Correlation Function studies at intermediate energies at CSHINE

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coauthor : Zhigang Xiao

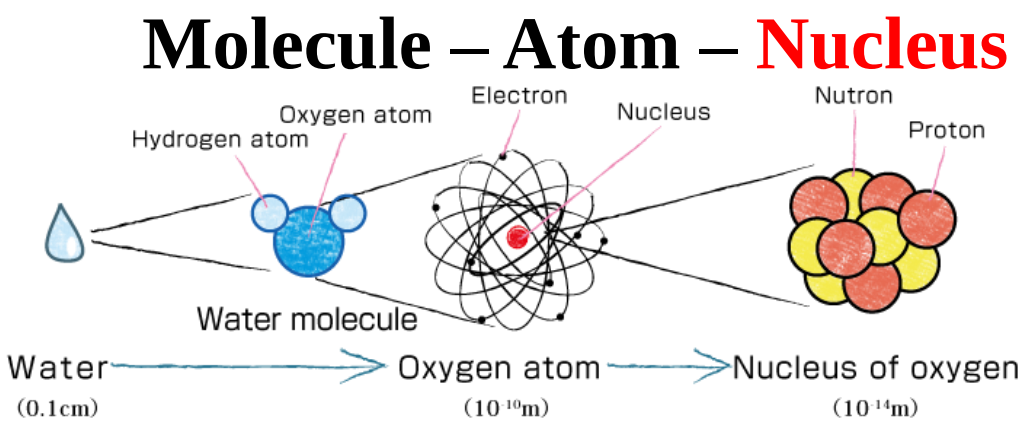
CSHINE
Compact Spectrometer for Heavy IoN Experiments

Tsinghua University

Content

- Research Background
- CSHINE Detector System
- HBT Method
- Isospin Chronology Result
- Summary

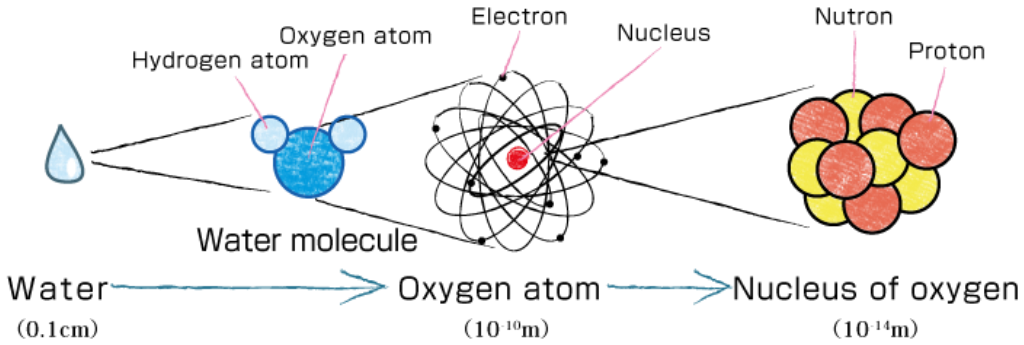
Nucleus, Isospin, Symmetry Energy



https://www.nishina.riken.jp/

Nucleus, Isospin, Symmetry Energy

Molecule – Atom – Nucleus



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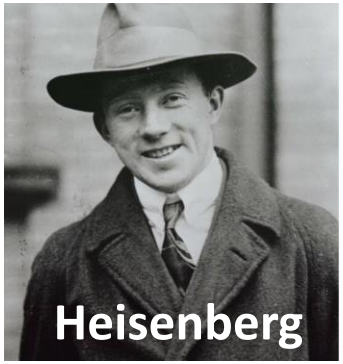
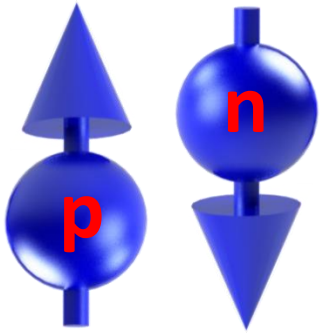
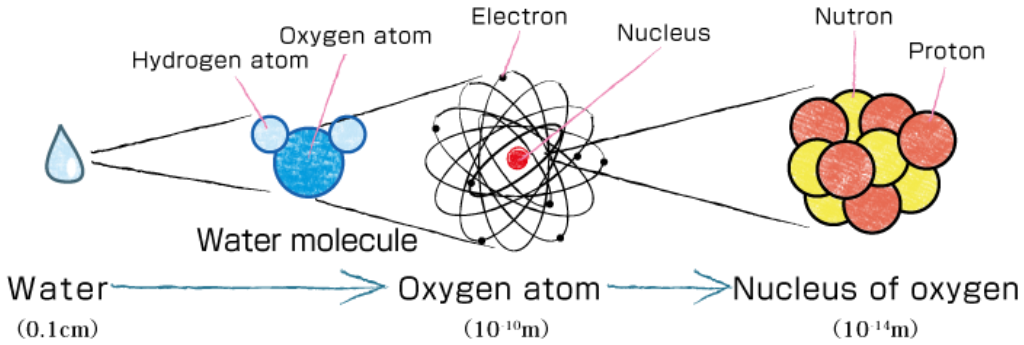




Isospin distinguishes proton and neutron

Nucleus, Isospin, Symmetry Energy

Molecule – Atom – Nucleus



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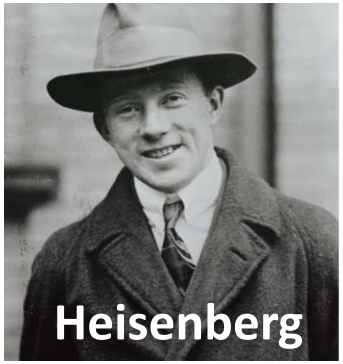
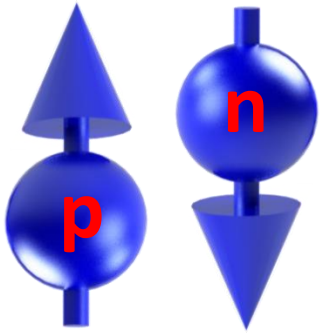
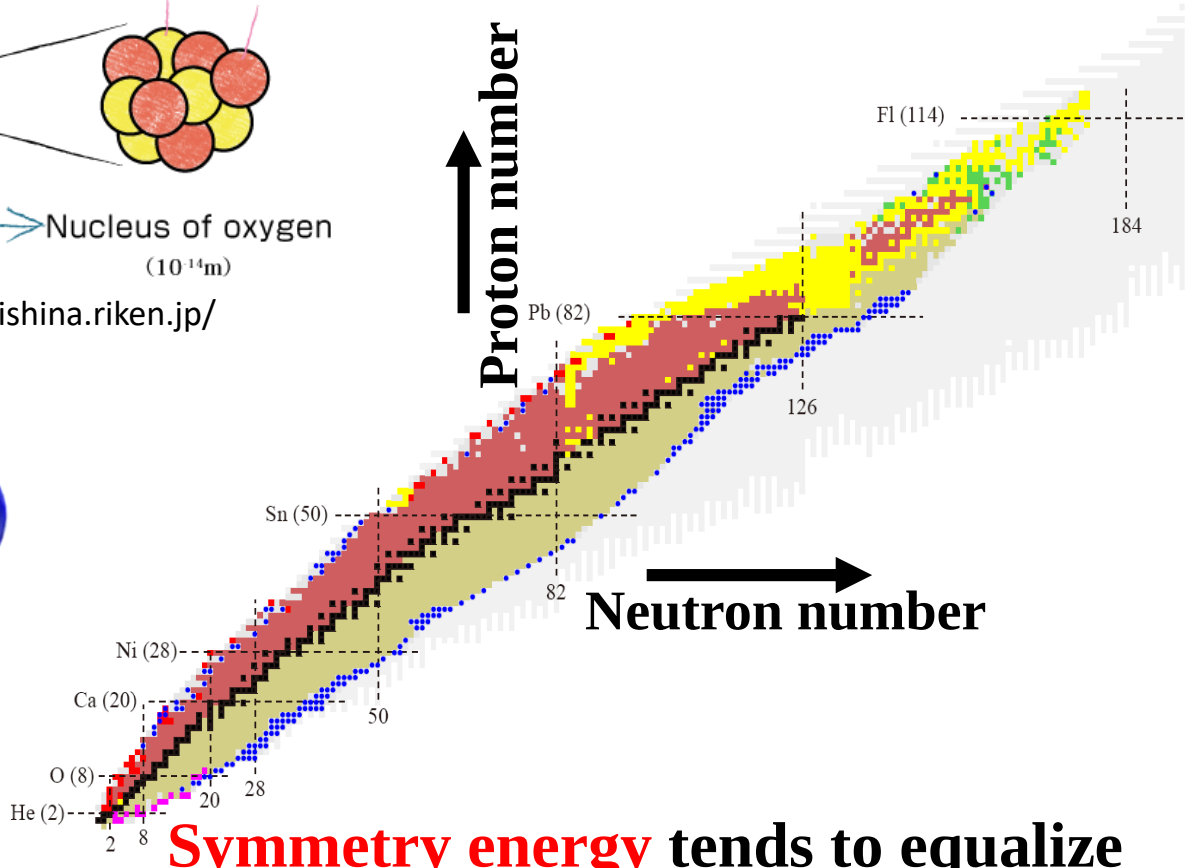




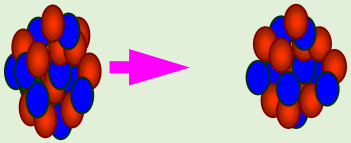


Isospin distinguishes proton and neutron

Symmetry energy tends to equalize the number of neutrons and protons

Heavy Ion Reaction, Isospin dynamic in zeptosecond scale

Heavy Ion Reaction~ 10^{-22}s



30MeV/u ^{40}Ar ^{197}Au

Velocity: ~0.25c Scale: ~10^{-14}m

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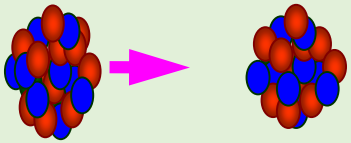

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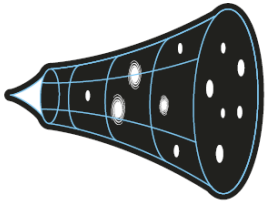


Heavy Ion Reaction
~ 10^{-22}s

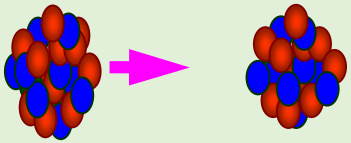
ATTOSECOND
~ 10^{-18}s

HEARTBEAT
~1s

AGE OF THE UNIVERSE
~10^{18}s

Heavy Ion Reaction, Isospin dynamic in zeptosecond scale

Heavy Ion Reaction~ 10^{-22}s



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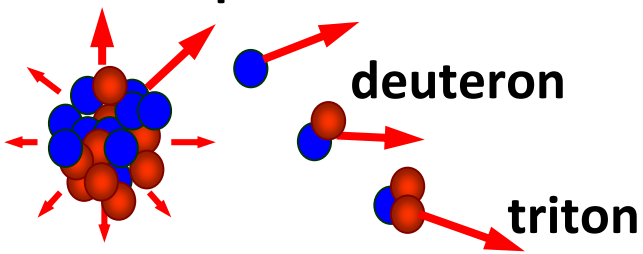
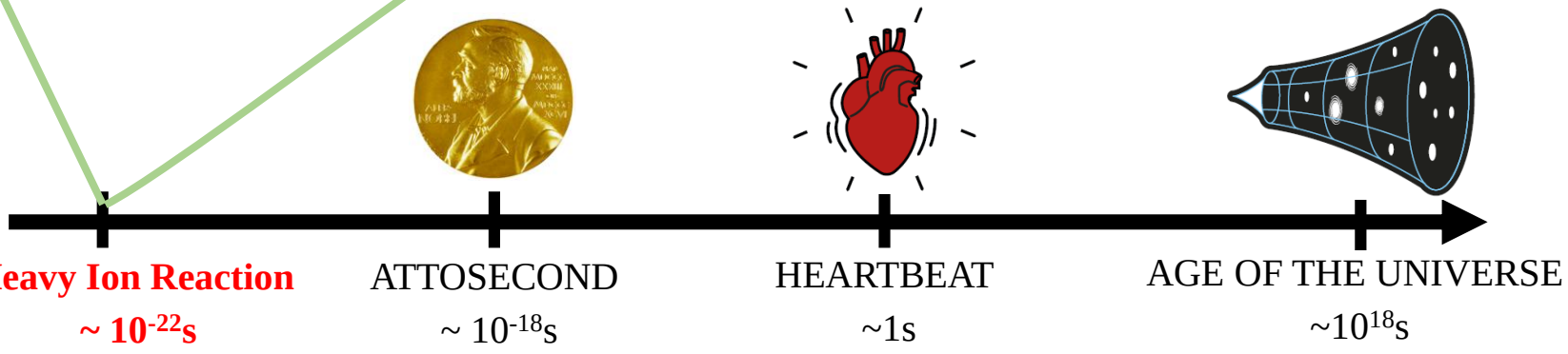


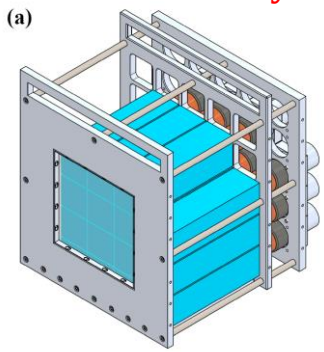
Question：Isospin dependent particle emission timescale and emission order?

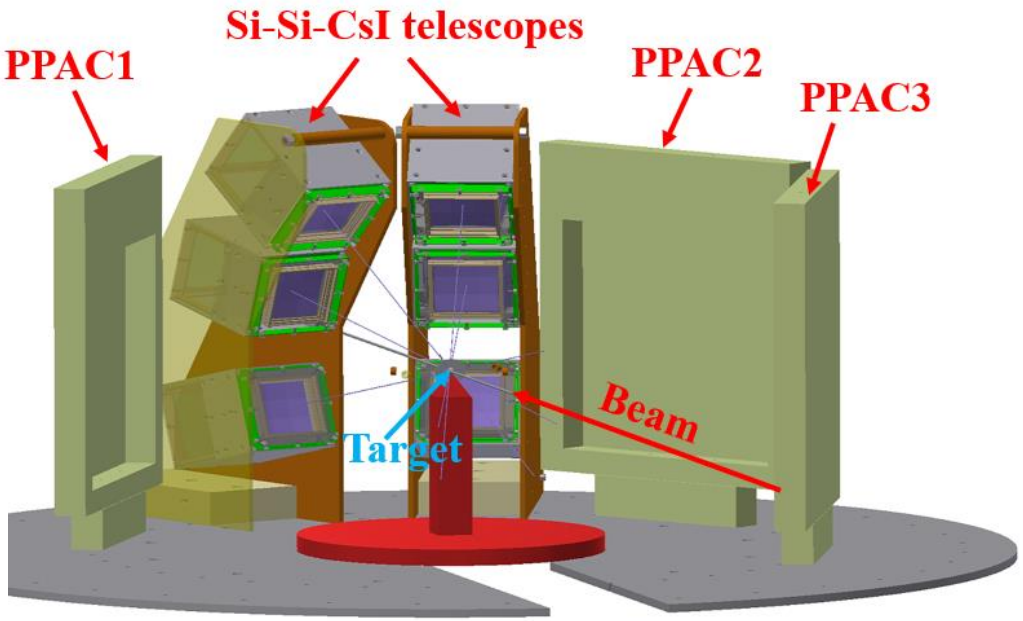


Compact Spectrometer for Heavy IoN Experiment(CSHINE)

CSHINE

Compact Spectrometer for Heavy IoN Experiments



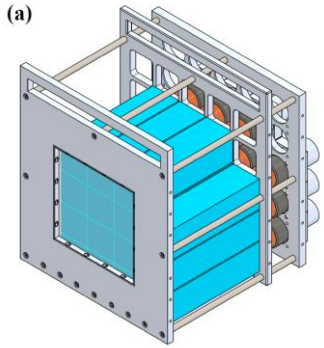


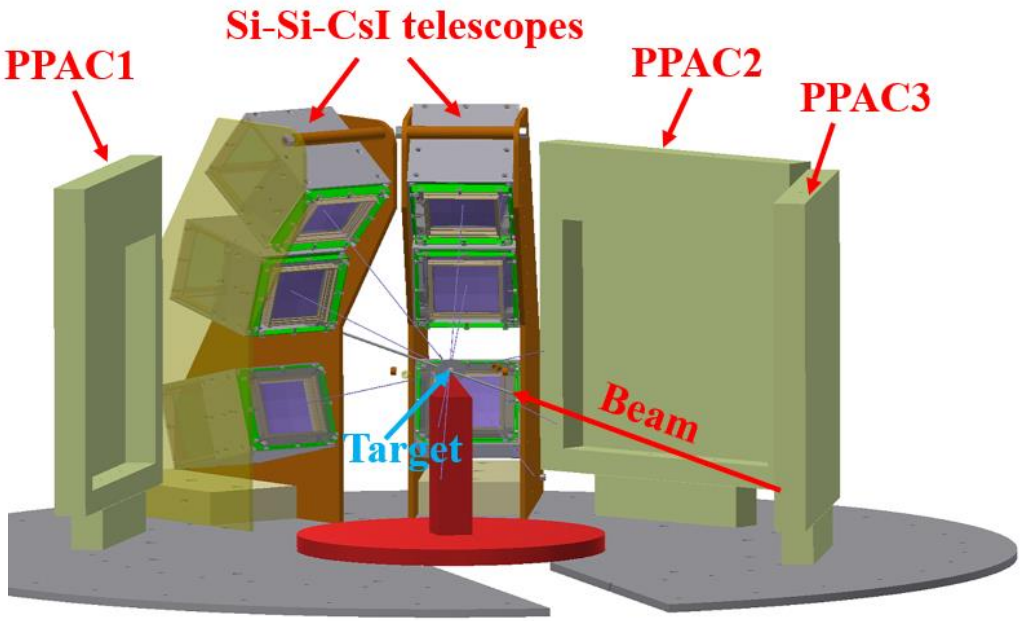
Compact Spectrometer for Heavy IoN Experiment(CSHINE)

CSHINE

Compact Spectrometer for Heavy IoN Experiments

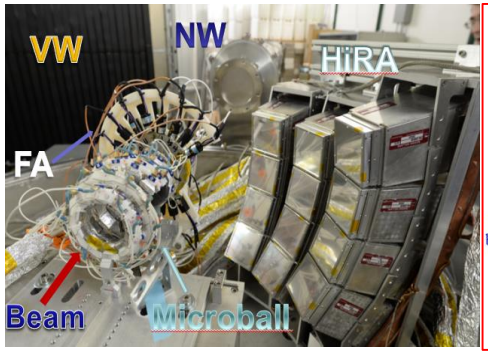
Gamma array



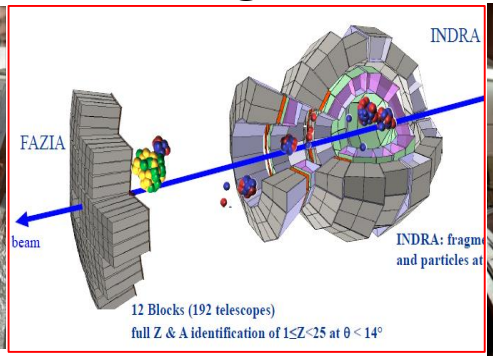


Compared with the large detector system in the world, CSHINE is relatively compact.

