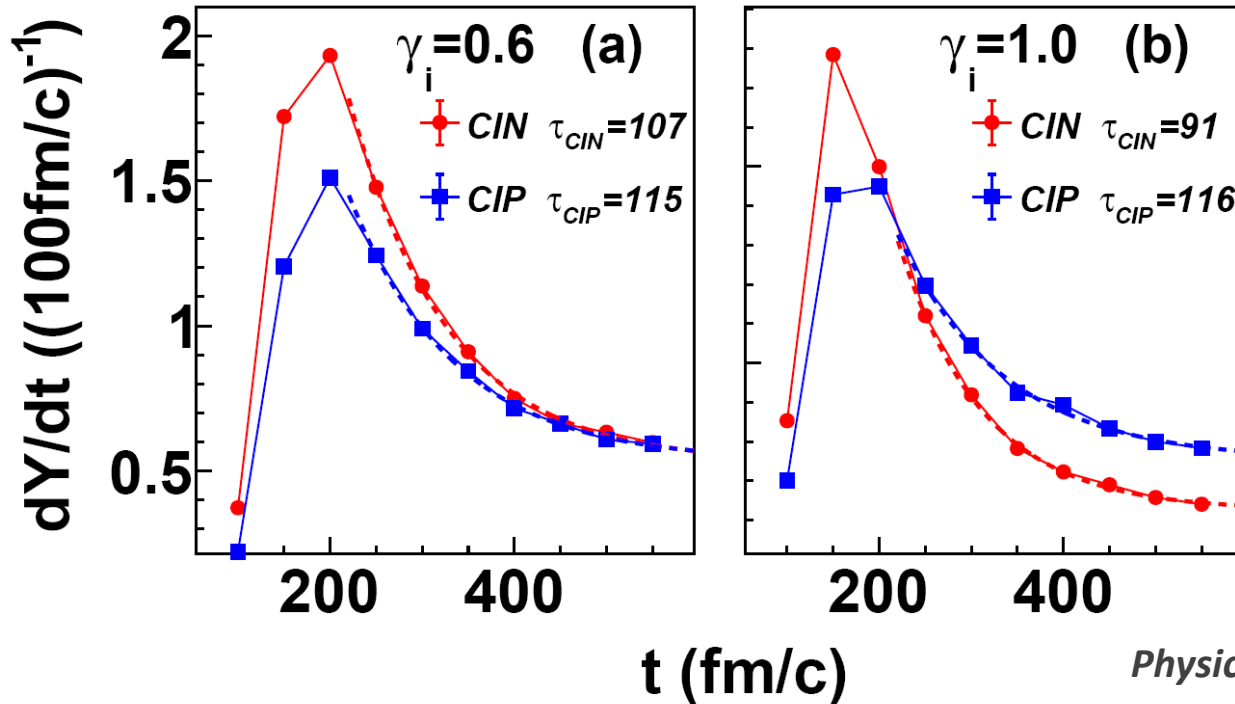


Consistent with the results of R. Ghetti et al[*PhysRevLett.91,092701.*].

Dynamic emission order in 61MeV/u $^{36}\text{Ar} + ^{27}\text{Al}$:

$$\tau_p > \tau_d > \tau_n$$

■ ImQMD calculation results of particle emission timescale



CIN: Coalescence
Invariant Neutron

CIP: Coalescence
Invariant Proton

Physics Letters B, 825, 136856 (2022)

