

Experimental Study of Bremsstrahlung Gamma Ray Emission and Short-Range Correlations in Low- Energy Heavy-Ion Collisions

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[*Phys. Rev. Research* 7, 043174 \(2025\)](#) & [*Phys. Rev. C* 113, 044613 \(2026\)](#)

SRC-EMC Workshop 2026

08 - 12 June 2026

Lawrence Berkeley National Laboratory, CA, USA

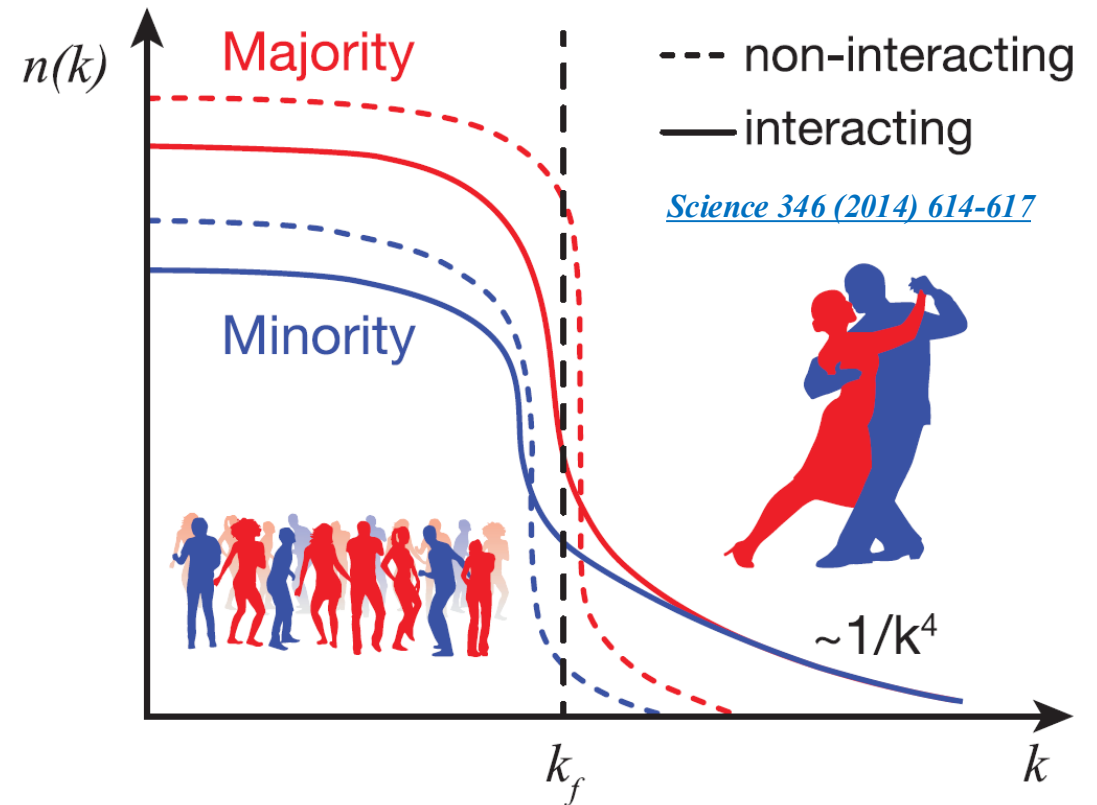
Short-Range Correlation (SRC)

◆ Nucleon Short-Range Correlations

- Nucleons in nuclei can form loosely bound deuteron-like pairs
- Dominated by neutron-proton (np) pairs
- Very small relative distance, very high relative momentum

◆ High Momentum Tail (HMT)

- Part of the nucleon momentum distribution extends beyond the Fermi Surface
- These high-momentum components cannot be explained by the mean field; they originate from SRC