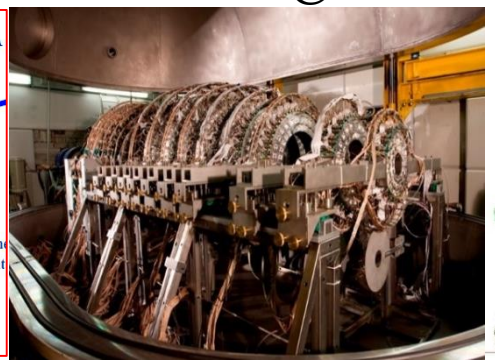
HiRA@FRIB



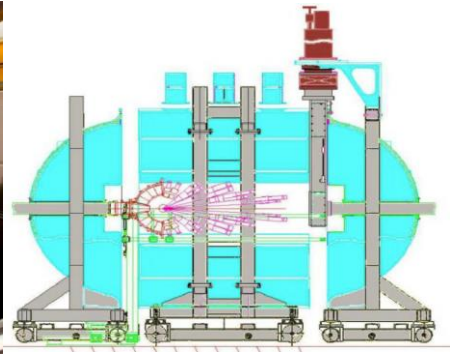
INDRA@GANIL



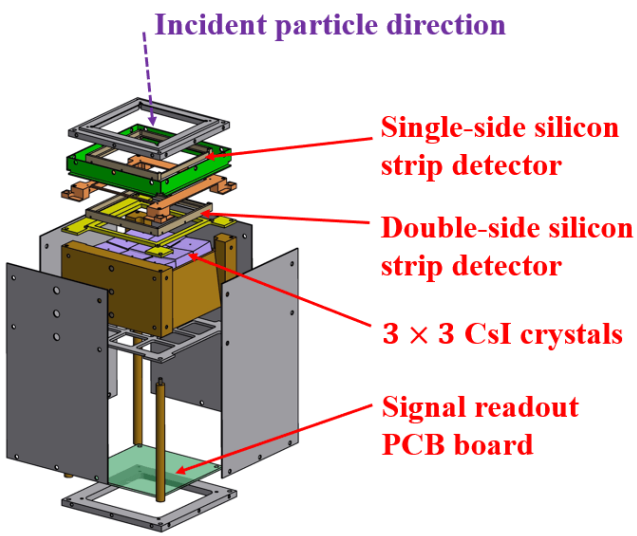
CHIMERA @ INFN

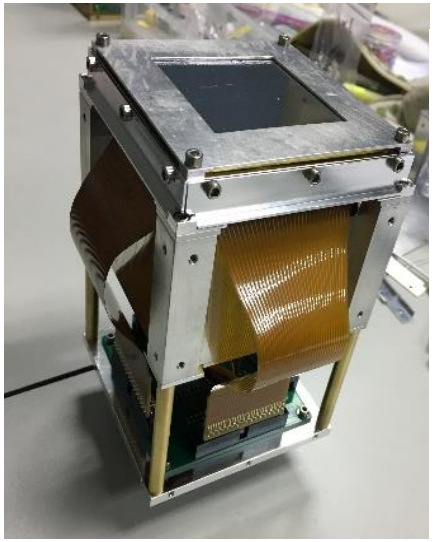


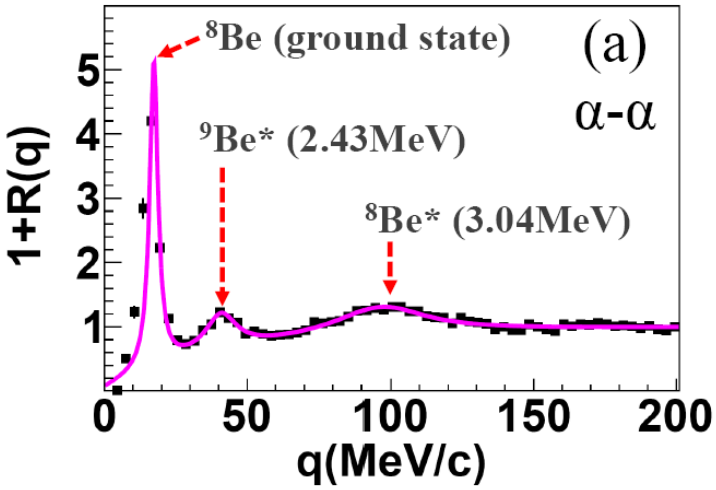
NIMROD@TAMU



Silicon Strip Detector Telescope (SSDT)



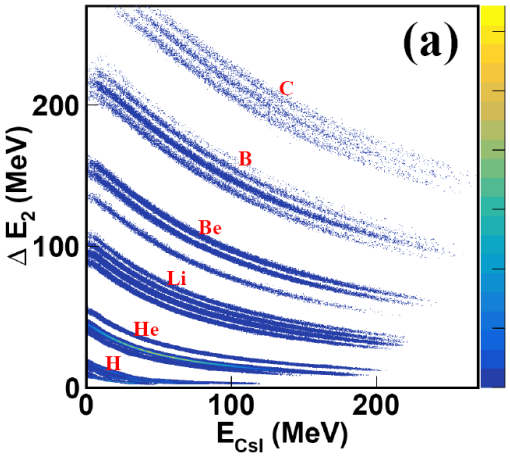


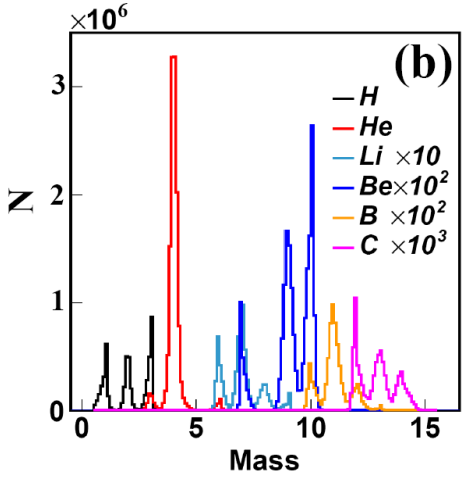


Silicon strip width: 2mm

SSDT energy resolution: 2%

For light charge particles

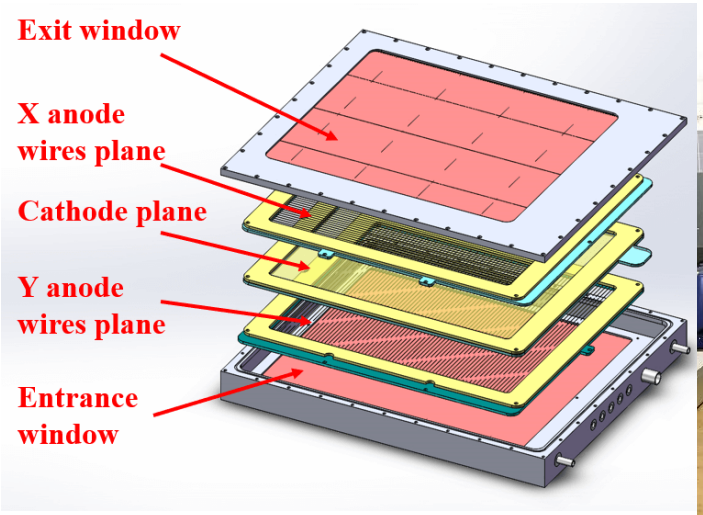


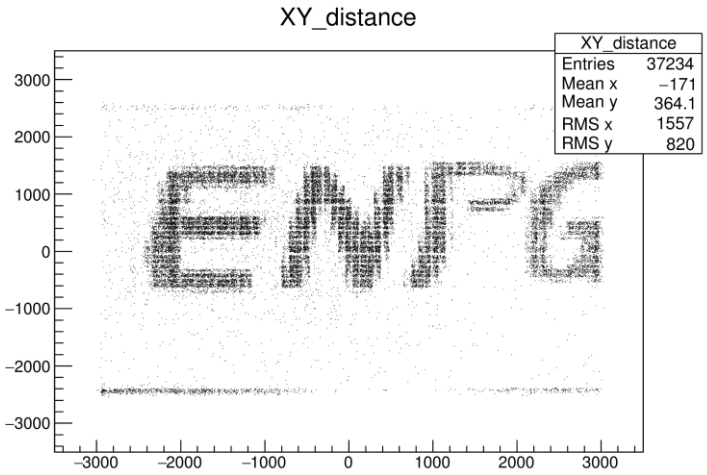


Nucl. Sci. Tech. 32, 4 (2021)

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

Parallel Plate Avalanche Chamber (PPAC)

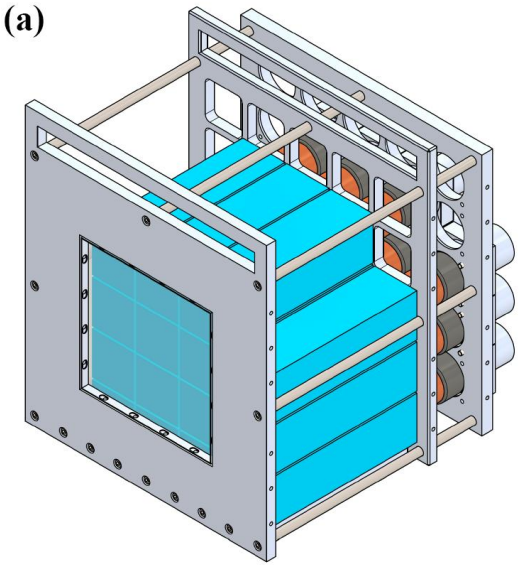


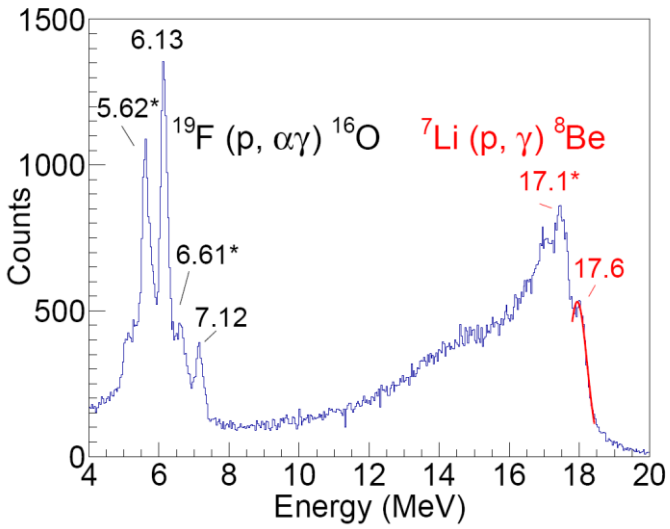


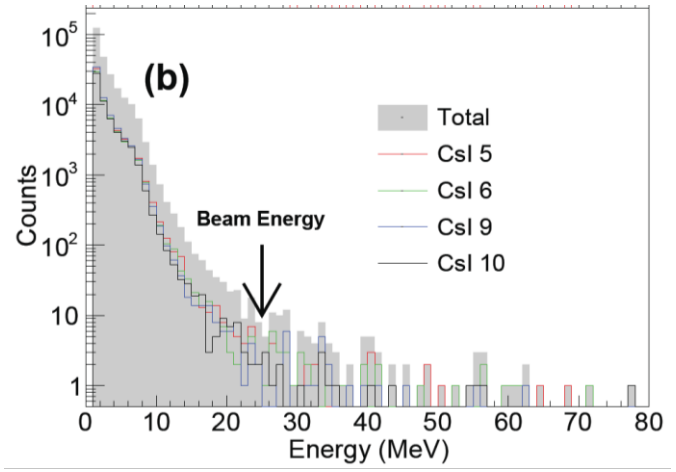
Time resolution: 260ps
Position resolution: 1.4mm
Sensitive area: 240mm*280mm
For fission fragments

Nuclear Engineering and Technology 52,3 (2019)

High Energy Gamma Detector Array







Energy resolution: 3%

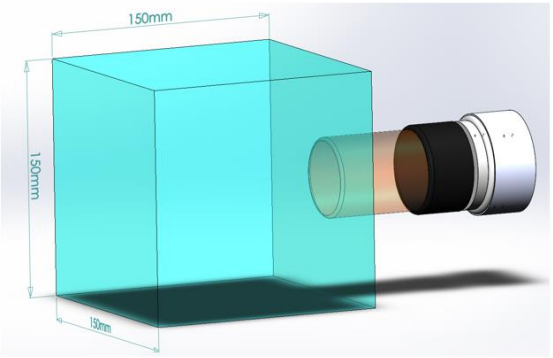
Energy range: 10-80MeV

For high energy gamma

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

CSHINE upgrade: Neutron detector Array

Heavy ion reAction Neutron MEasurement detectoR (HANMER)

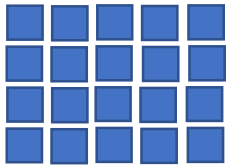


Plastic scintillator + PMT

15cm * 15cm * 15cm

4 * 5 units

For neutron



Physics studies at CSHINE:

①Light charge particles

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

②Fission fragments

a, Fast fission
b, Fission dynamics
c, Folding angle
d, Neck formation
…

③High energy gamma

a, np bremsstrahlung
b, Short Range Corr.
c, np->d + gamma
d, Eγ spectrum
…

④Future plane

a, n-n HBT correlation
b, t and ^{3}He emission
c, θ(n/p) distribution
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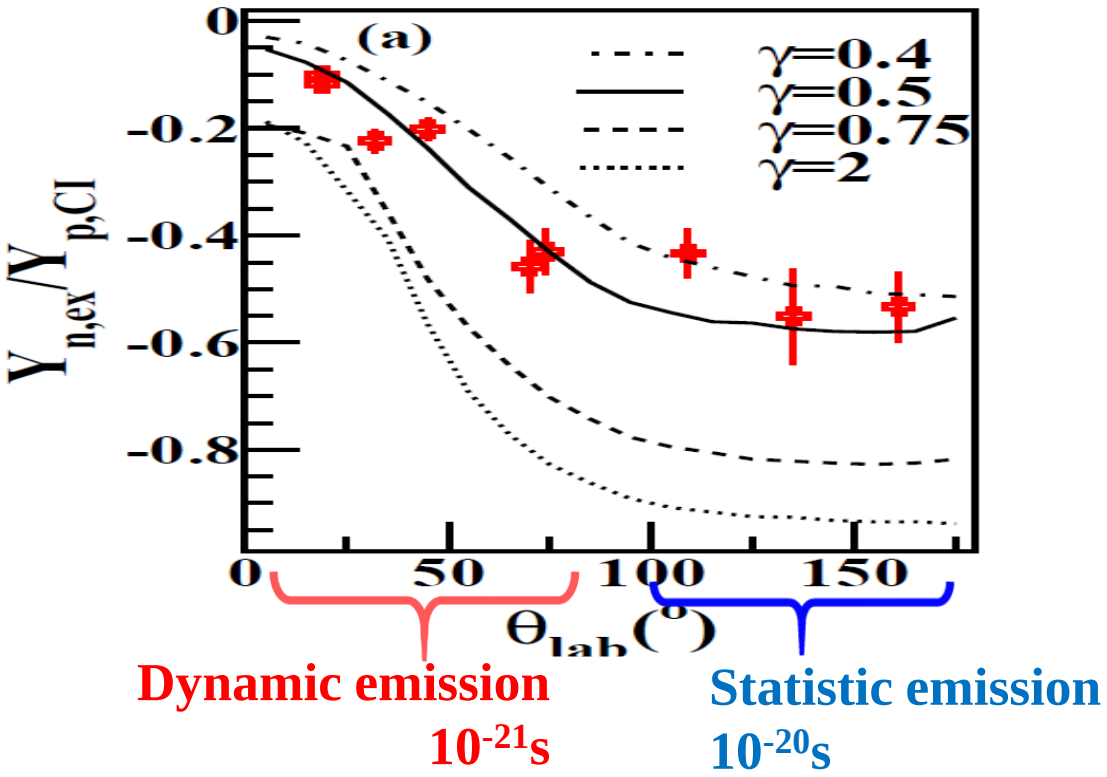
Previous knowledge of Isospin Relaxation

Neutron excess probe:

$$\frac{Y_{\mathrm{n,ex}}}{Y_{\mathrm{p,CI}}} = \frac{\sum y_i(N_i - Z_i)}{\sum y_i Z_i},$$

Time → Angle



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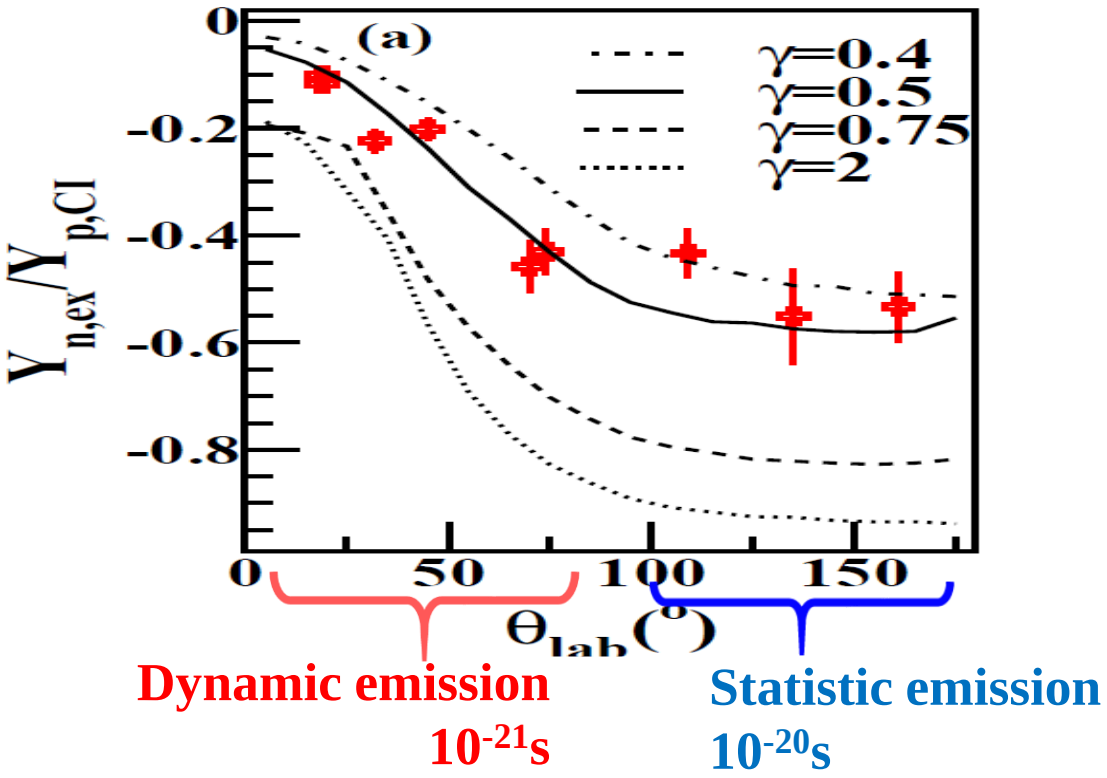
Result: Neutron rich particle emitted earlier!

PRC 95, 041602(R) (2017)



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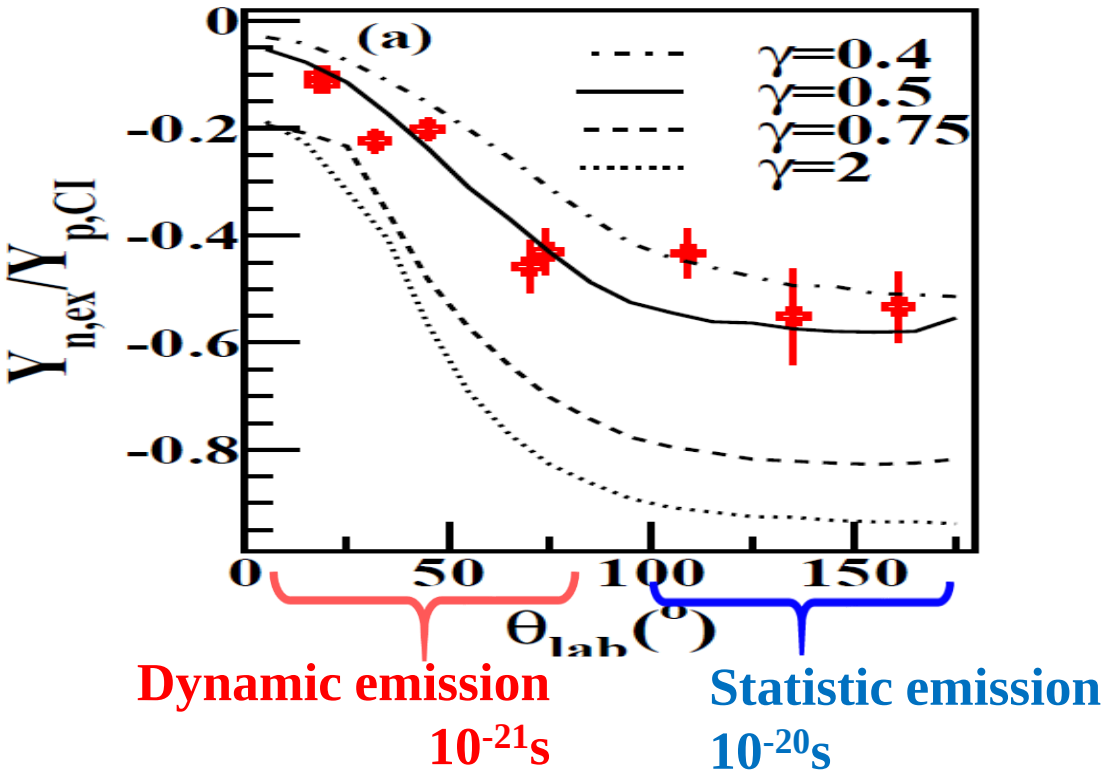

One-body observable at final state only delivers qualitative picture of isospin dynamics.