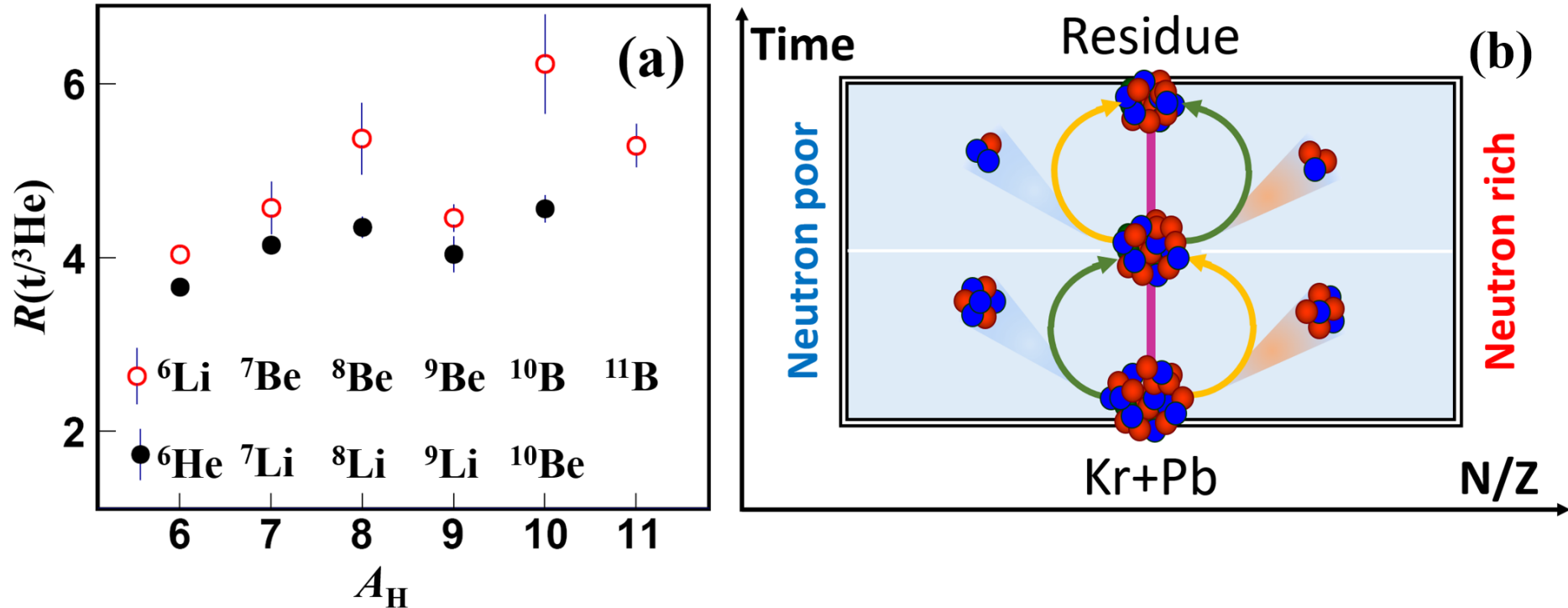
$(\tau_{CIP} - \tau_{CIN})_{\gamma_i=1.0}$ is larger than $(\gamma_i=0.6)$, showing dependence on $E_{\text{sym}}(\rho)$

A new way to study $E_{\text{sym}}(\rho)$ and isospin dynamics

Further Question: Coupling between isospin dynamics and **light particle formation**?

*Observing the ping-pong modality of the isospin degree of freedom in **cluster emission** from heavy-ion reactions (Physical Review C 107, L041601 (2023))*

🍀 Isospin “ping-pang” emission



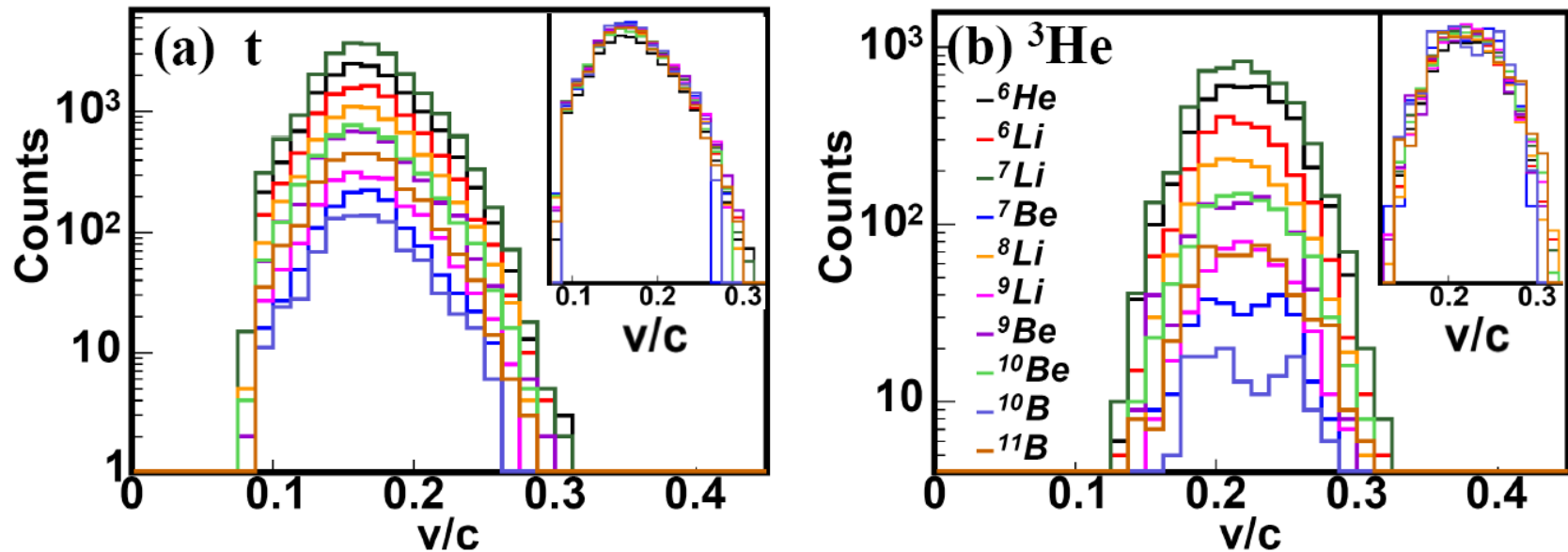
Same mass and different neutron number for the neutron rich or poor IMFs