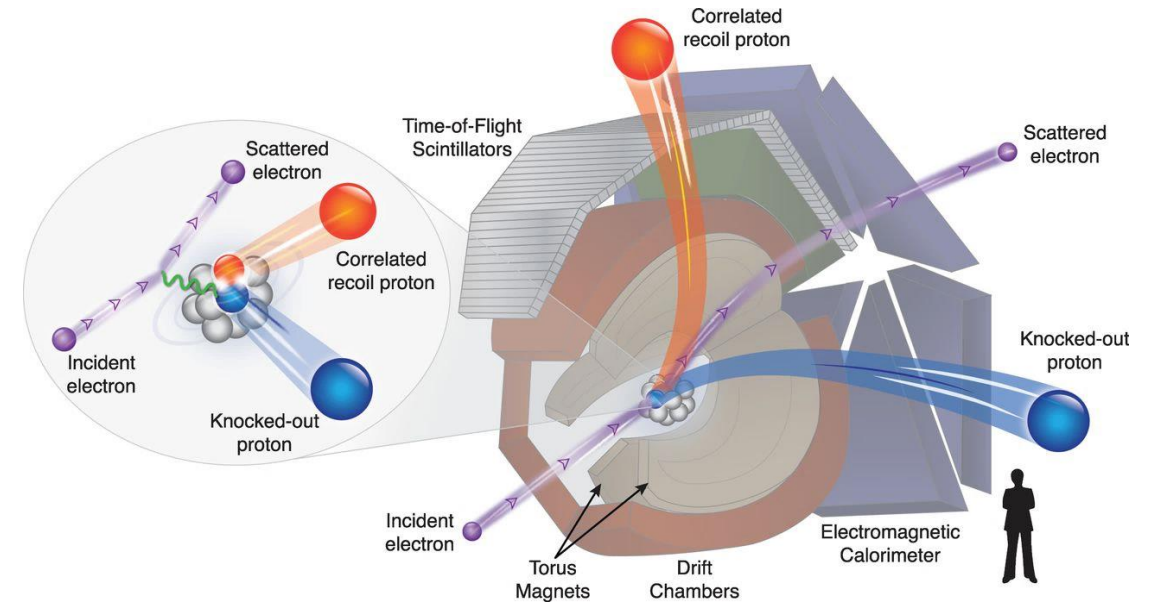
✓ Physical significance:

- closely related to the EMC effect
- SRC modifies the quark distribution inside nucleons
- linking nucleon structure to quark degrees of freedom [Phys.Rev.Lett. 133 \(2024\) 15, 152502](#)

Experimental Observations of SRCs

Main experimental method:

- Electron-nucleus scattering provides the benchmark for SRC studies.
 - Well-known of electromagnetic
 - Provide relatively precise SRC probes
 - ~20% of nucleons in heavy nuclei form np SRC pairs
- Proton-knockout and other reaction probes also support the SRC picture, but final-state interactions and model dependence make precision extraction harder.
- The real question is whether a **different reaction observable** can recover the same SRC scale in a clean and quantitative way.

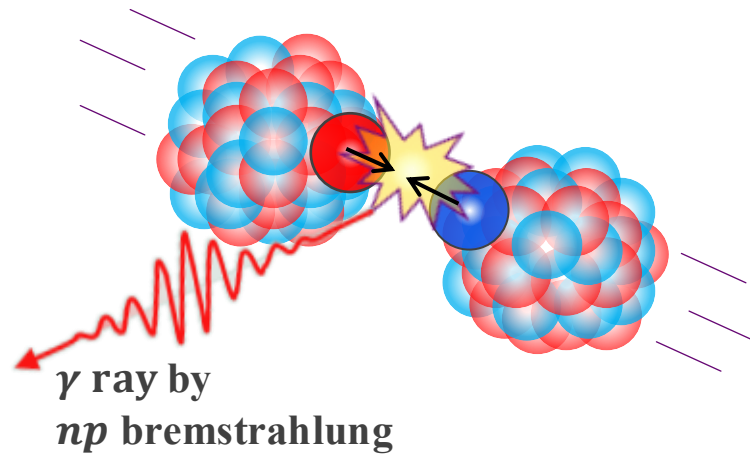


[*Science 346 \(2014\) 614-617*](#)

Motivation for this work:

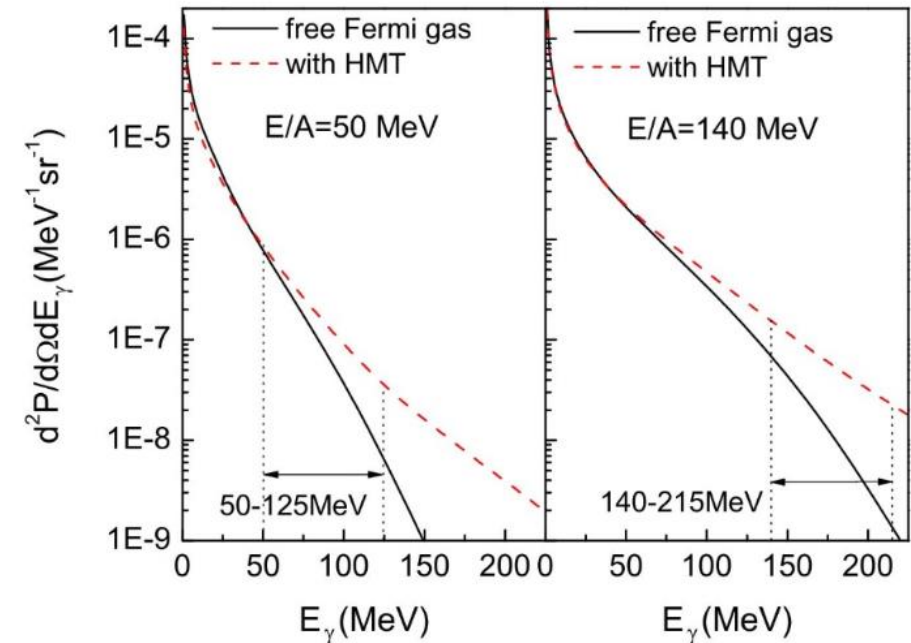
Can hard photons from heavy-ion collisions provide that clean reaction-based probe?