HBT intensity interferometer

How to determine particle emission timescale and order quantitatively?

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HBT is an approach to extract space and time information of the emission source!

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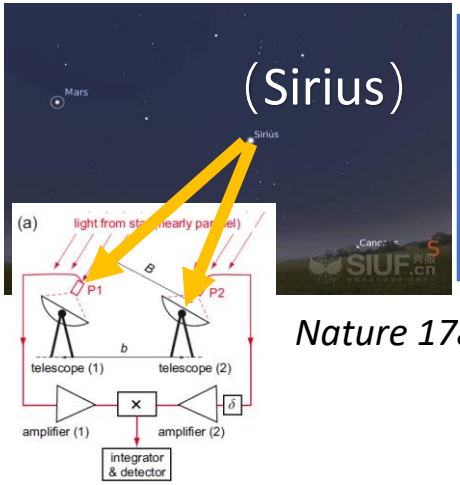
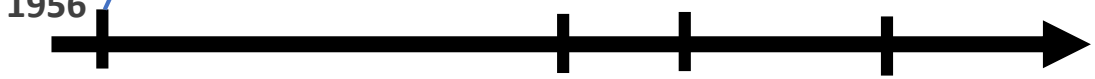


- 1956, Hanbury Brown and Twiss; Angular diameter of Sirius (Astronomy)

Nature 178, 4541 (1956)



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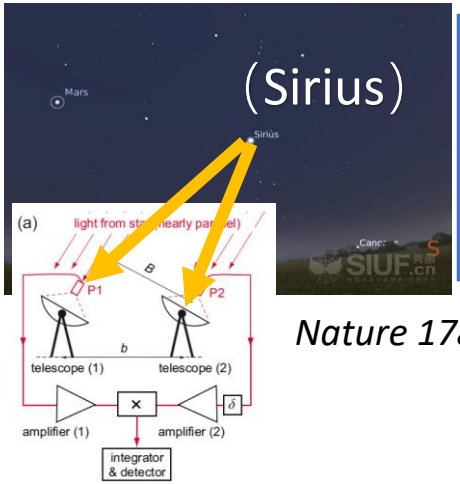

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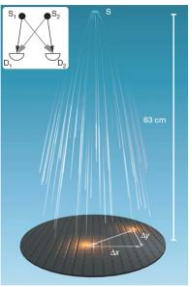
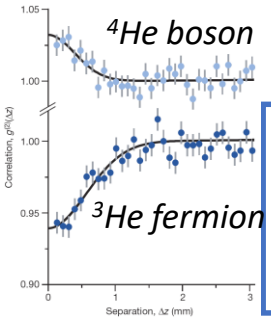
1956 — 2007





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Nature 445, 402(2007)

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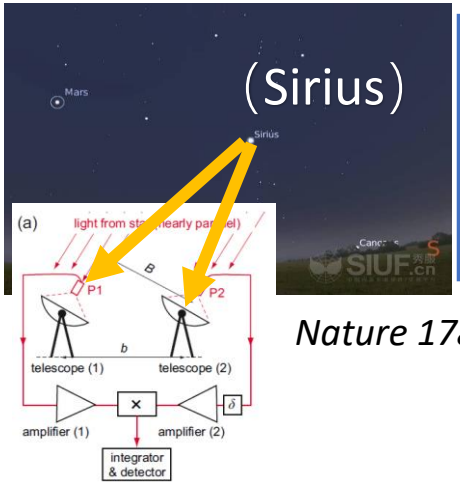

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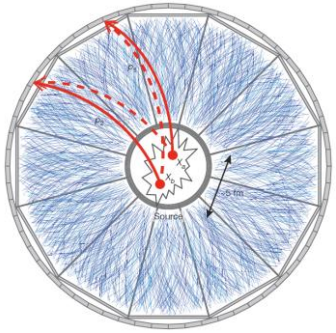
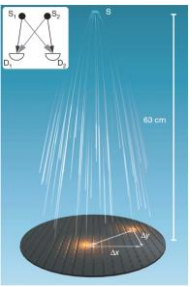
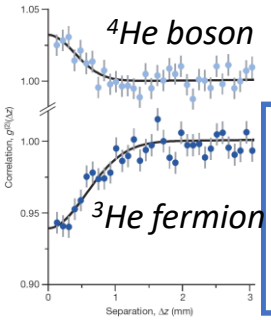


Nature 527, 345(2015)

1956 — 2007 — 2015





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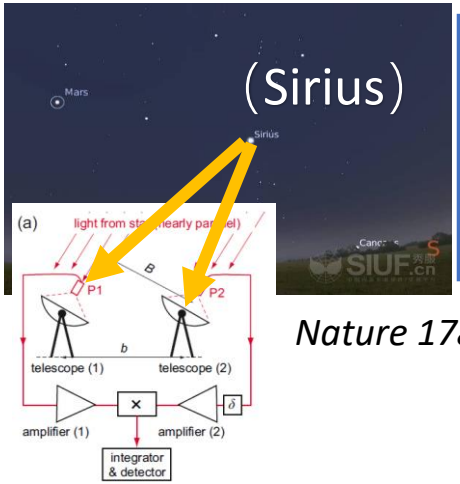

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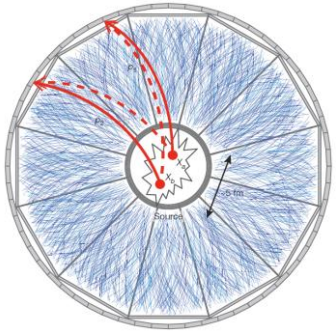
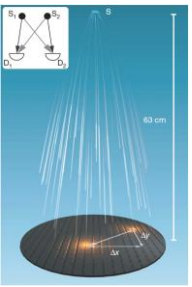
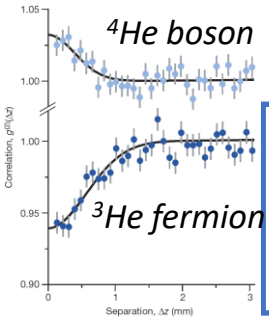


Nature 527, 345(2015)

1956 — 2007 — 2015 — 2022

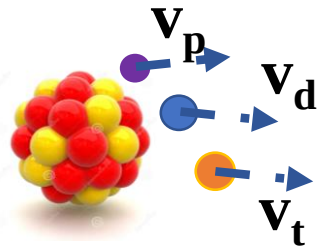




Nature 445, 402(2007)

➢ 2007, T. Jeltes et al.; Quantum performance (Atom physics)

➢ 2022, ENPG group; isospin chronology (Nuclear physics)



Physics Letters B, 825, 136856 (2022)

HBT principle (Nuclear emission source)

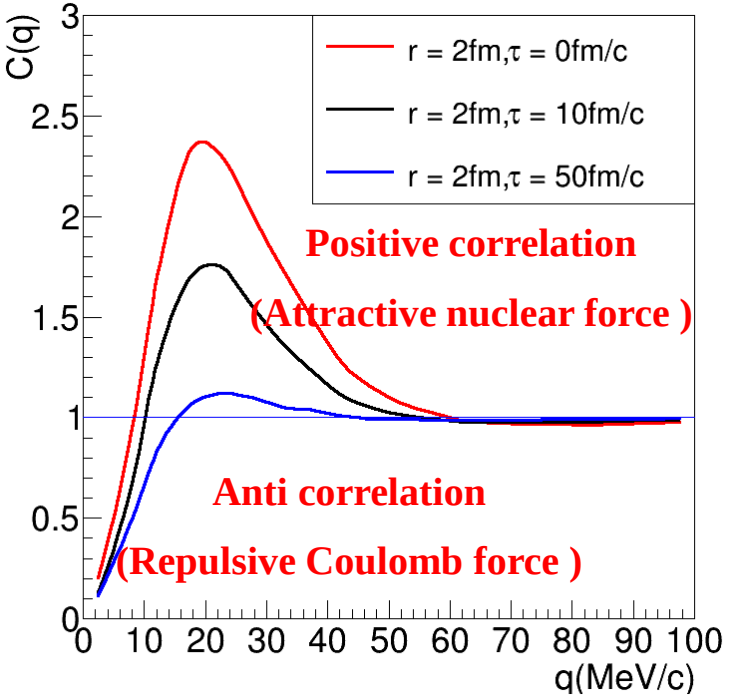
1977， S. Koonin use HBT to proton-proton correlation

The temporal and spatial distribution of proton emission from the emission source

$$\frac{1}{\sigma}\frac{d\sigma}{dp_1 dp_2} = \int_{-\infty}^{\infty} dt_1 dt_2 \int dr_1 dr_2 D(r_1 t_1, p_1) D(r_2 t_2, p_2) \times \left\{ \frac{1}{4} \left| {}^1\Psi_{p_1 p_2}(r_1, r_2) \right|^2 + \frac{3}{4} \left| {}^3\Psi_{p_1 p_2}(r_1, r_2) \right|^2 \right\}$$

Wave function and relative motion

1977_S. Koonin_PLB



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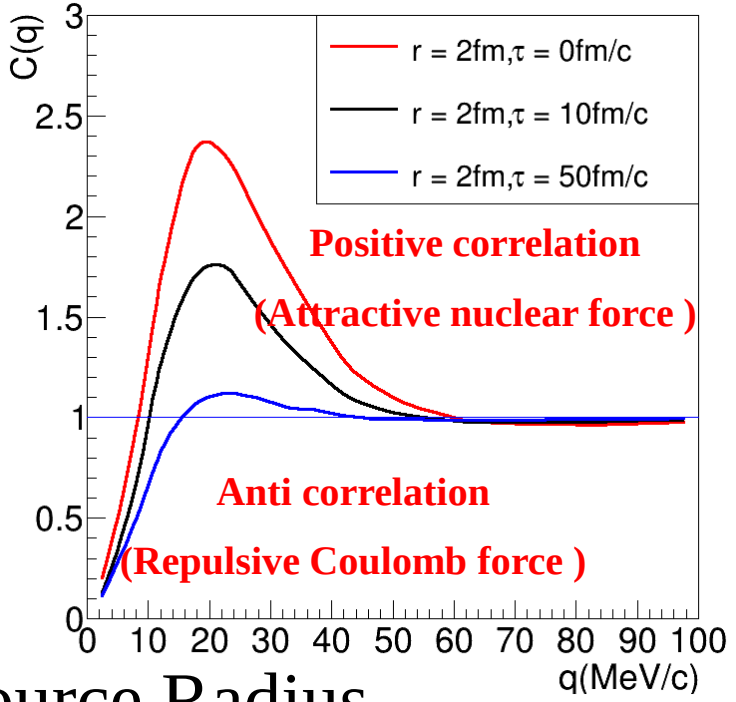

HBT function Application

- Emission source
  - Source Radius
  - Emission time scale
- Final state interaction
  e.g. p-Λ interaction

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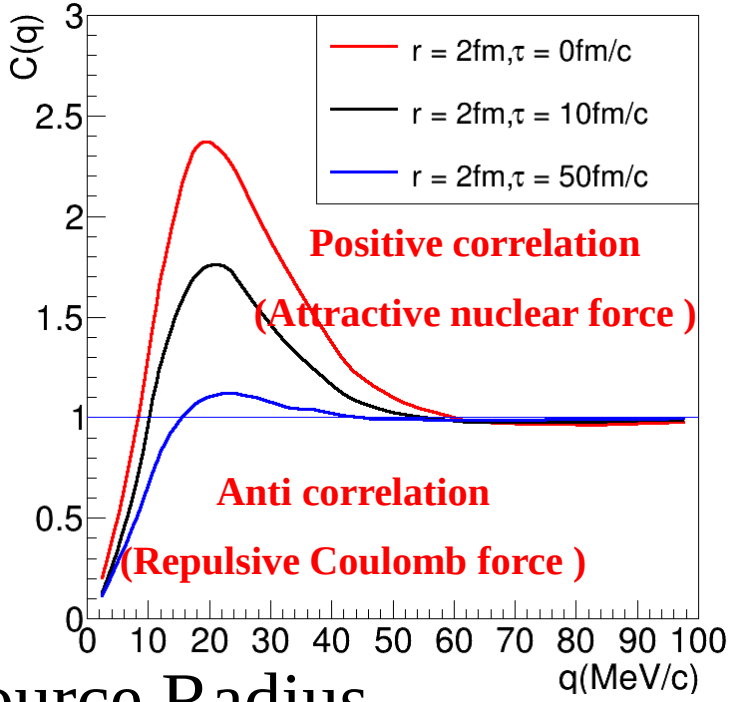

HBT function

Application

- Emission source
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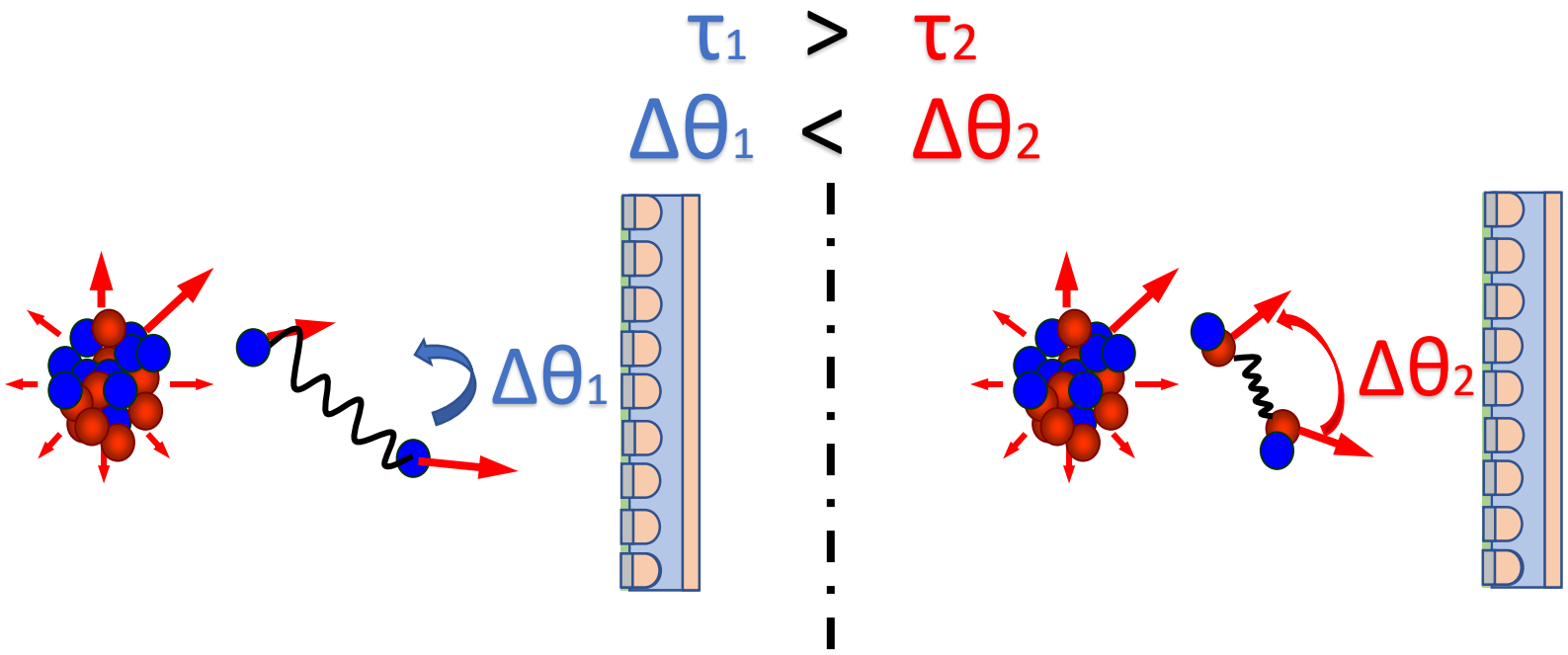
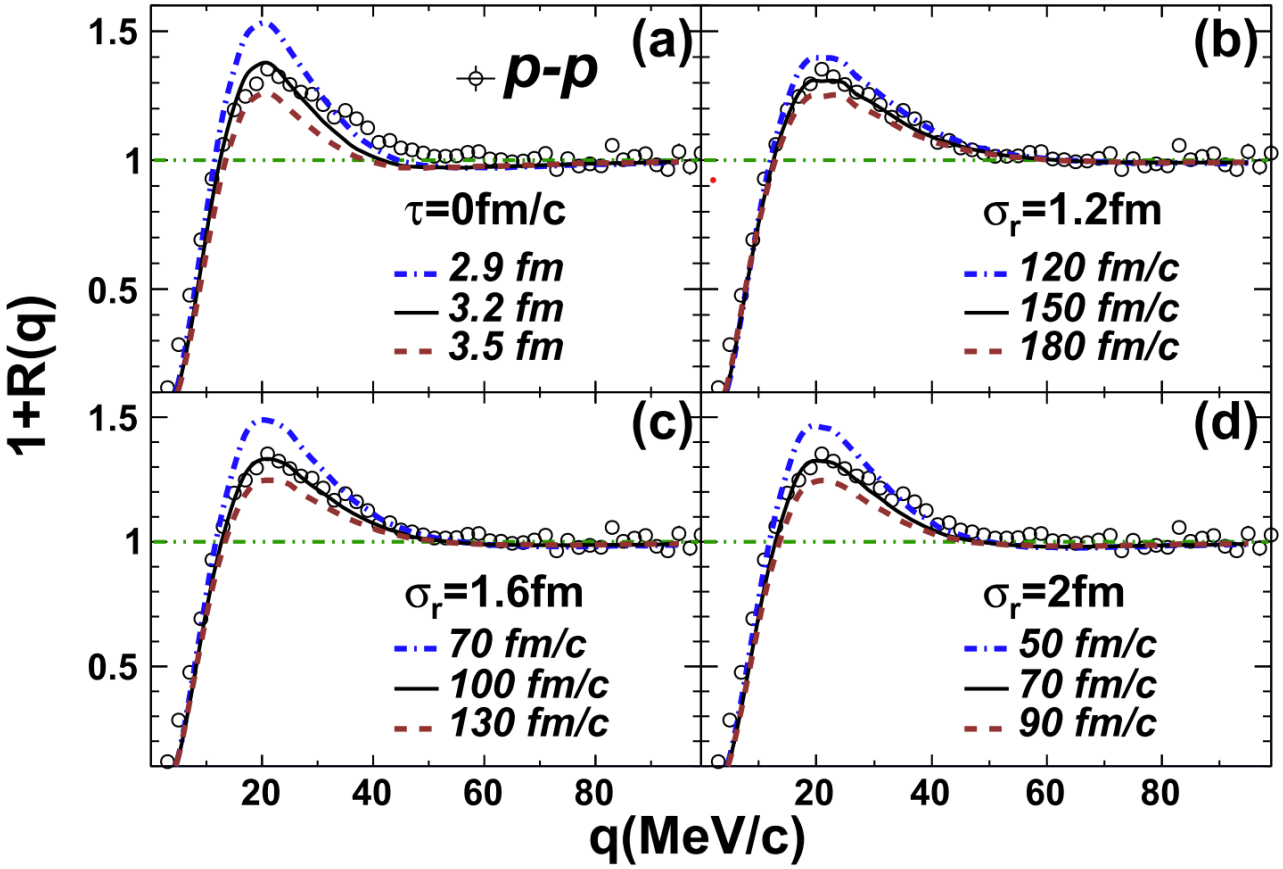
  - Emission time scale
- Final state interaction
  e.g. p-Λ interaction

Simple understand between HBT and emission timescale



When the emission timescale is shorter,
the separate angle of two particles will be larger.