Yield ratio of t and ${}^3\text{He}$ $R(t/{}^3\text{He})$ for neutron rich trend of coincident light particles

If a neutron-rich IMF is emitted early, a neutron-poor light particle is more likely to be emitted later.

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

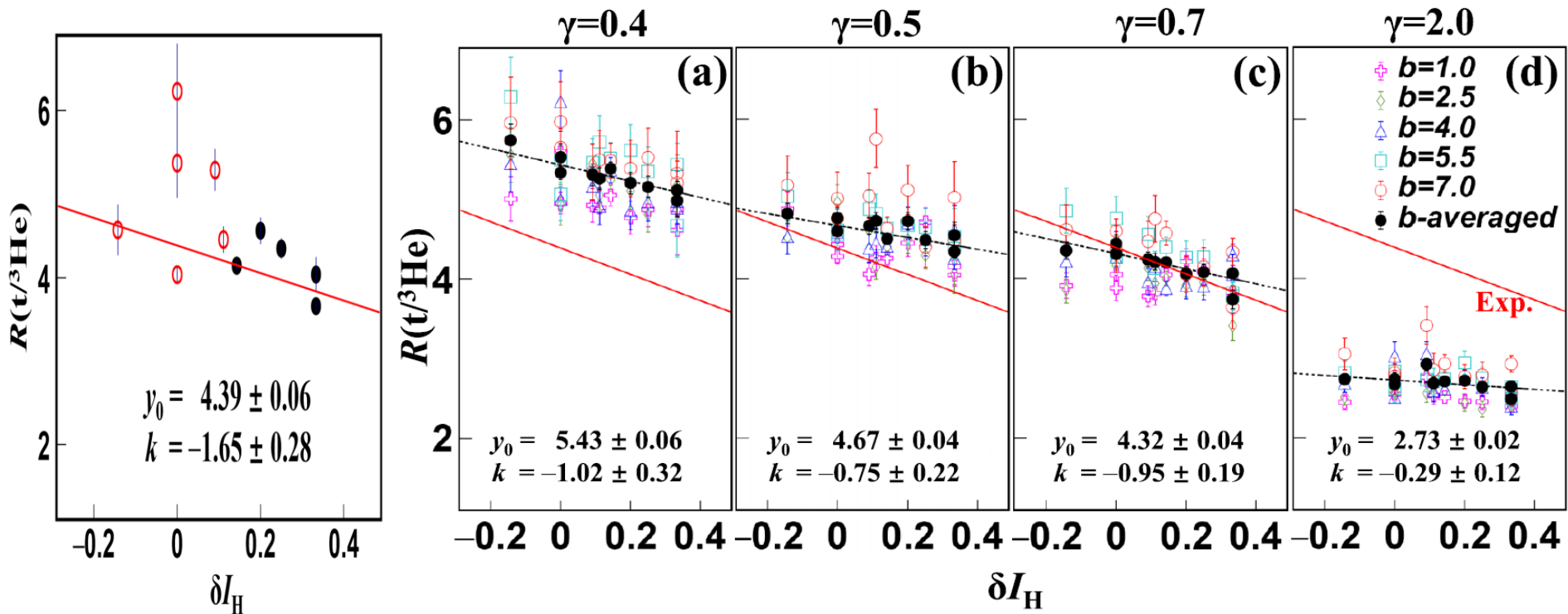
✿ Velocity spectra (Thermal Dynamic)