Bremsstrahlung gamma Energy Spectrum in Heavy Ion Collisions (HICs)



- High energy photons emitted from HICs (mainly from np bremsstrahlung)
- Photons are largely unaffected by the nuclear matters - clean probe

- SRCs enhance the high-momentum components
- γ -ray spectrum becomes harder due to HMTs



[Phys.Lett.B 755 \(2016\) 486-490](#)

IBUU-MDI Transport Model

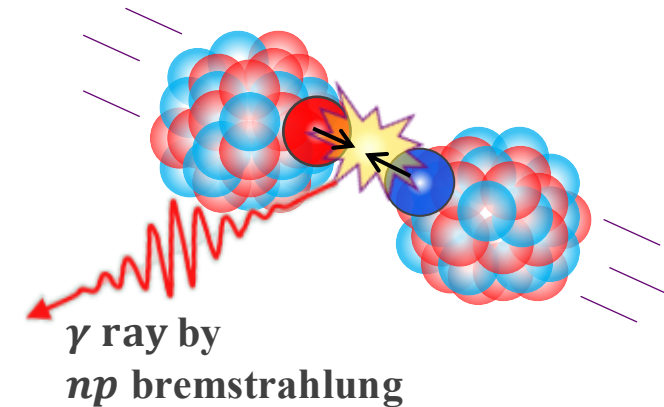
- Boltzmann-Uehling-Uhlenbeck (BUU) transport model

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{r}} f - \nabla_{\mathbf{r}} U \cdot \nabla_{\mathbf{p}} f = I_{\text{coll}}$$

- $f(\mathbf{r}, \mathbf{p}, t)$: Probability of finding a particle at time t with momentum \mathbf{p} at position \mathbf{r}
- U : Mean-field potential
- I_{coll} : Two-body collision term

- IBUU-MDI simulations:

- Incorporating isospin degrees of freedom
- Momentum-dependent nucleon interaction potential (MDI)
- **Initial single-nucleon momentum distribution** $n(k)$ that includes HMT (nucleon correlations during the collision process are not considered)



- Probability of photon production

$$\frac{d^2 P}{d\Omega dE_\gamma} = 1.67 \times 10^{-7} \times \frac{\left[1 - \left(\frac{E_\gamma}{E_{\text{max}}}\right)^2\right]^\alpha}{\frac{E_\gamma}{E_{\text{max}}}}$$