Proton correlation function compared with CRAB calculation:



Physics Letters B, 825, 136856 (2022)

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

^{40}Ar@30MeV/u + ^{197}Au

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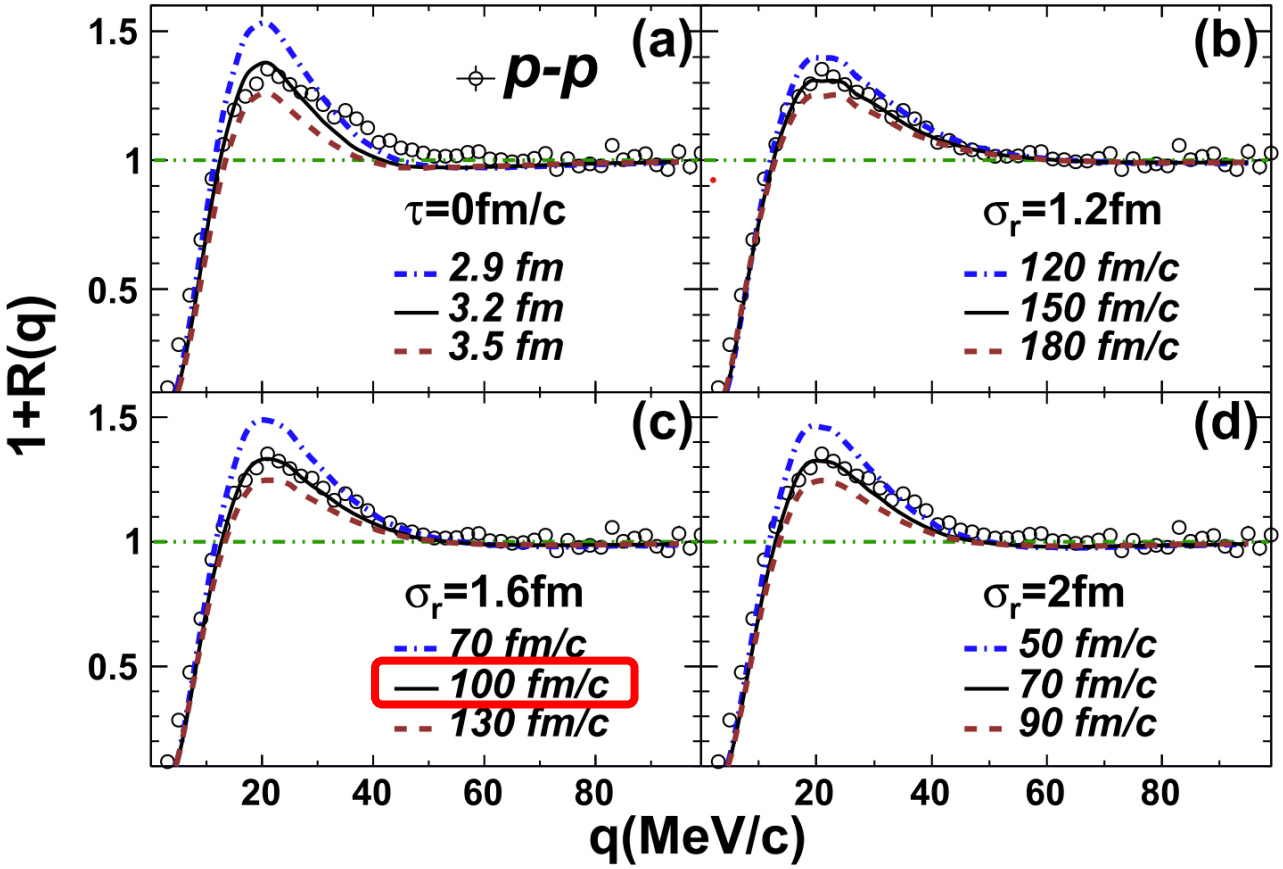

Best fit, Proton emission timescale: $\tau_p \approx 100\mathrm{fm}/c$

Physics Letters B, 825, 136856 (2022)

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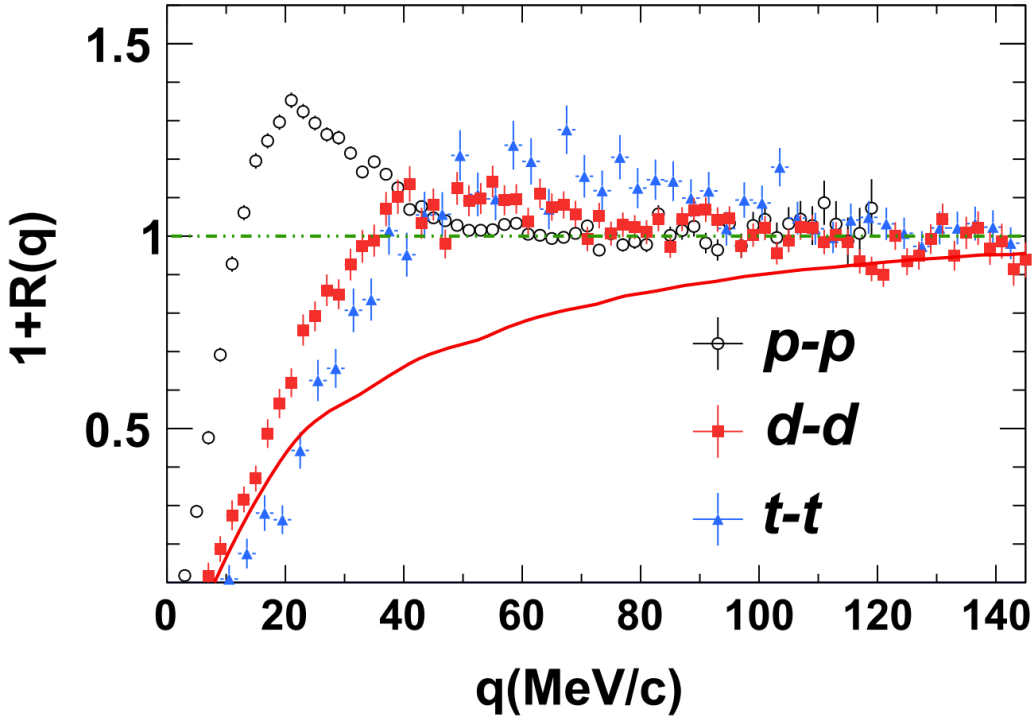
Deuteron-deuteron and triton-triton correlation function:



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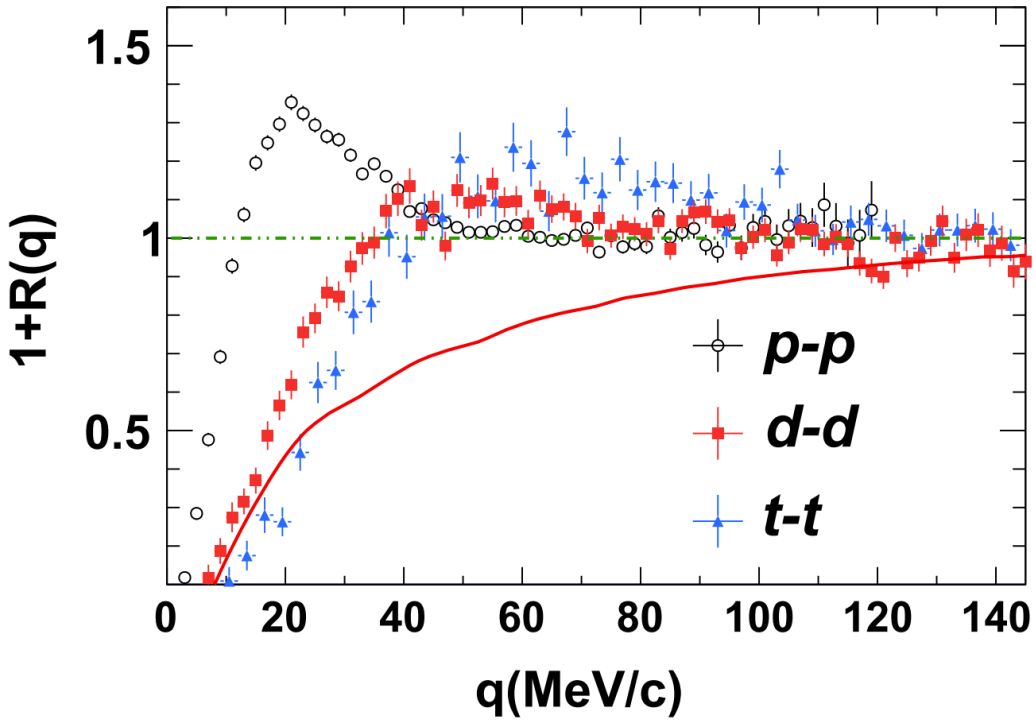

Original plan: Get the p,d,t timescale with CRAB,
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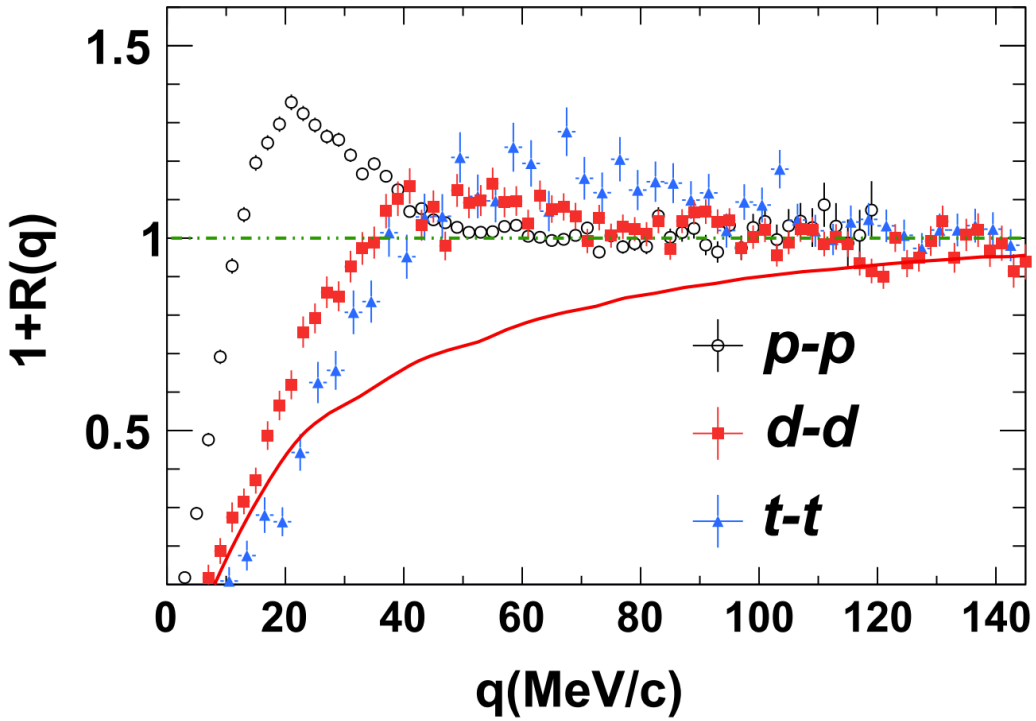

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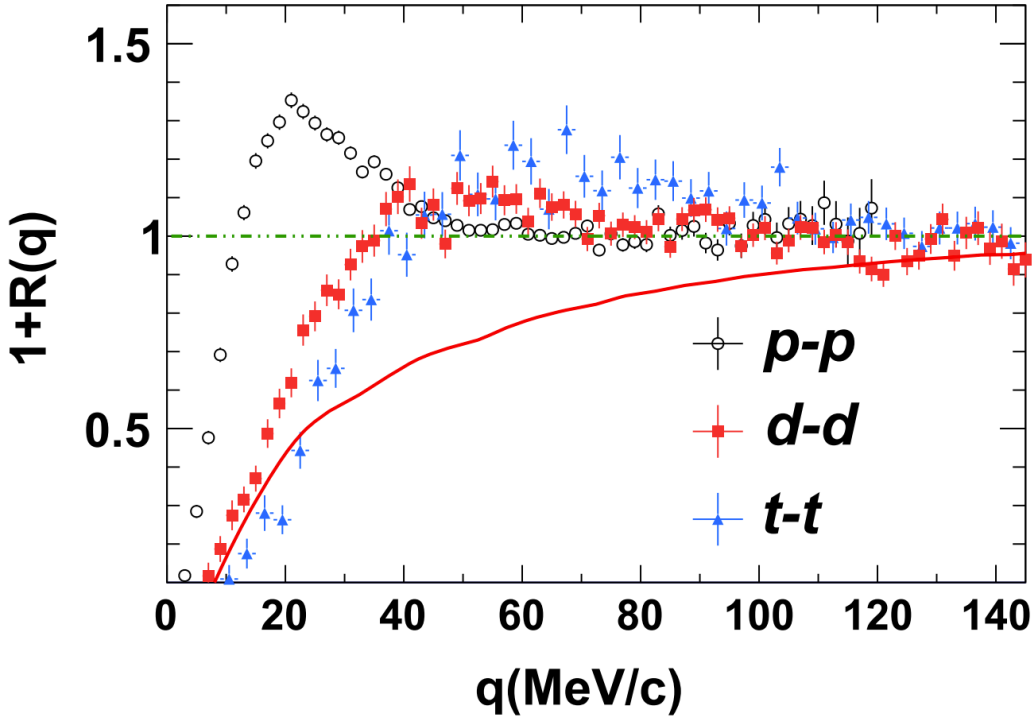

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Question: How to determine the emission order of p,d,t?

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* **]**

Particle emission order

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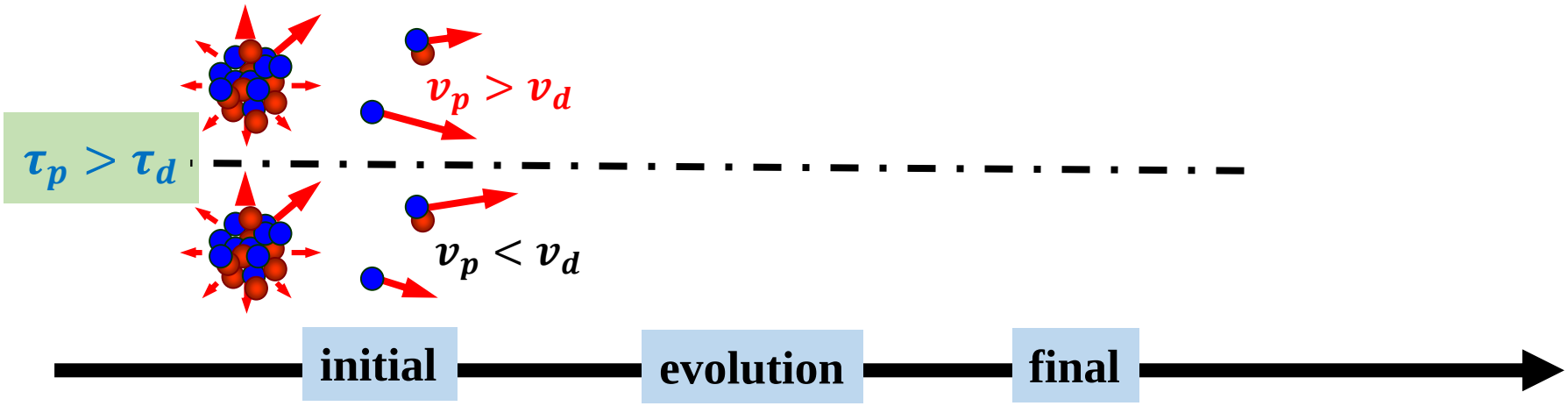
Taking proton and deuteron as example:



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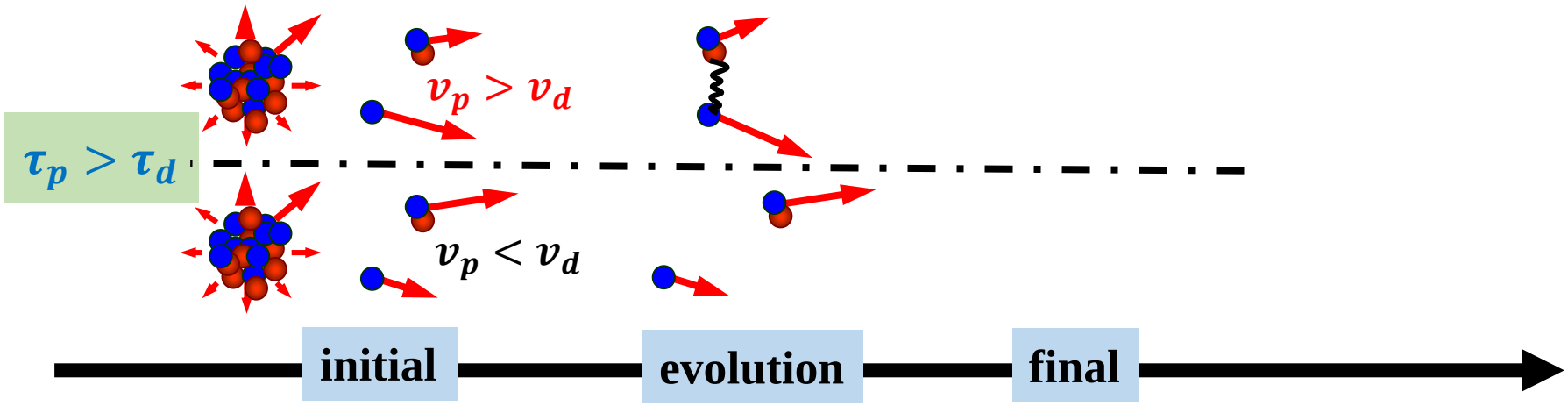

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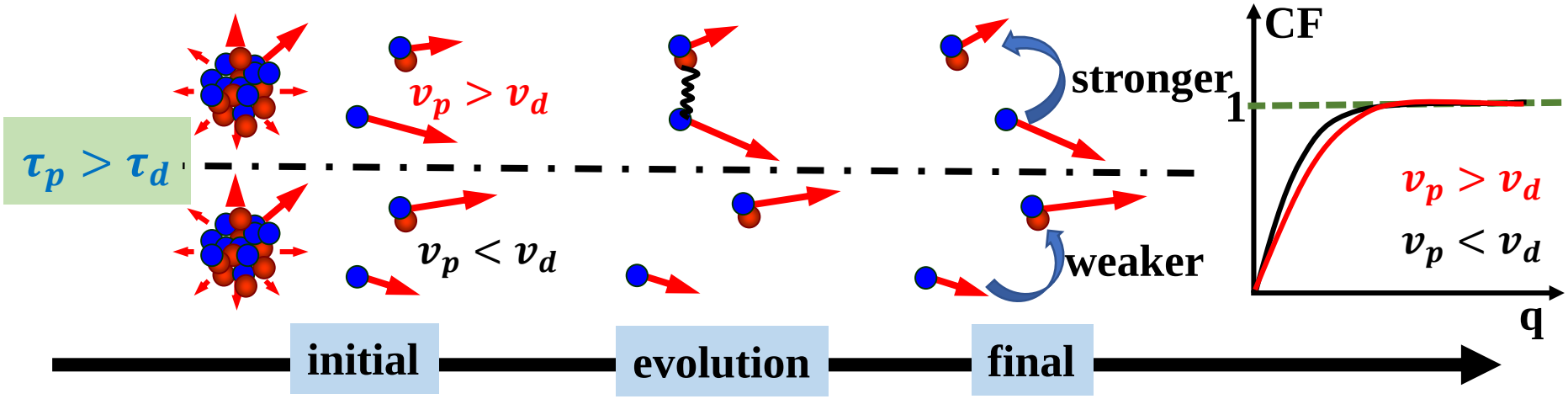