Velocity spectra of both t and ^3He exhibit scaling behavior over different IMFs (“Ping-pang” emission is **not** caused by thermal dynamic process)

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

🍀 Isospin anti-correlation and ImQMD calculation

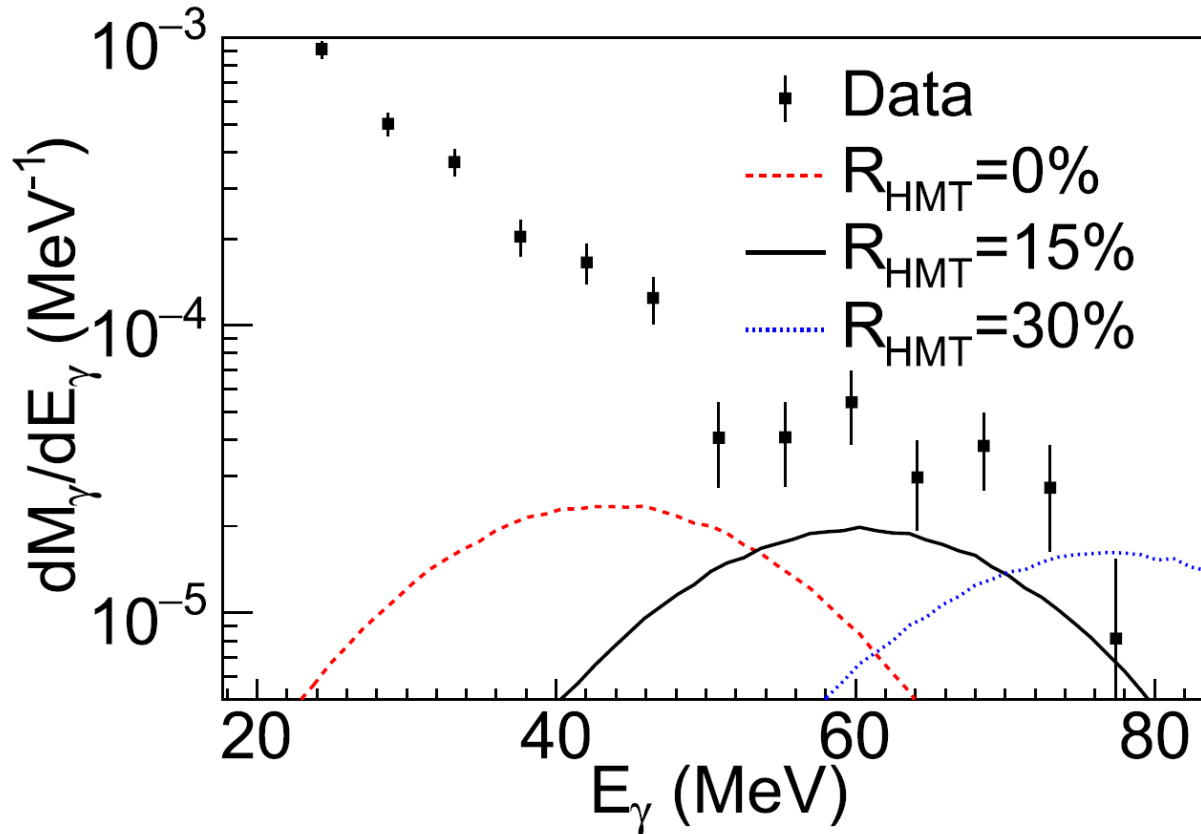


Isospin anti-correlation is a precise probe for symmetry energy

Y.J. Wang, et al., Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions (*Physical Review C* 107, L041601 (2023))

■ $n+p \rightarrow d+\gamma$

To understand the dip and broad hump-like structure on right side.



15% agrees the best with the hump-like structure in $45 < E_\gamma < 75 \text{ MeV}$

Y.H. Qin, et al., *Probing high-momentum component in nucleon momentum distribution by neutron-proton bremsstrahlung γ -rays in heavy ion reactions* (Physics Letters B, 850, 138514 (2024))