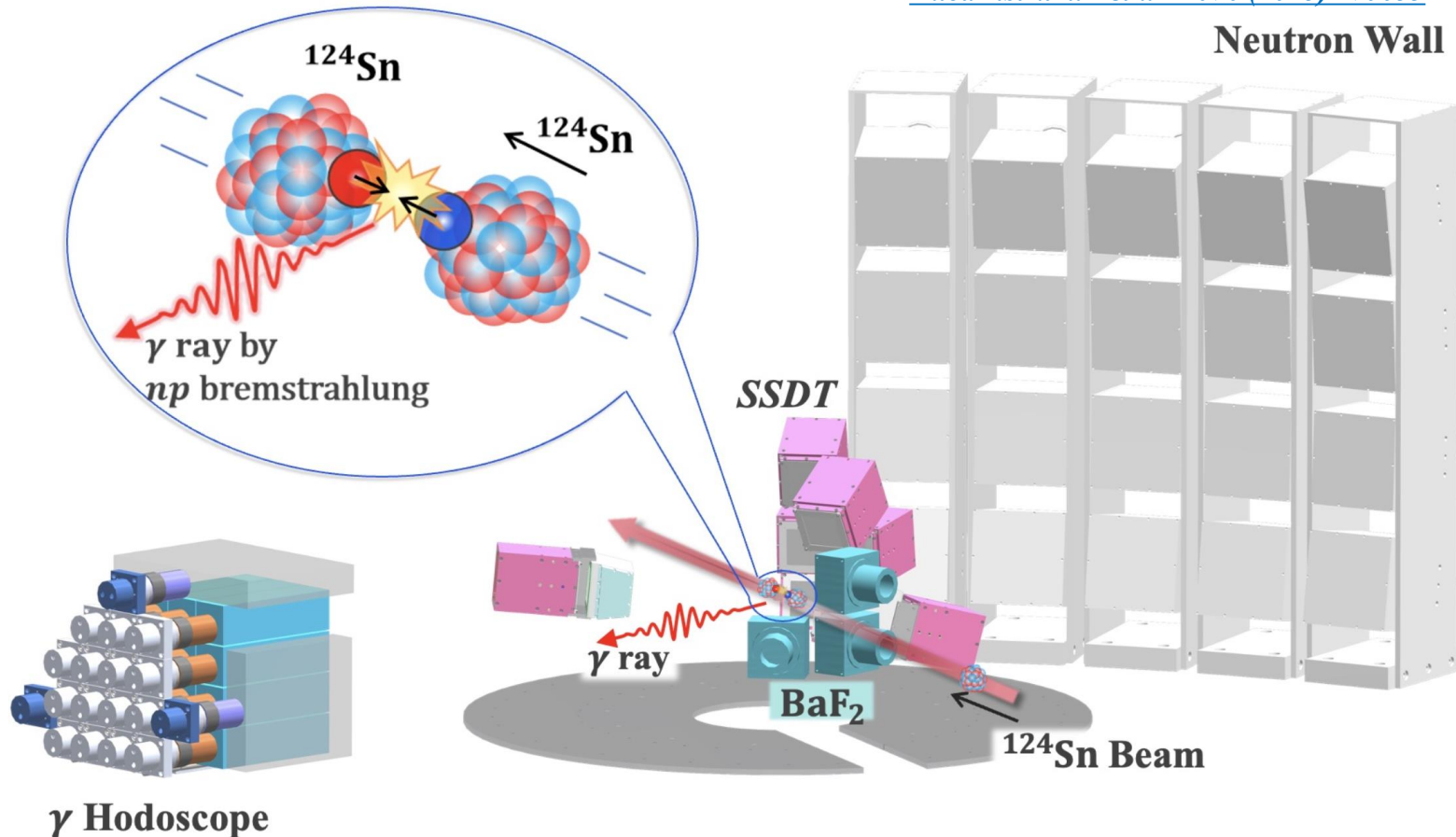
- E_γ : Energy of produced photon
- E_{max} : Total available energy of np (c.m.)
- $\alpha = 0.7319 - 0.5898\beta_i$, (β_i -nucleon velocity)

Compact Spectrometer for Heavy Ion Experiment (CSHINE)



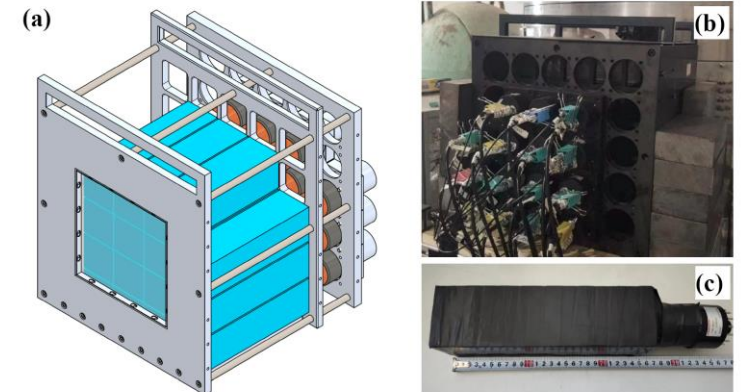
RIBLL1, HIRFL, IMP, Lanzhou

[Nucl.Instrum.Meth.A 1070 \(2025\) 170055](#)



[Nucl.Instrum.Meth.A 1029 \(2022\) 166461](#)

- Silicon-strip telescopes (SSDTs): Charged particles
- Neutron Wall: Neutrons
- BaF_2 : Start timing information
- γ hodoscope: Energetic bremsstrahlung γ -rays



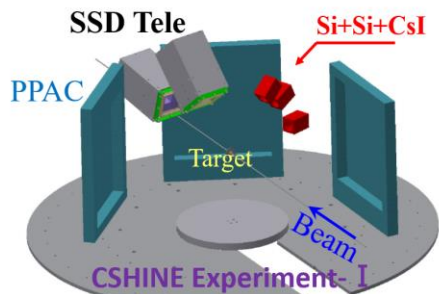
Resolution: $\sim 3\%$; Range: up to 100MeV