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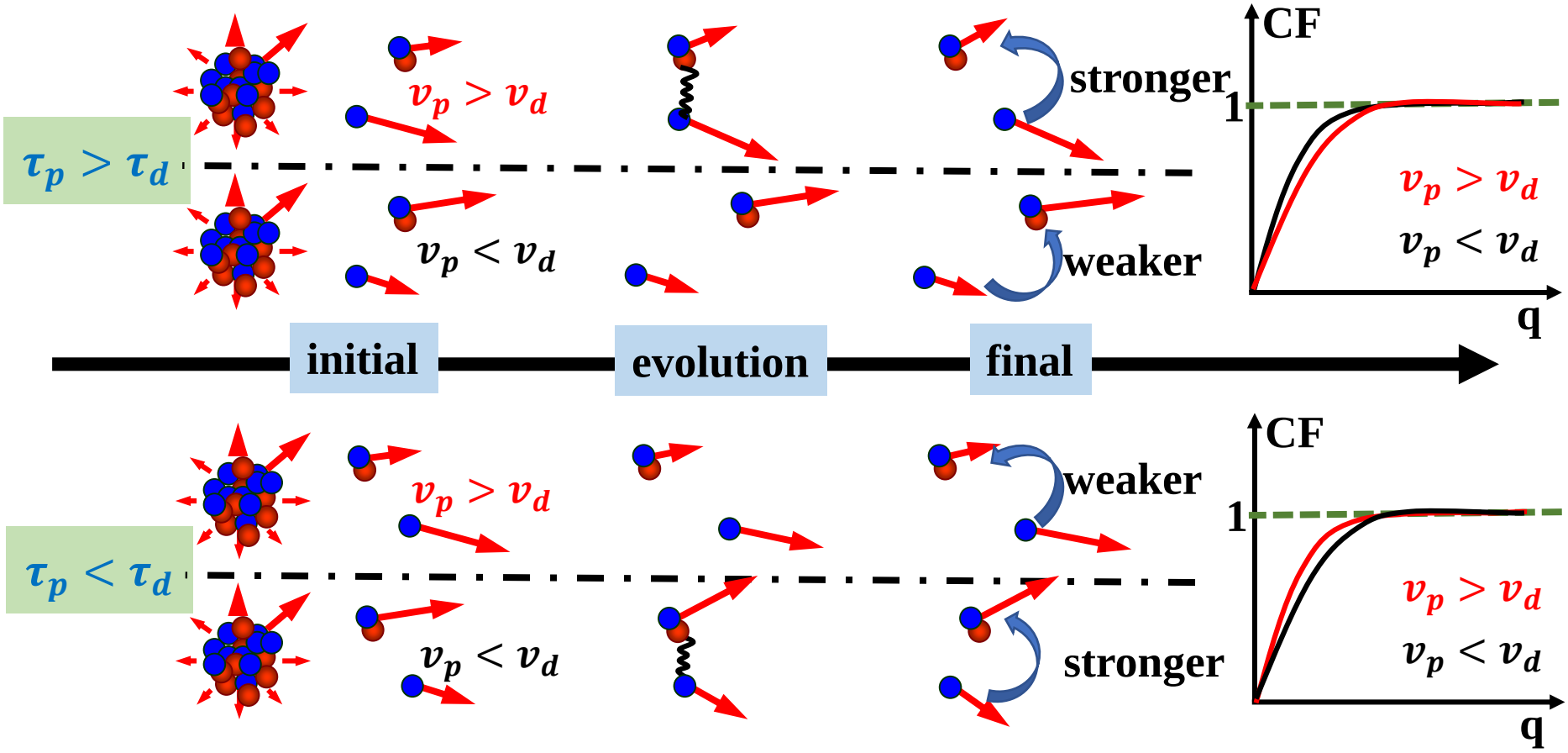

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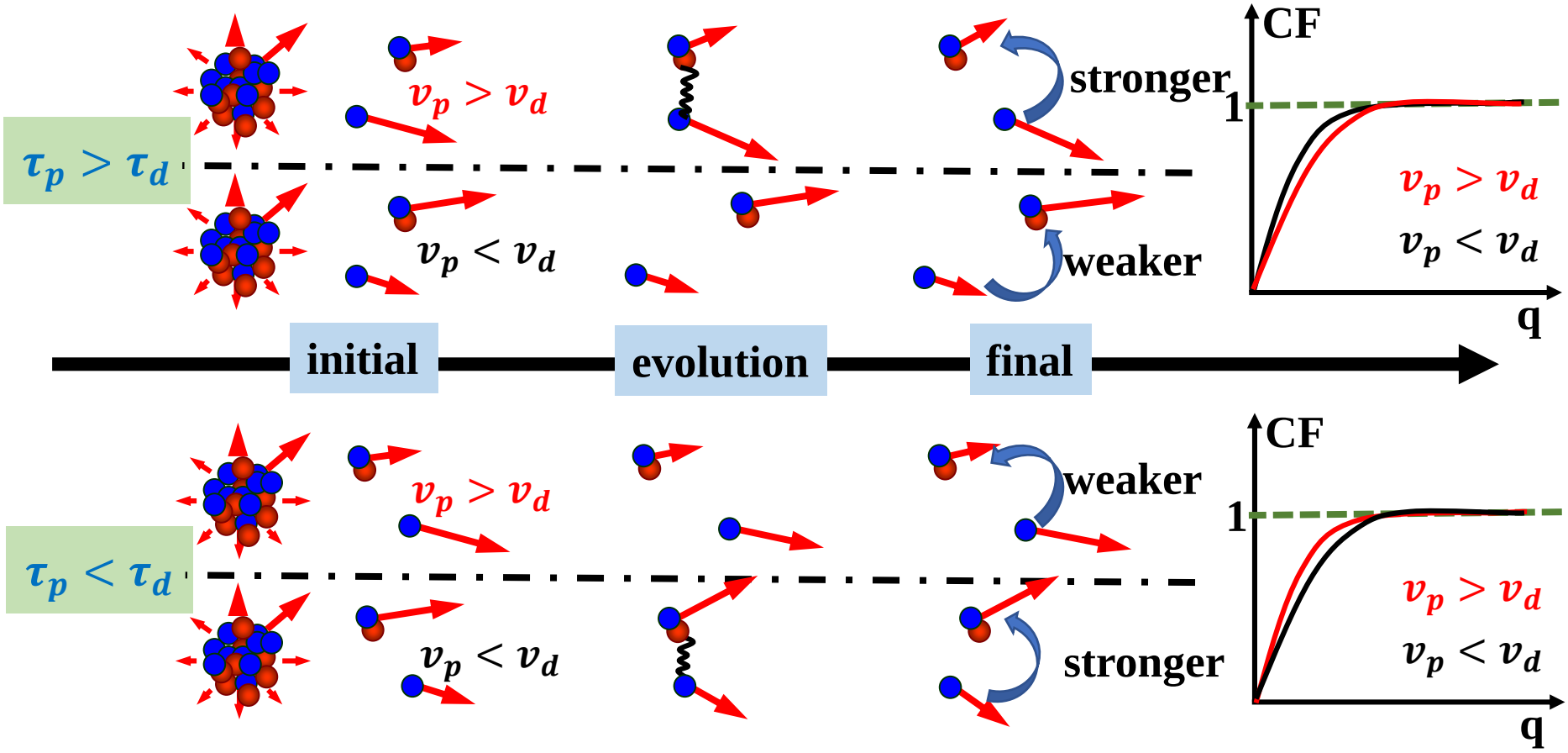
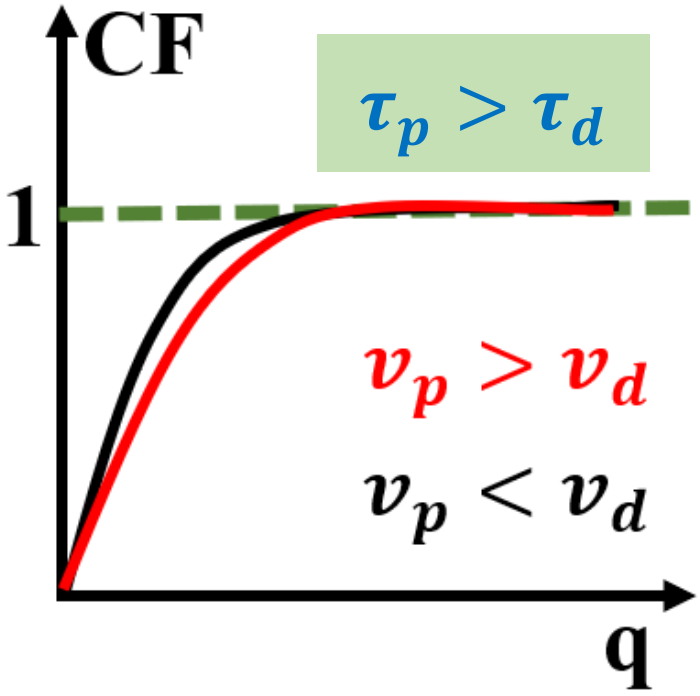
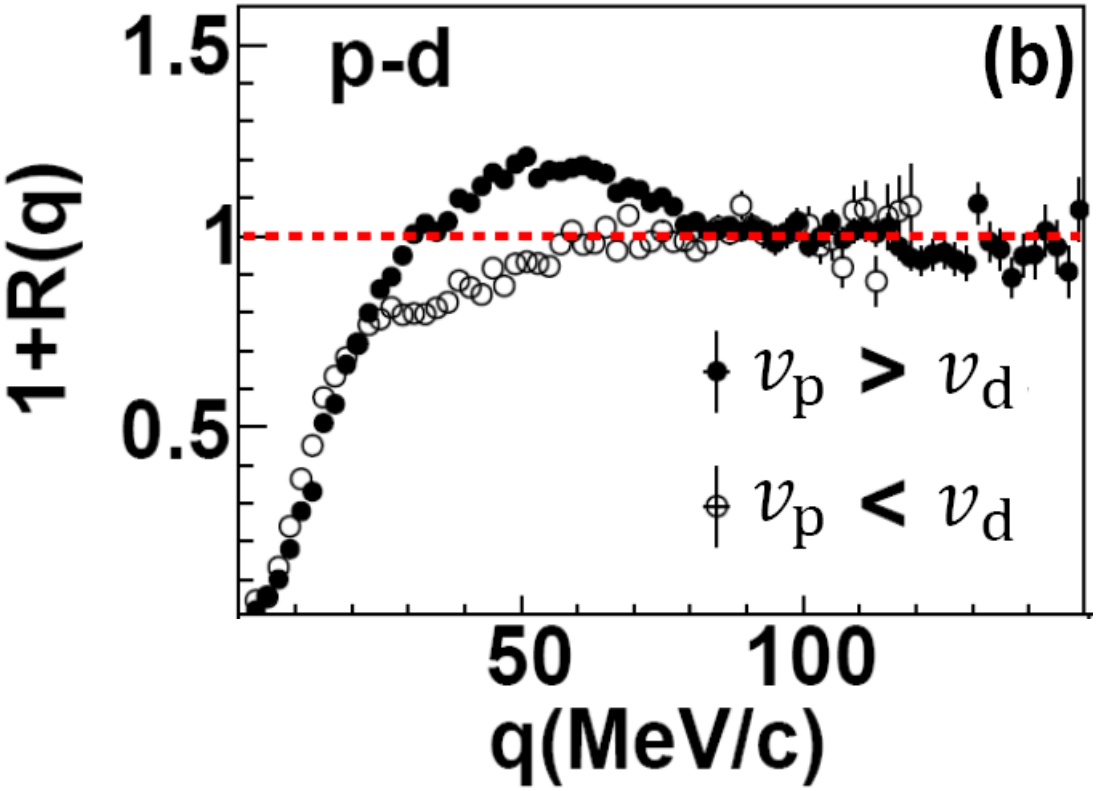


Particle with higher velocity showing strong anti-correlation means this particle is emitted later!

Particle emission order

^{40}Ar@30MeV/u + ^{197}Au





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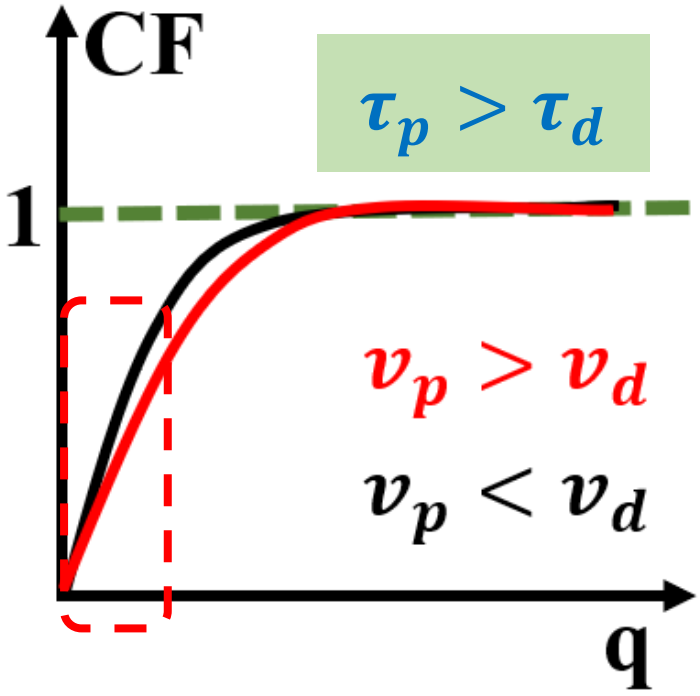

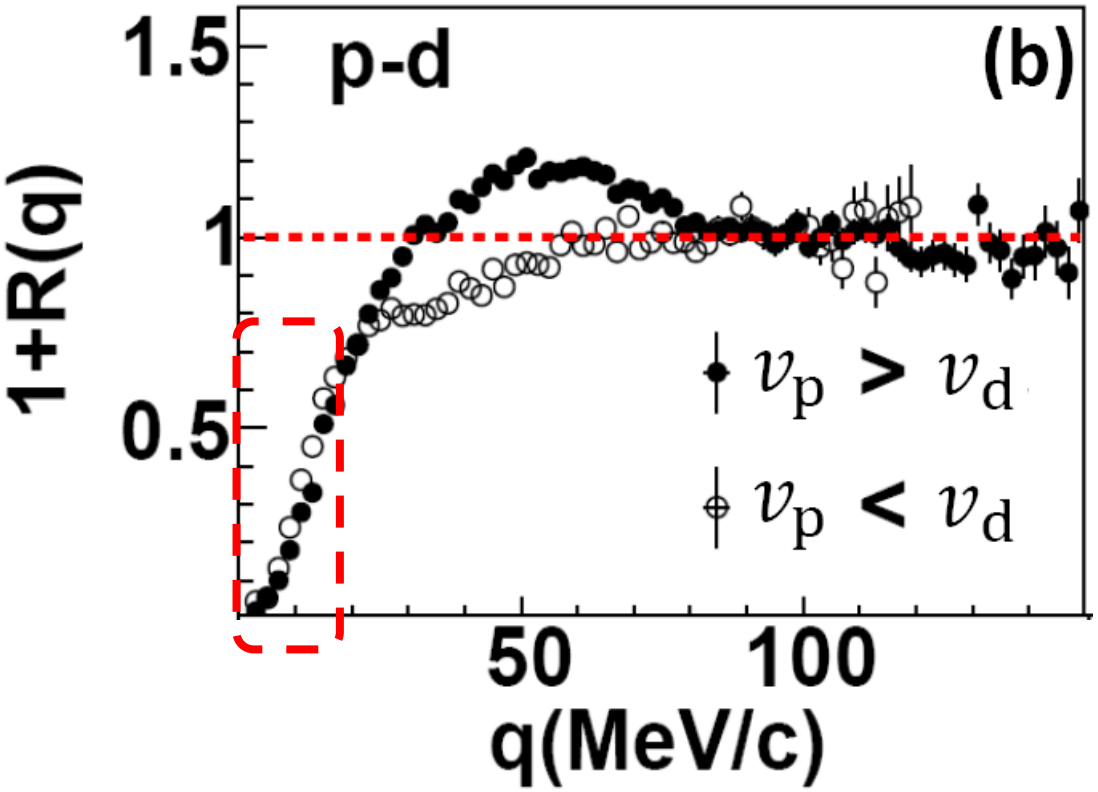

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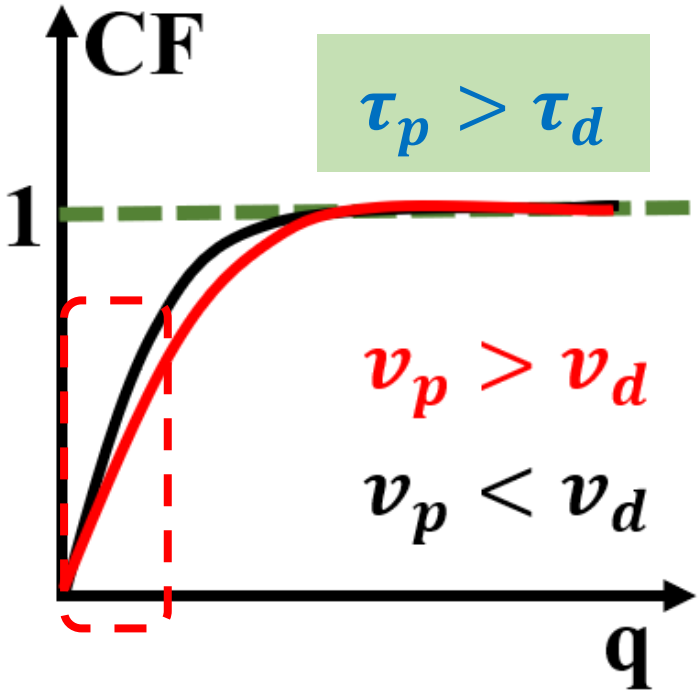

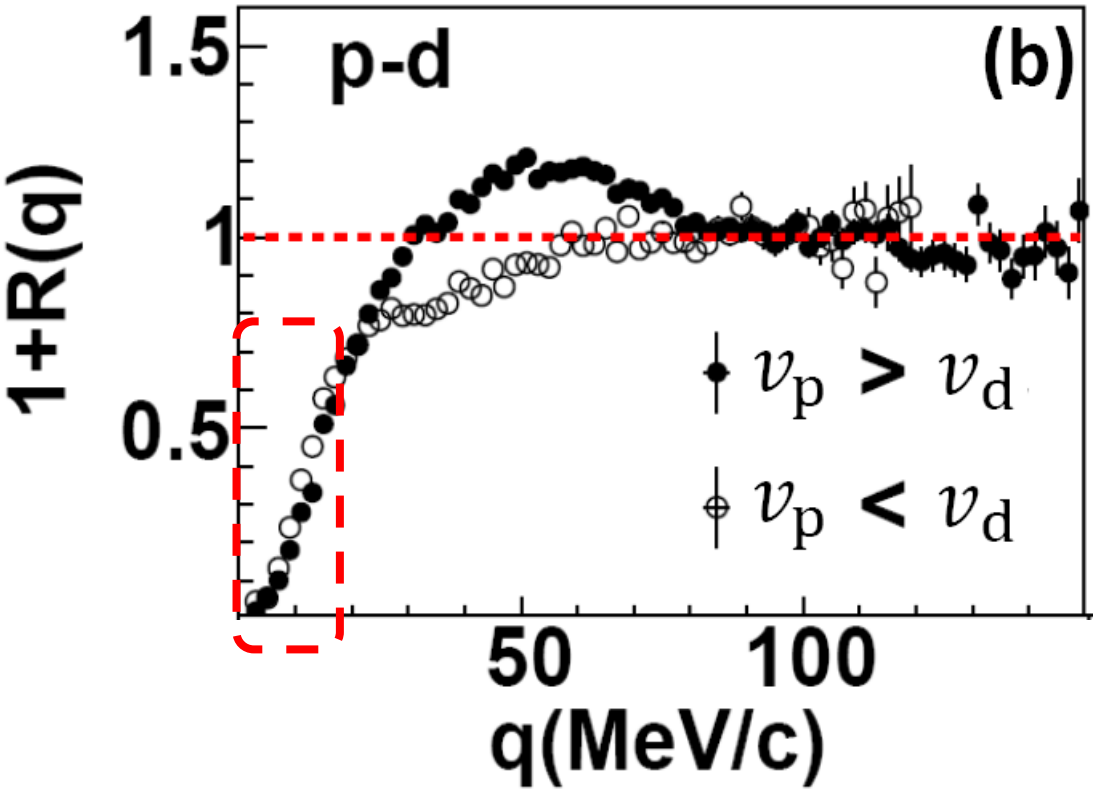

Deuteron is emitted earlier than proton! $\tau_p > \tau_d$

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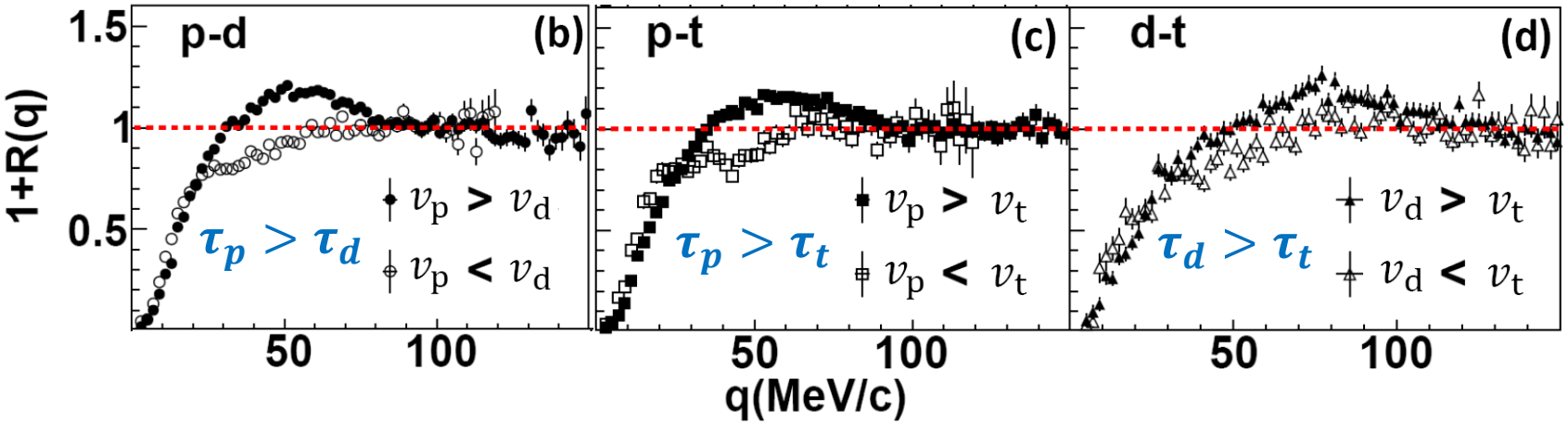

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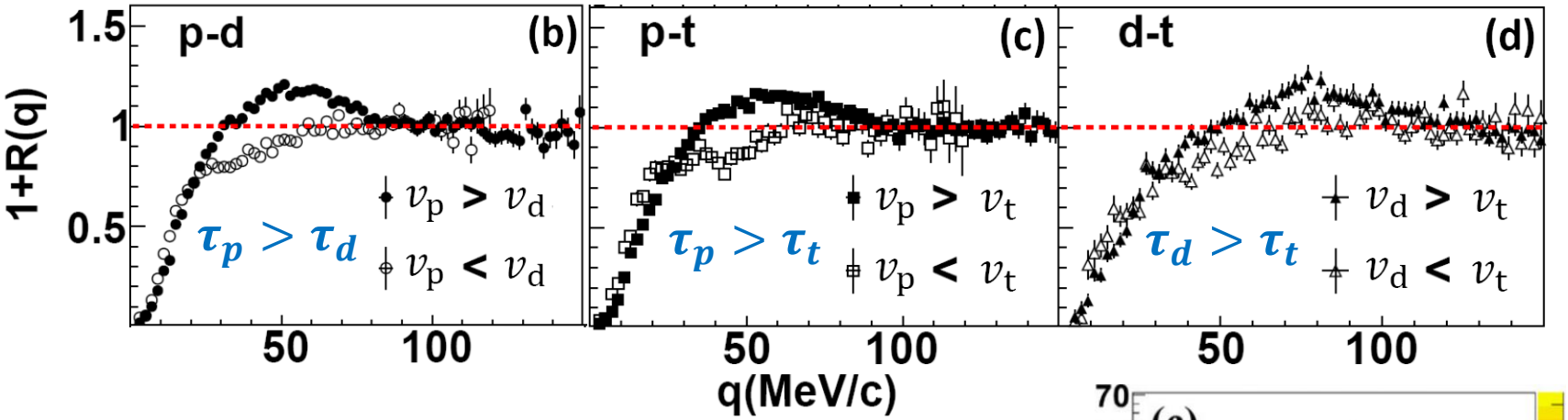
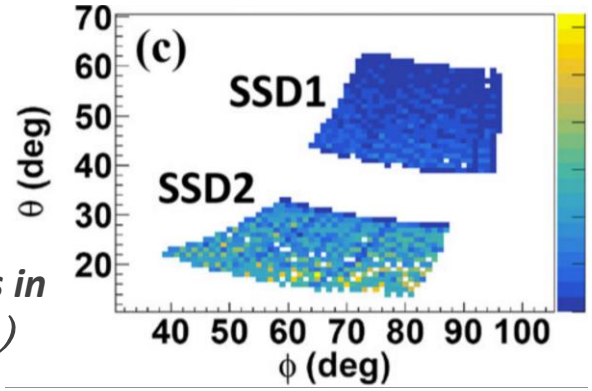


$$\tau_p > \tau_d > \tau_t$$

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)）



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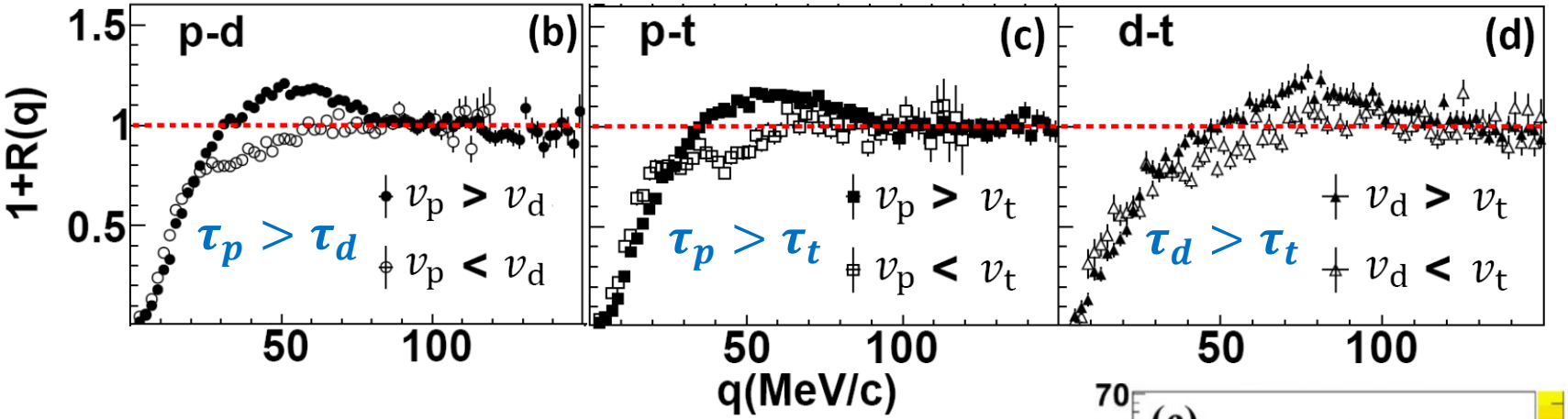

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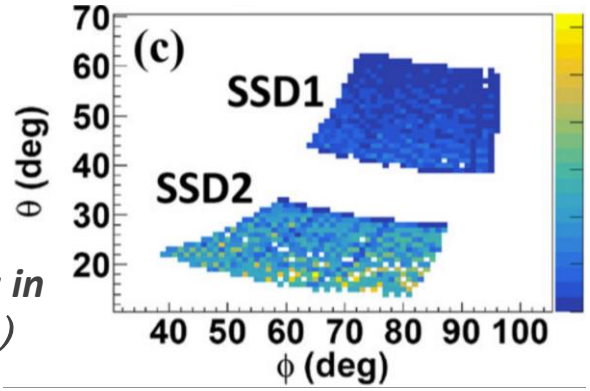
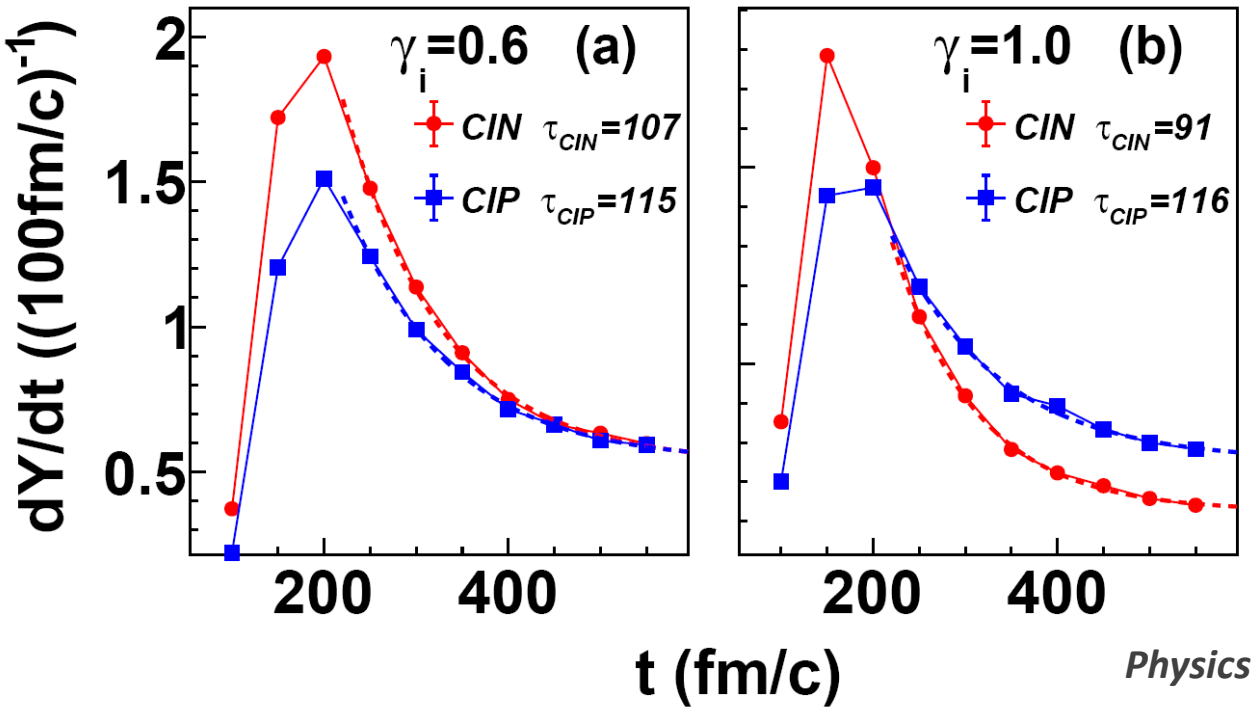


Consistent with the results of R. Ghetti et al[*PhysRevLett.91,092701.* **].**

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

$$\tau_p > \tau_d > \underline{\tau_n}$$

ImQMD calculation results of particle emission timescale



CIN: Coalescence Invariant Neutron

CIP: Coalescence Invariant Proton

Physics Letters B, 825, 136856 (2022)

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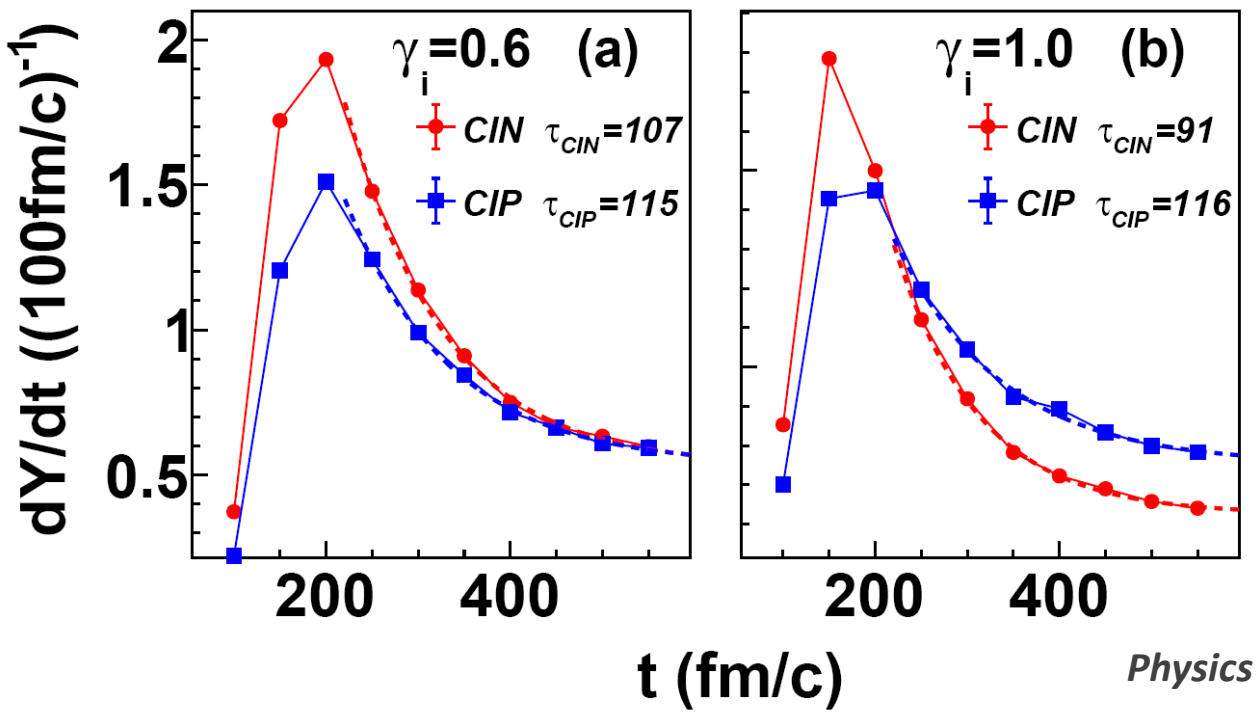

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Physics Letters B, 825, 136856 (2022)

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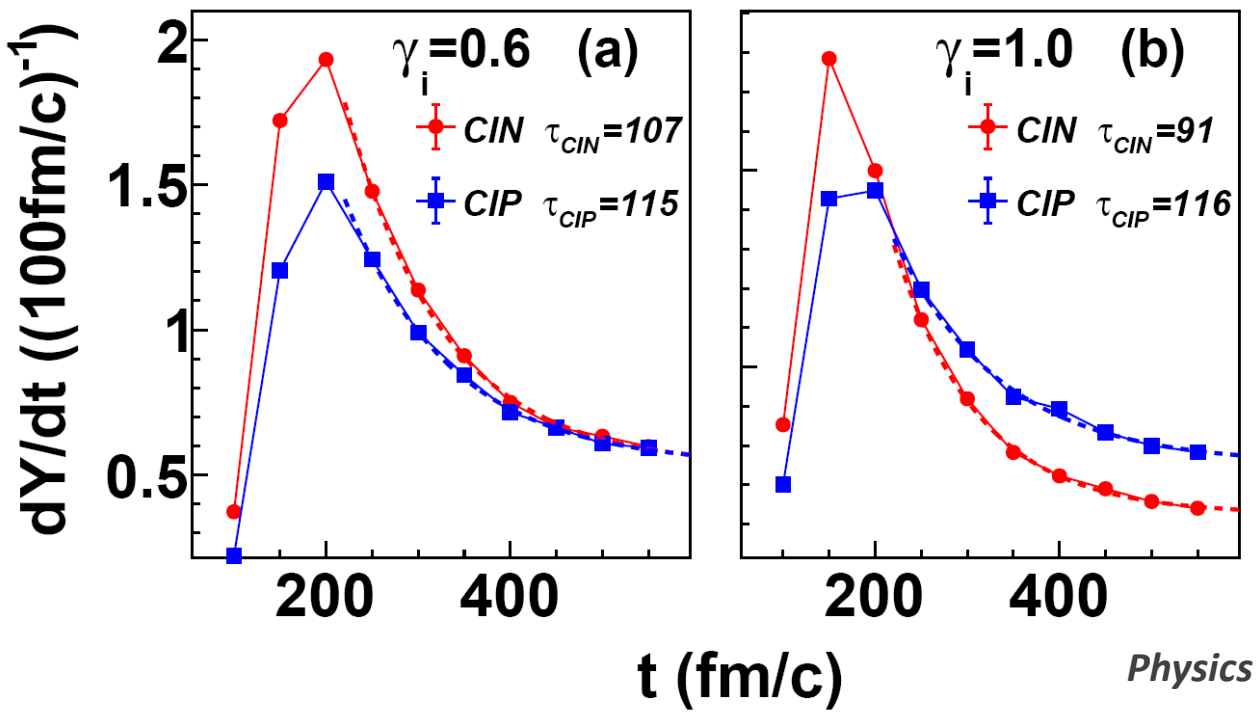

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A new way to study $E_{sym}(\rho)$ and isospin dynamics

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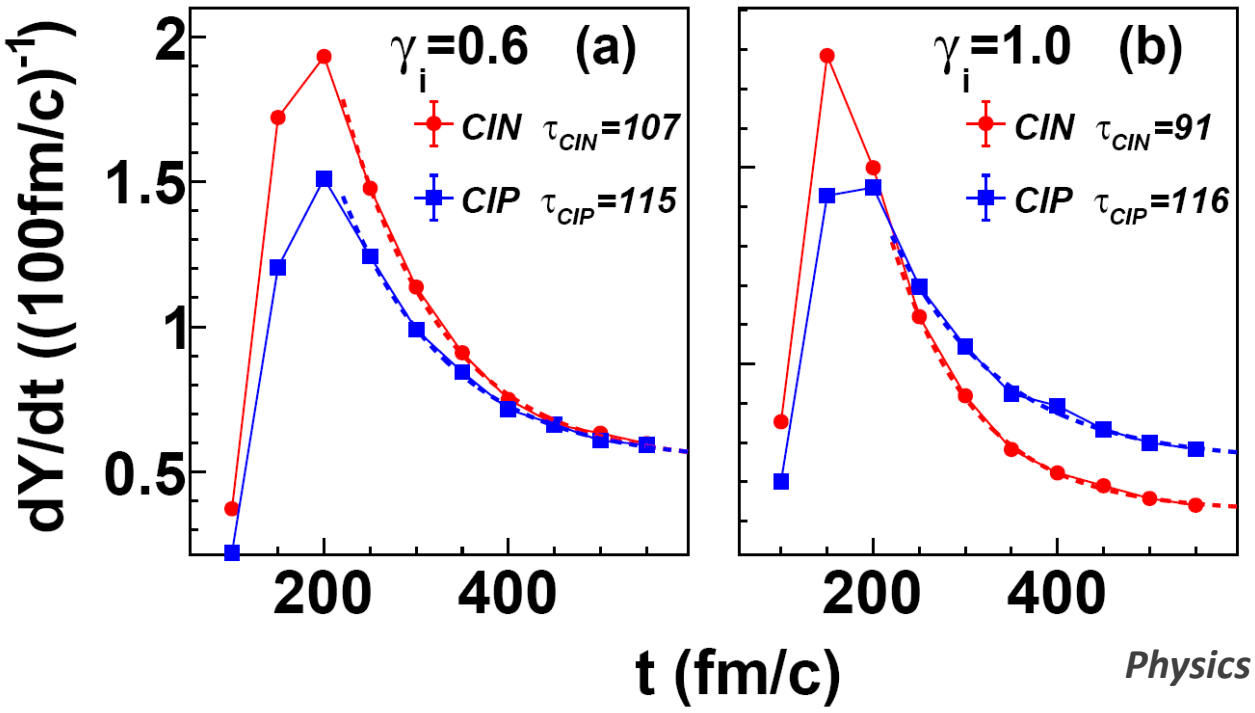