[Nucl.Instrum.Meth.A 1053 \(2023\) 168330](#)

CSHINE Experiments: proof of concept

30MeV/u $^{40}\text{Ar} + ^{197}\text{Au}$

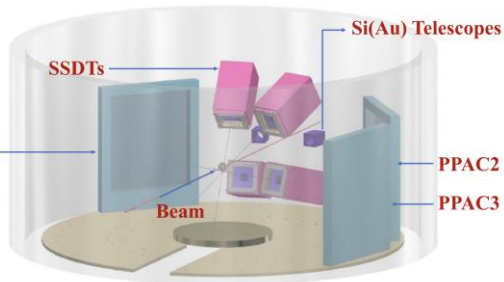
2018



[Nucl.Instrum.Meth.A 1011 \(2021\) 165592](#)

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

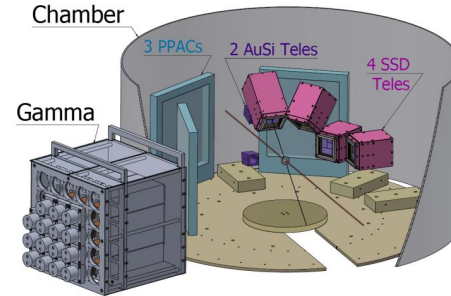
2019



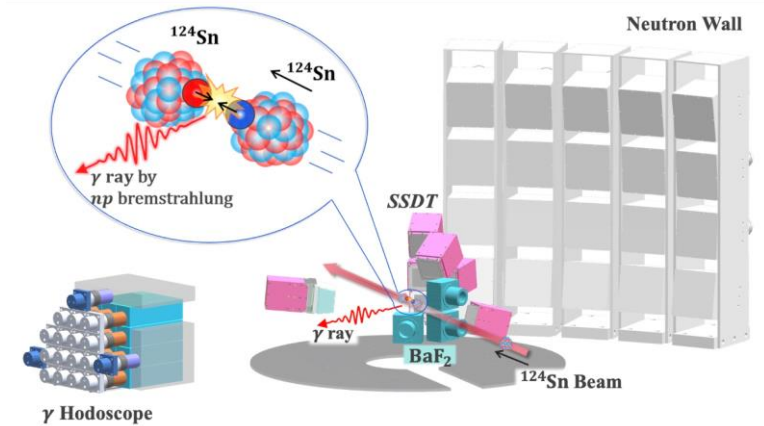
[Nucl.Sci.Tech. 33 \(2022\) 4, 40](#)

25MeV/u $^{86}\text{Kr} + ^{124}\text{Sn}$

2022



[Nucl.Instrum.Meth.A 1053 \(2023\) 168330](#)



[Nucl.Instrum.Meth.A 1070 \(2025\) 170055](#)

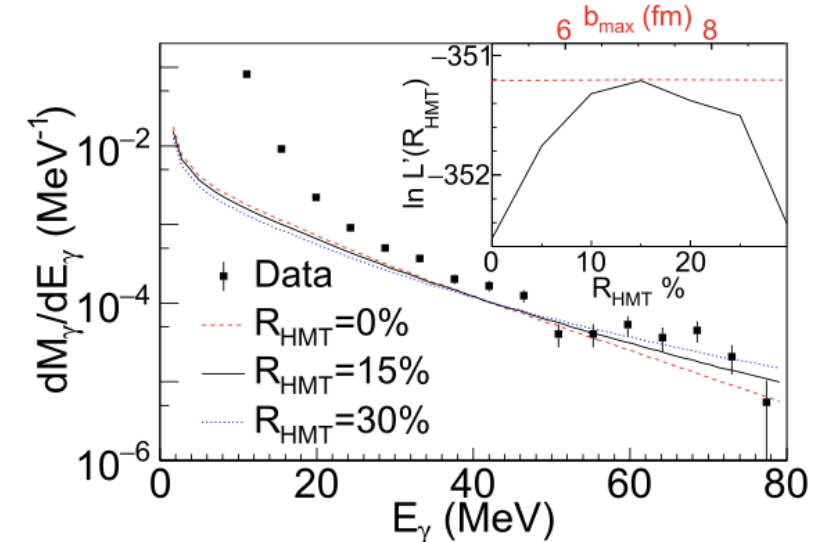
2024

25MeV/u $^{124}\text{Sn} + ^{124}\text{Sn}$

please look forward to...