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A new way to study $E_{sym}(\rho)$ and isospin dynamics

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

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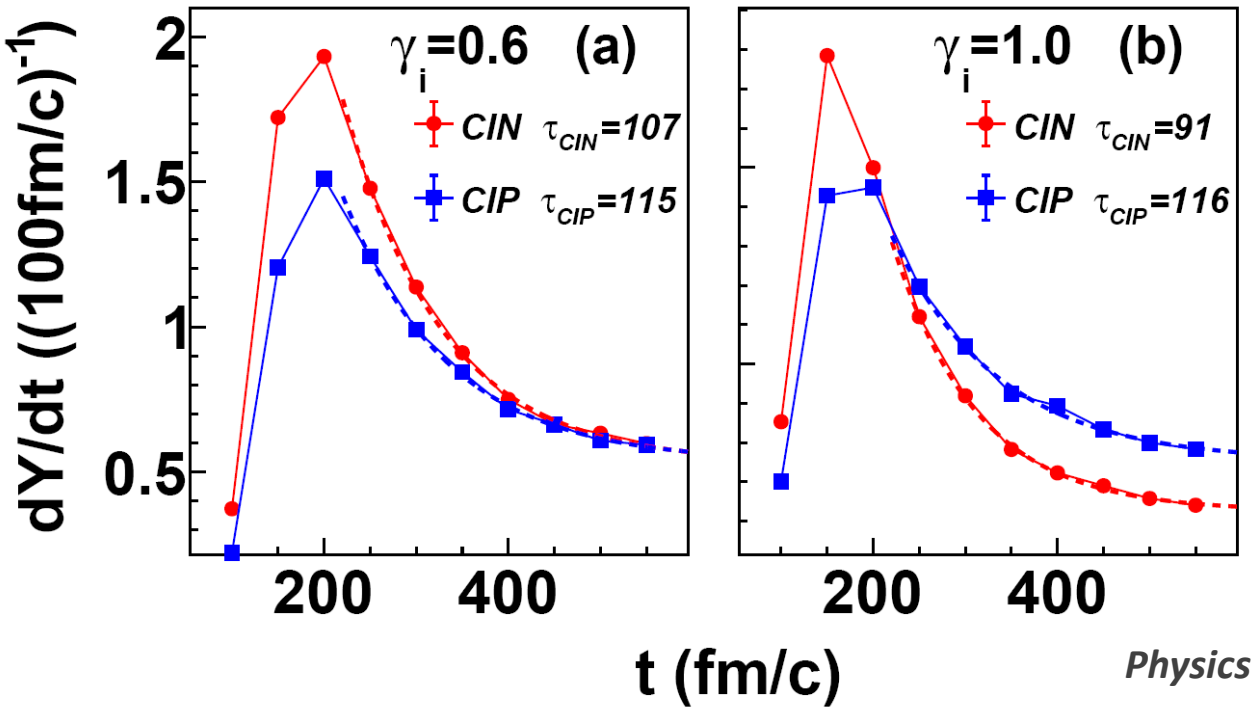

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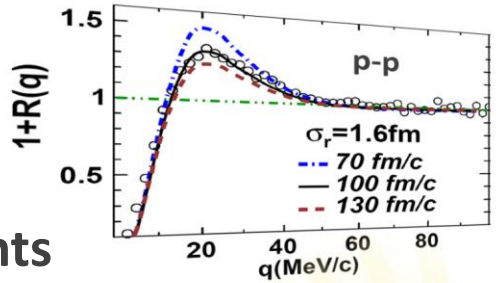
Observing the ping-pong modality of the isospin degree of freedom in cluster emission from heavy-ion reactions（Physical Review C 107, L041601 (2023)）

Summary

① CSHINE system,
HIRs in RIBLL1, IMP, Lanzhou, China
HBT correlation function measurements



CSHINE
Compact Spectrometer for Heavy IoN Experiments

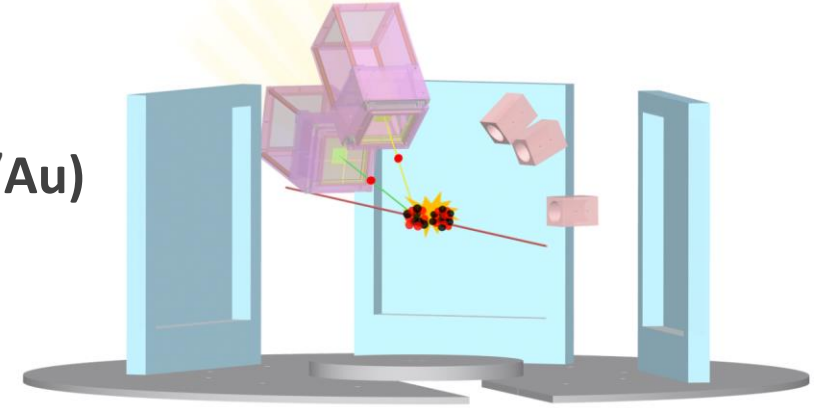
② Isospin chronology (^{40}Ar@30MeV/u + ^{197}Au)
Proton emission timescale:

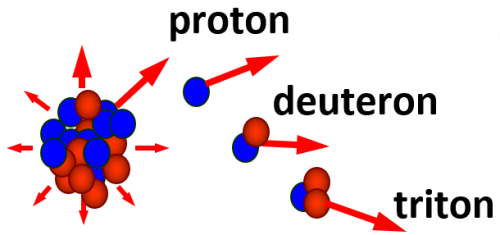
$$\tau_p \approx 100\mathrm{fm}/c$$

Emission order of hydrogen isotopes:

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

Neutron rich particle emitted earlier



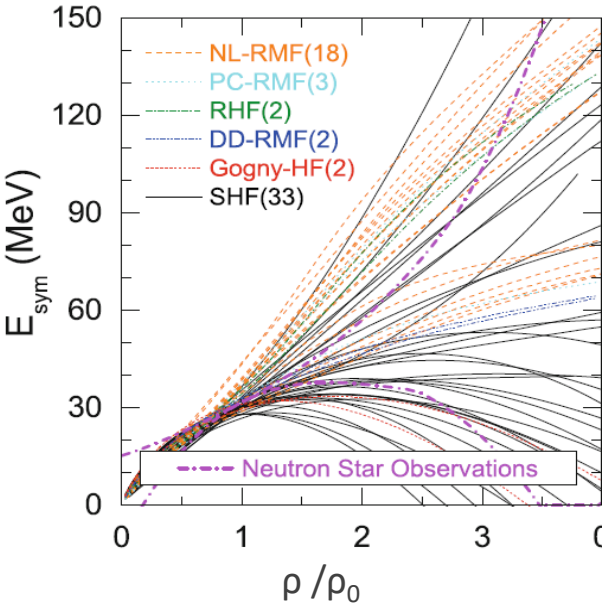


③ Future plan: a, n-n HBT correlation; b, t and ^{3}He emission
c, θ(n/p) distribution; d, Resonance decay
…

backup

Current situation of Esym

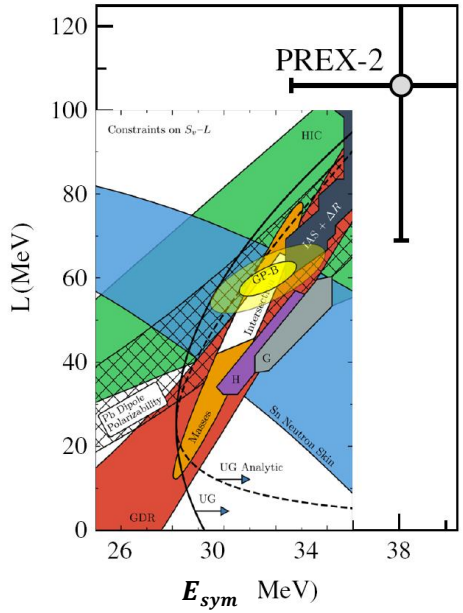
B.A.Li et. al. Eur. Phys. J. A (2019) 55: 117



$E_{sym}(\rho_0)$ = 31.6±2.7 MeV

$L(\rho_0)$ = 58.9±16 MeV

PRL 126, 172503 (2021) neutron skin



$E_{sym}(\rho_0)$ = 38.1±4.7 MeV

$L(\rho_0)$ = 106±37 MeV

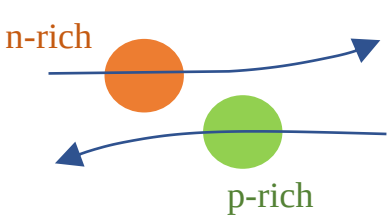
How Esym influence Heavy ion reaction(HIR) process?

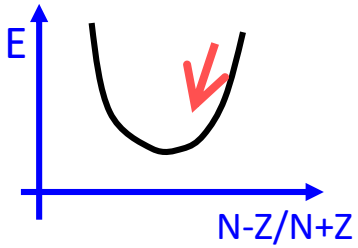
Eur. Phys. J. A (2014) 50: 36

1. Isospin Diffusion:

$$j_{\mathrm{np}} = j_n^I - j_p^I = -(D_n^I - D_p^I)\nabla I$$

$$D_n^I - D_p^I \propto 4\rho E_{sym}(\rho)$$

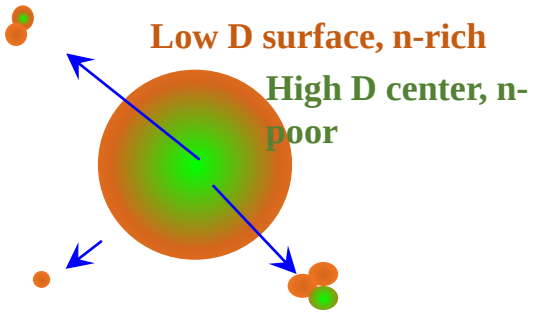


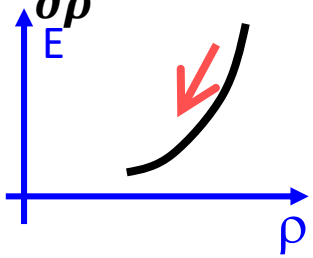


2. Isospin Drift:

$$j_{\mathrm{np}} = j_n^\rho - j_p^\rho = (D_n^\rho - D_p^\rho)\nabla\rho$$

$$D_n^\rho - D_p^\rho \propto 4I\frac{\partial E_{sym}(\rho)}{\partial\rho}$$





Experiments on CSHINE

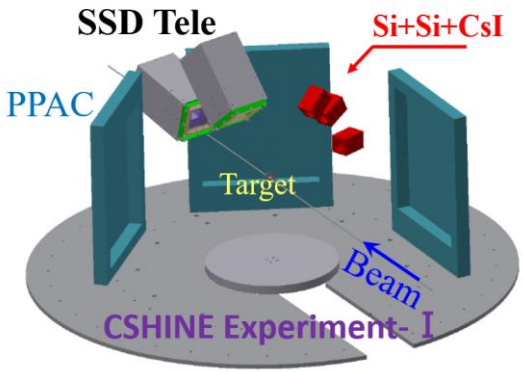
At RIBLL1, HIRFL, IMP, Lanzhou

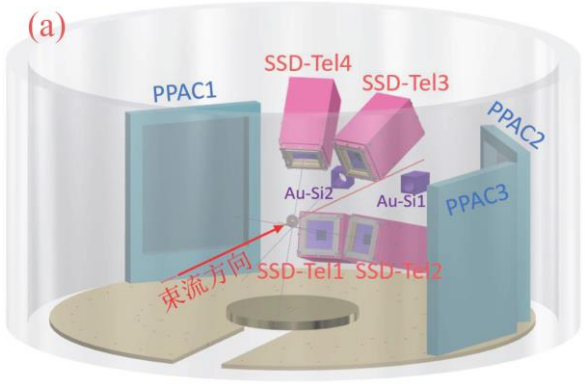
2018, ^{40}Ar@30MeV/u + ^{197}Au
2*SSDT + 3*PPAC

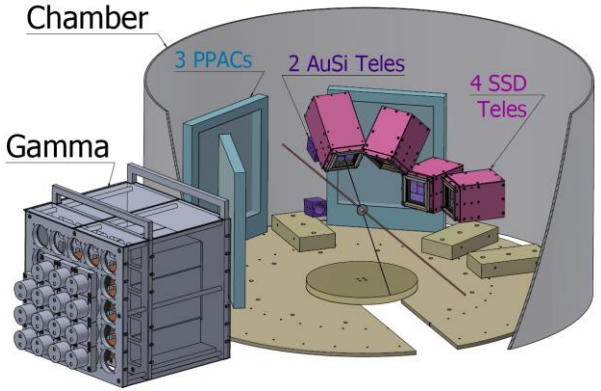
2019, ^{86}Kr@25MeV/u + ^{208}Pb
4*SSDT + 3*PPAC

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

2018 — 2019 — 2022





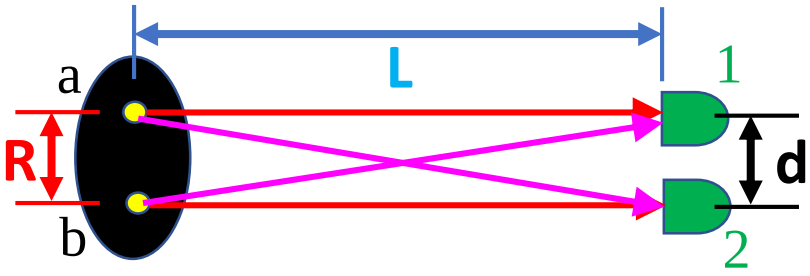


HBT principle (Light source)

- light emitted from source as spherical wave

$$A = \alpha\, e^{ik|\vec{r}-\vec{r_a}|+i\varphi_a}/|\vec{r}-\vec{r_a}|$$

$$I = A^2$$



- Two-point correlation function defination

$$C\left(\vec{d}, k_1, k_2\right) = \frac{\langle I_1 I_2\rangle}{\langle I_1\rangle\langle I_2\rangle} = 1 + 2\frac{\langle\alpha^2\rangle\langle\beta^2\rangle}{(\alpha^2+\beta^2)^2}\cos\left[\left(\vec{k}_2-\vec{k}_1\right)\cdot\vec{R}\right]$$

- Continuous source correlation function （Fourier transform of the density distribution of source）

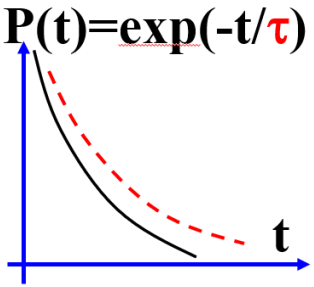
$$C\left(\vec{d}, k_1, k_2\right) - 1 = \left|\int \rho(r) e^{i(\vec{k}_1-\vec{k}_2)\cdot\vec{r}} d^3r\right|^2$$

Physics result1: Isospin chronology

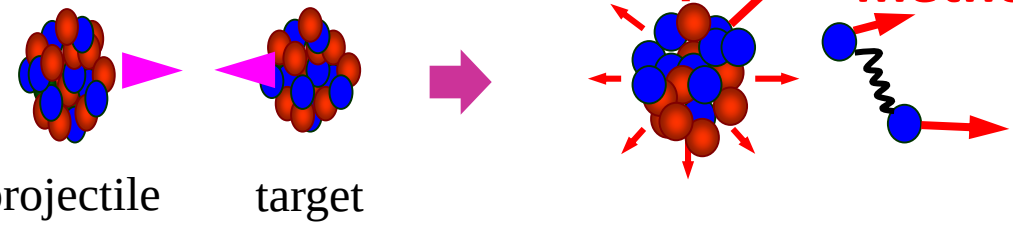
- What's the relationship between **emission timescale** and $E_{sym}(\rho)$?

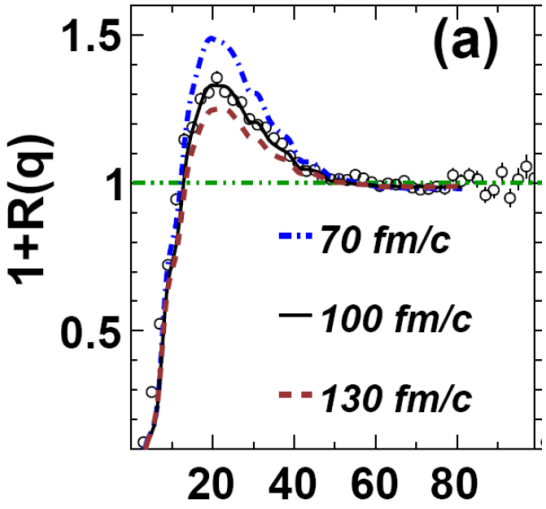
  More stiffer $E_{sym}(\rho)$, more neutron-rich particles easier emission!

- Emission timescale τ

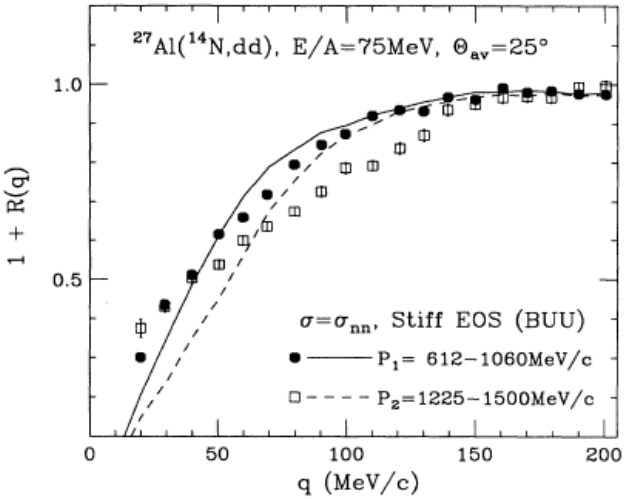


Heavy Ion Reaction

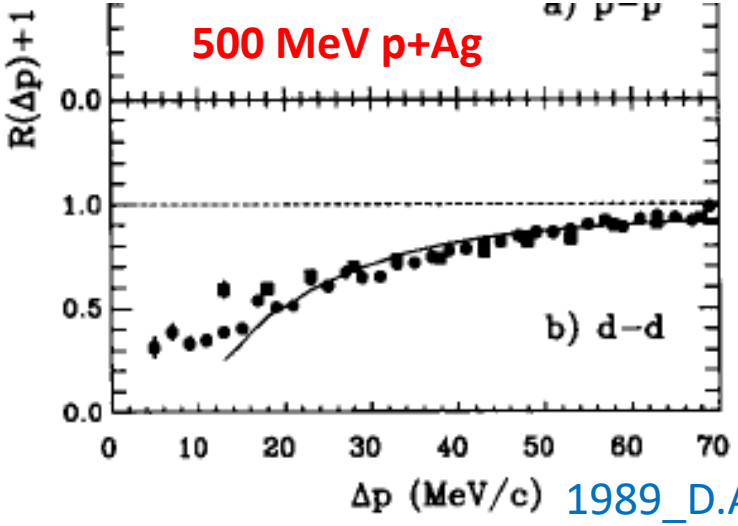




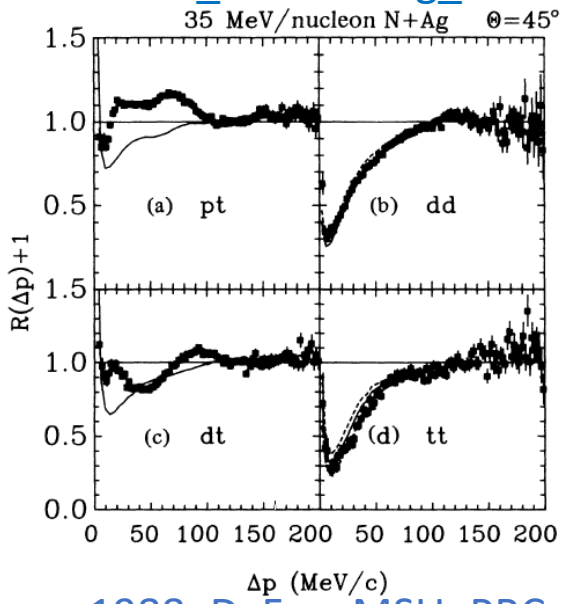
Deuteron-deuteron correlation function



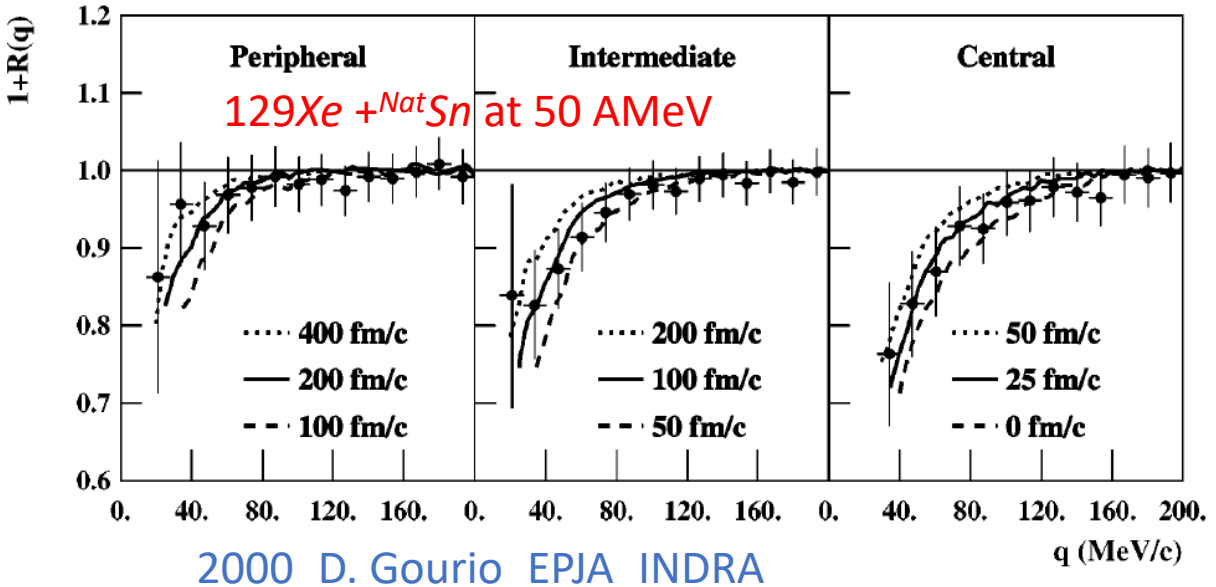
1993_W. G. Gong_PRC



1989_D.A. CEBRA_MSU_PLB

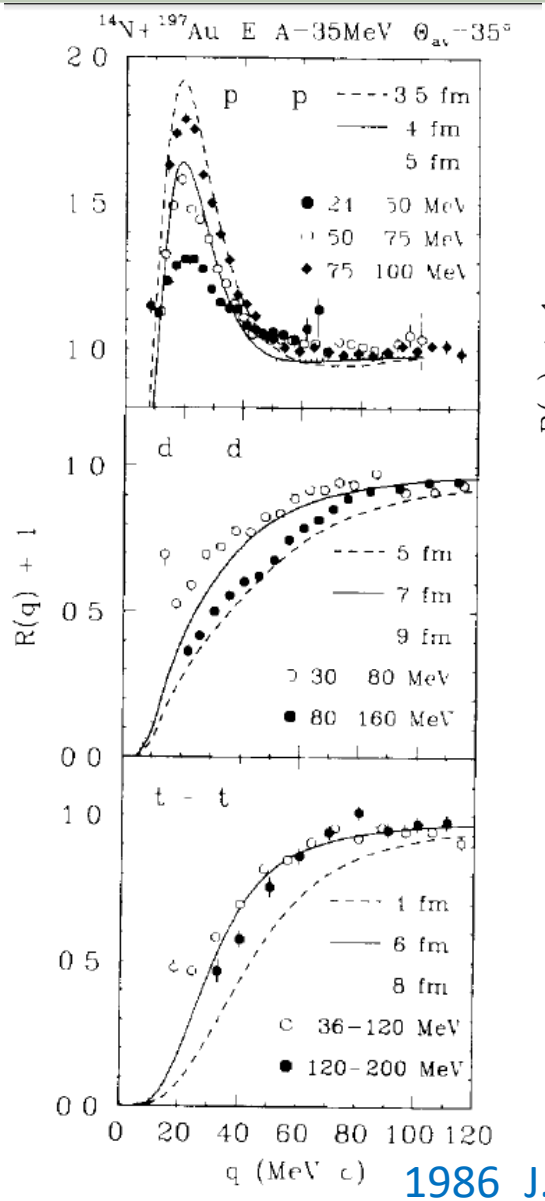


1988_D. Fox_MSU_PRC

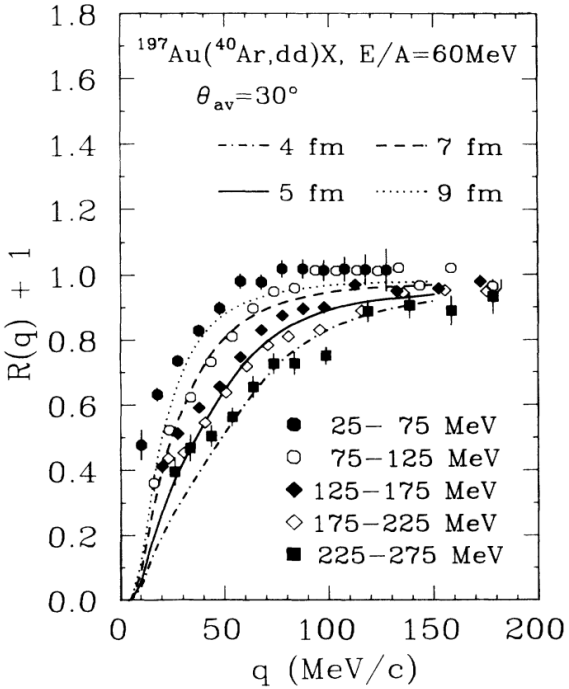


2000_D. Gourio_EPJA_INDRA

Deuteron-deuteron correlation function



1986_J. POCHODZALLA_MSU_PLB



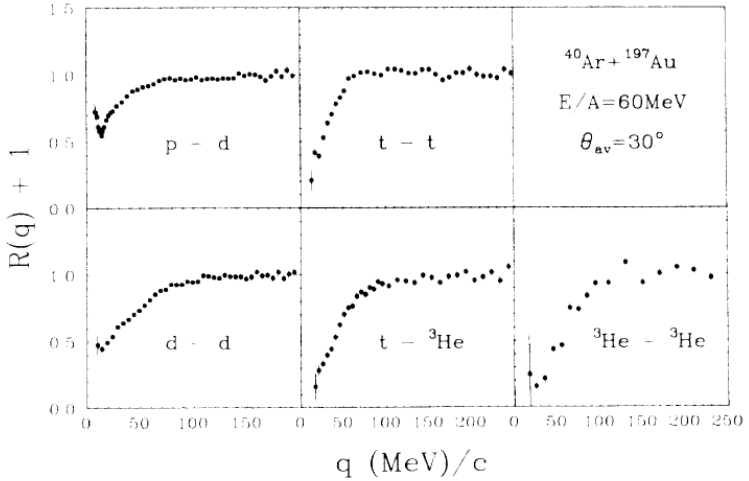
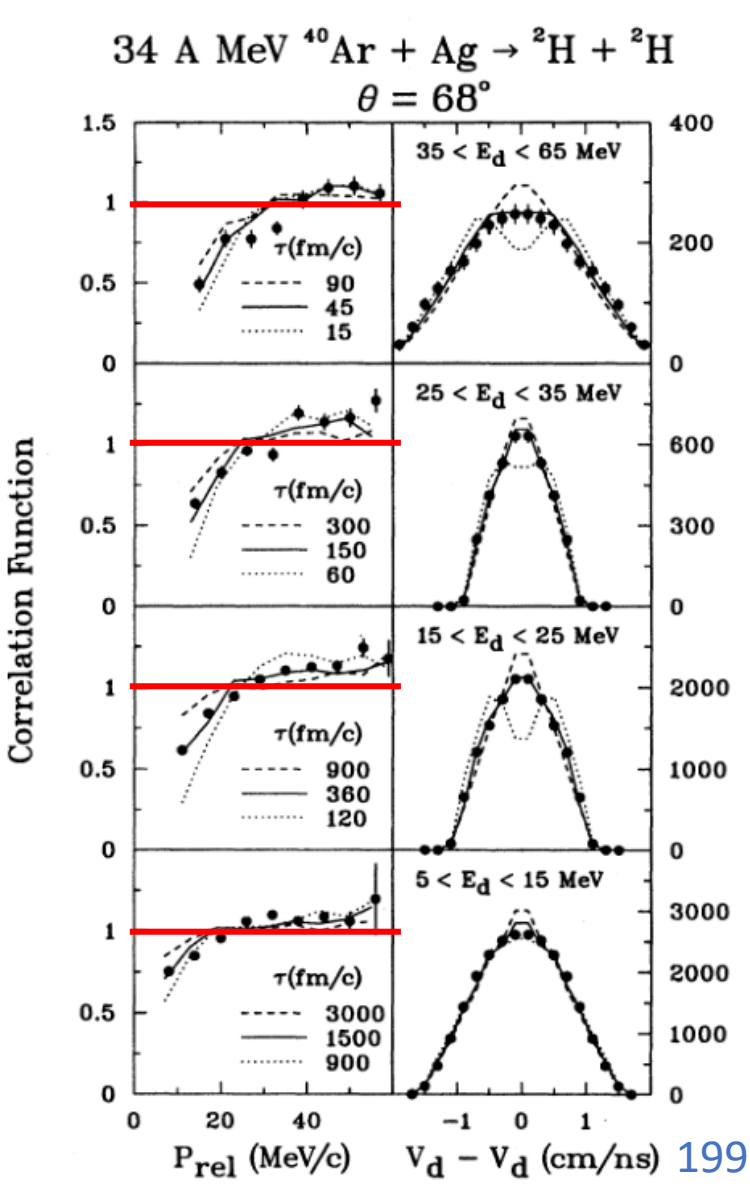
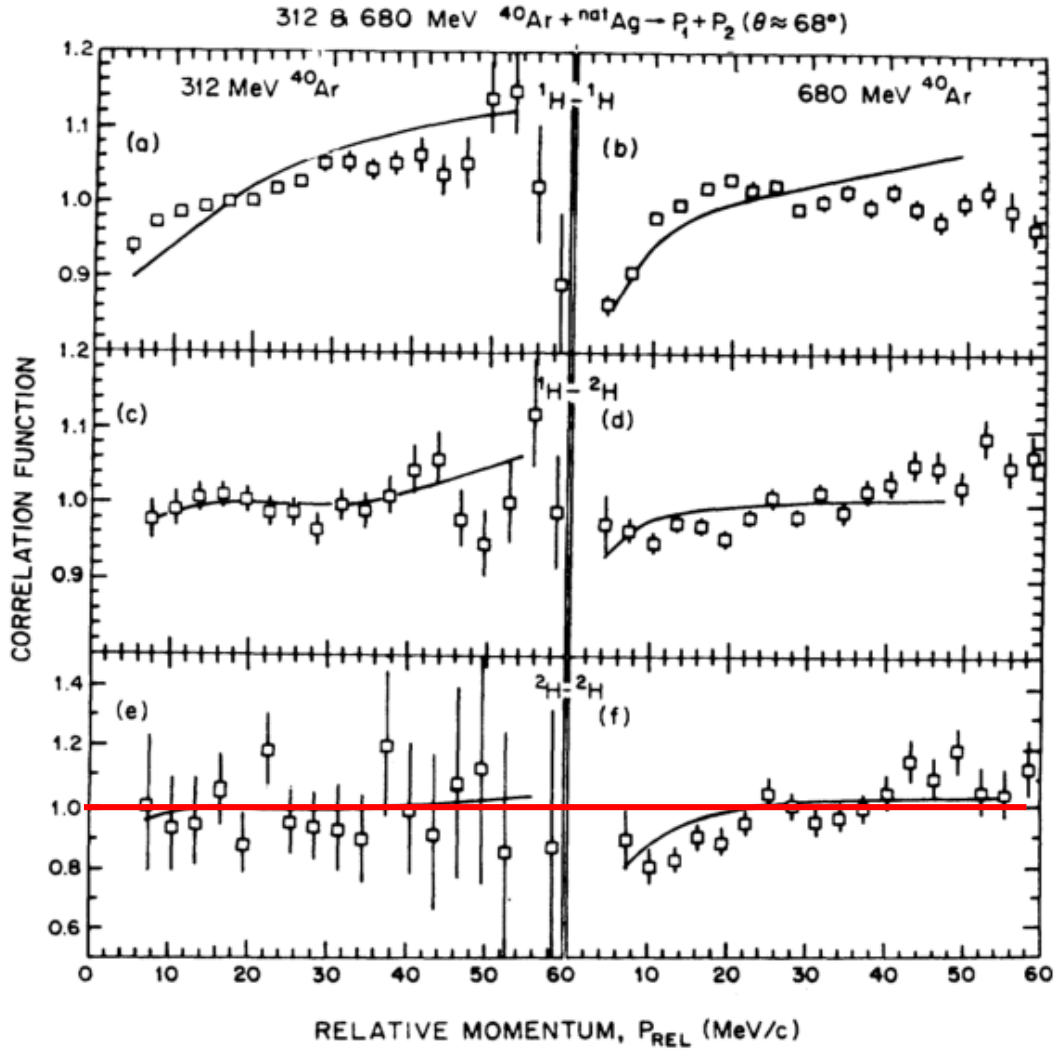


FIG. 13. p-d, d-d, t-t, t-^{3}He, and ^{3}He-^{3}He correlation functions.

1987_J. Pochodzalla_PhysRevC.35.1695

Deuteron-deuteron correlation function

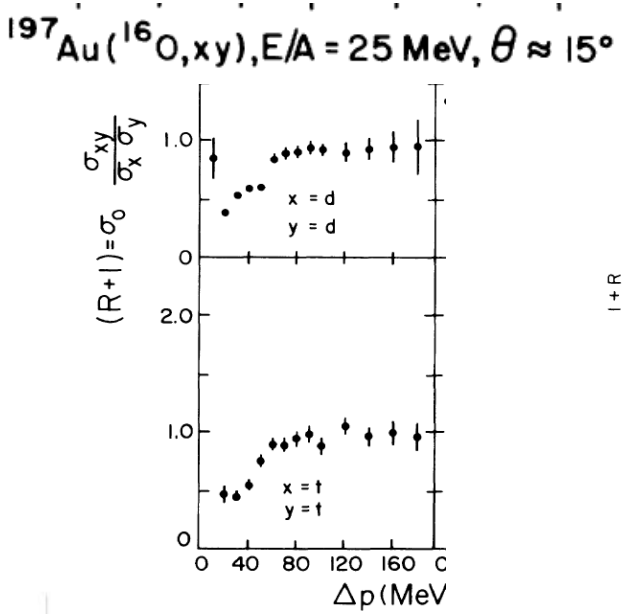


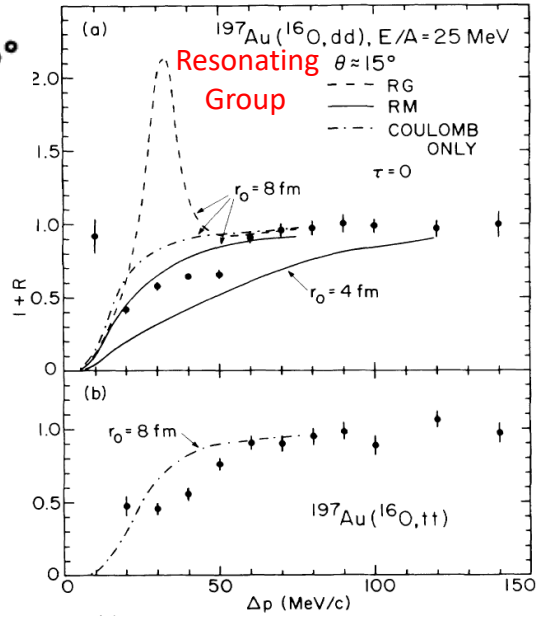


1991_A. Elmaani_PhysRevC.43.R2474

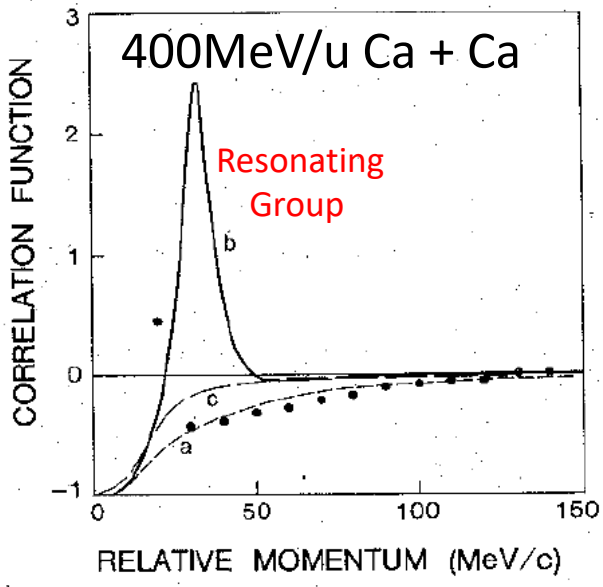
1995_C. J. Gelderloos_PhysRevC.52.R2834

Deuteron-deuteron correlation function

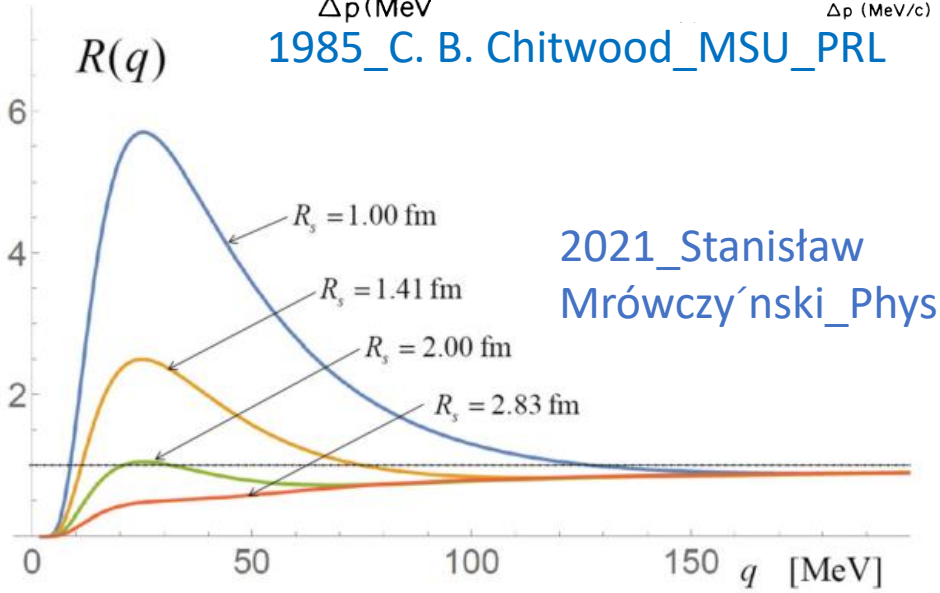




1985_C. B. Chitwood_MSU_PRL



1986_David H. Boal_PRC



2021_Stanisław Mrówczy´nski_PhysRevC.104.024909

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