- ✓ First time using the γ detection array in the CSHINE
- ✓ Successfully measured bremsstrahlung γ spectrum, revealing the presence of non-zero HMT [Phys.Lett.B 850 \(2024\) 138514](#) [Phys.Lett.B 857 \(2024\) 139009](#)

Limitations: 1. Low statistics and limited energy detection range
2. **Asymmetric collision system** prevents determination of nucleon SRC fraction in a specific nucleus

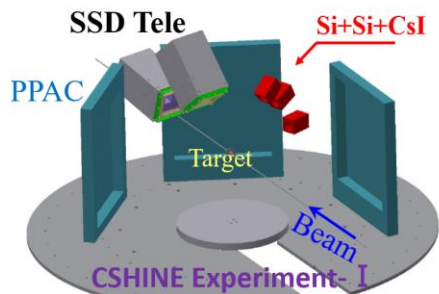


[Phys.Lett.B 850 \(2024\) 138514](#)

New Experiments of CSHINE

30MeV/u $^{40}\text{Ar} + ^{197}\text{Au}$

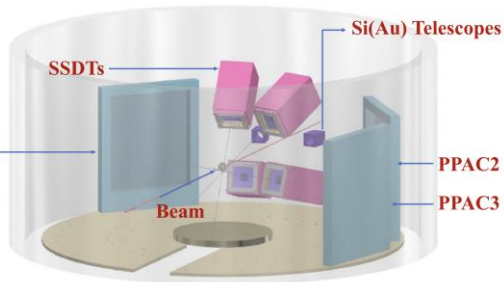
2018



[Nucl.Instrum.Meth.A 1011 \(2021\) 165592](#)

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

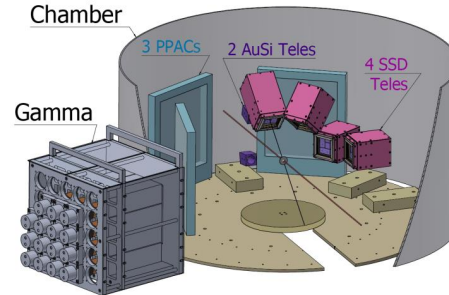
2019



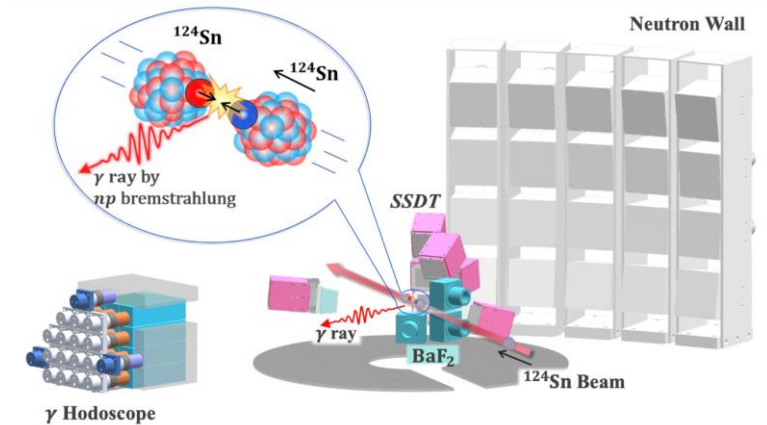
[Nucl.Sci.Tech. 33 \(2022\) 4, 40](#)

25MeV/u $^{86}\text{Kr} + ^{124}\text{Sn}$

2022



[Nucl.Instrum.Meth.A 1053 \(2023\) 168330](#)



[Nucl.Instrum.Meth.A 1070 \(2025\) 170055](#)

2024

please look forward to...

25MeV/u $^{124}\text{Sn} + ^{124}\text{Sn}$

Upgrades:

- Added plastic scintillator array
- improved noise suppression

❑ **Higher statistics:** better data reliability

❑ **Extended energy range:** (>100 MeV), improved HMT measurement

❑ **Symmetric Collision System:** SRC fraction in a specific nucleus

- **Goal:** Precisely confirm SRC via high-energy γ -rays

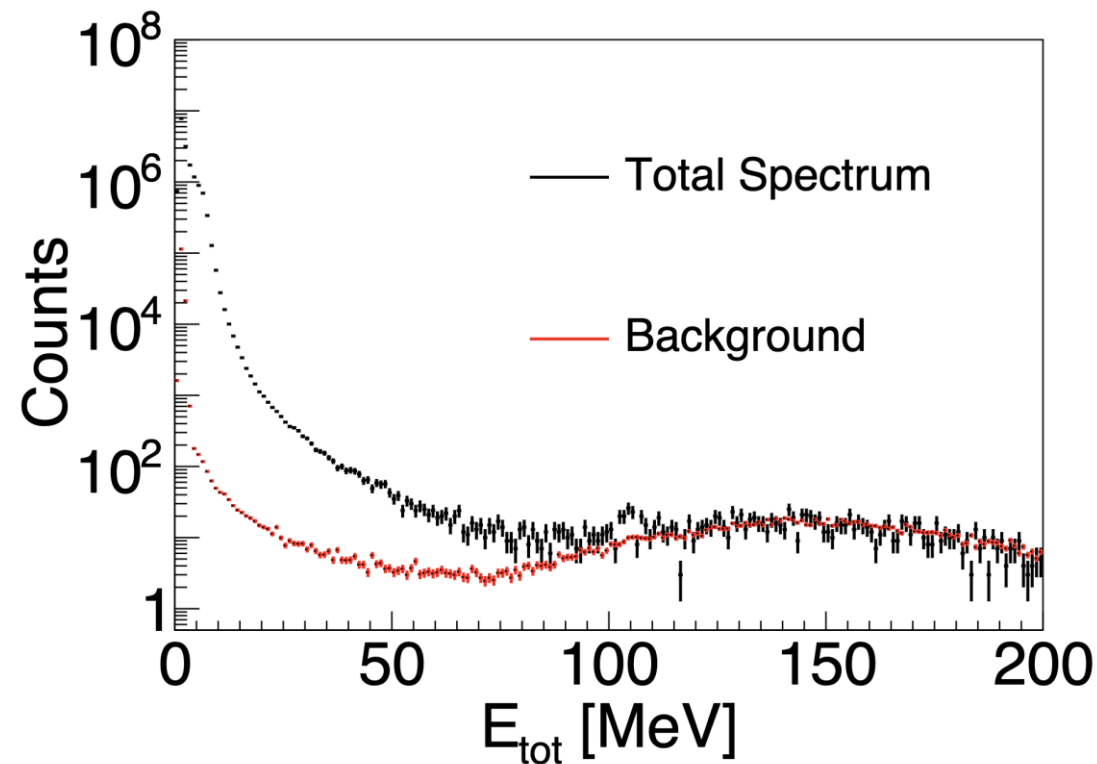
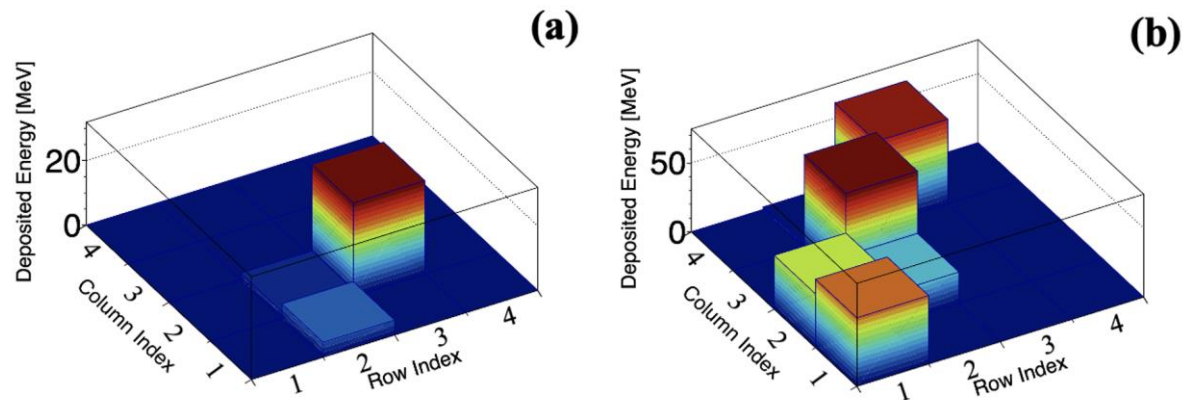
Reconstructions

□ *Reconstruction of events*

- The highest energy deposition – primary (core)
- Central 4 blocks of the array
Sum with 3×3 neighboring blocks (within 50 ns)
- Edge blocks of the array
No signal in the adjacent plastic scintillator veto detector

□ *Spectrum generation*

- Cosmic-ray event normalization: >110 MeV
- Subtract the scaled beam-off BKG spectrum from the beam-on spectrum



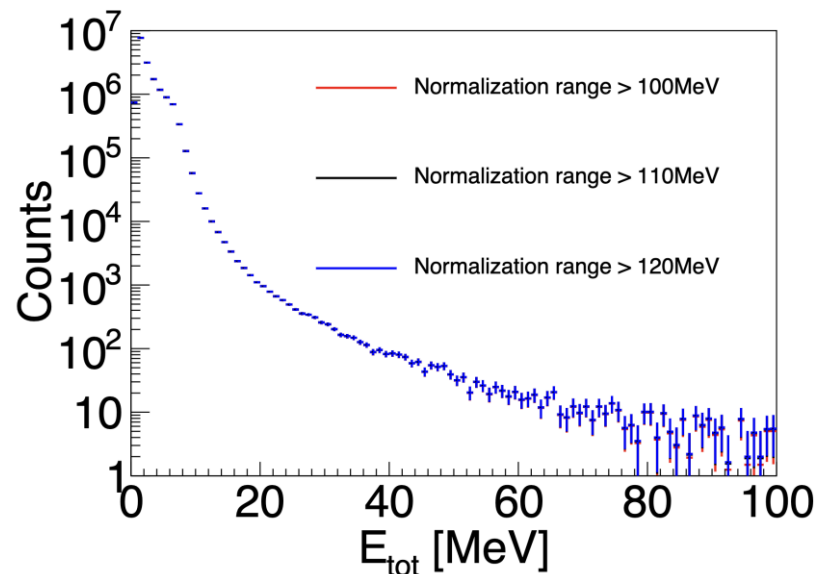
- Analysis window: 35–100 MeV

Error Analysis

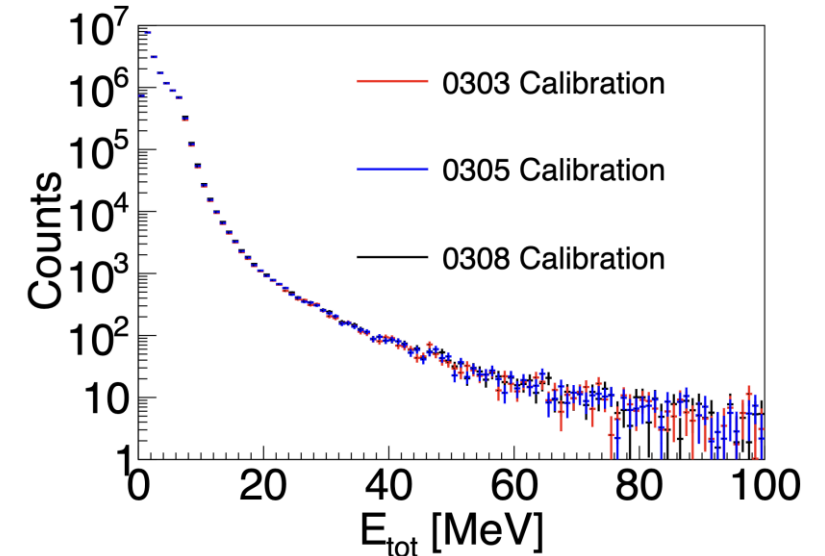
- ❑ **Statistic Errors:** Poisson distribution
- ❑ **Systematic Errors:** Calibration methods, trigger modes

(a) Cosmic-ray normalization: >110 MeV

- *no significant variations*

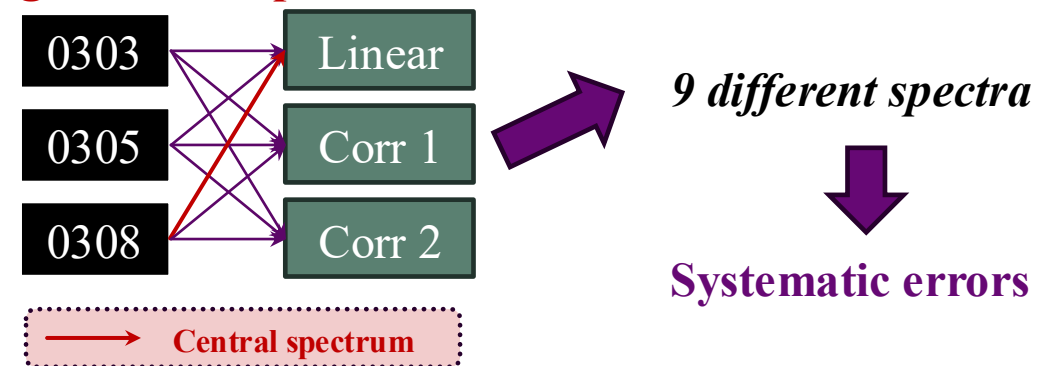


(b) Radioactive source calibration datasets from different measurements



(c) The detector response at higher γ energy levels (proved **approximately linear**) [Nucl.Instrum.Meth.A 1080 \(2025\) 170787](#)

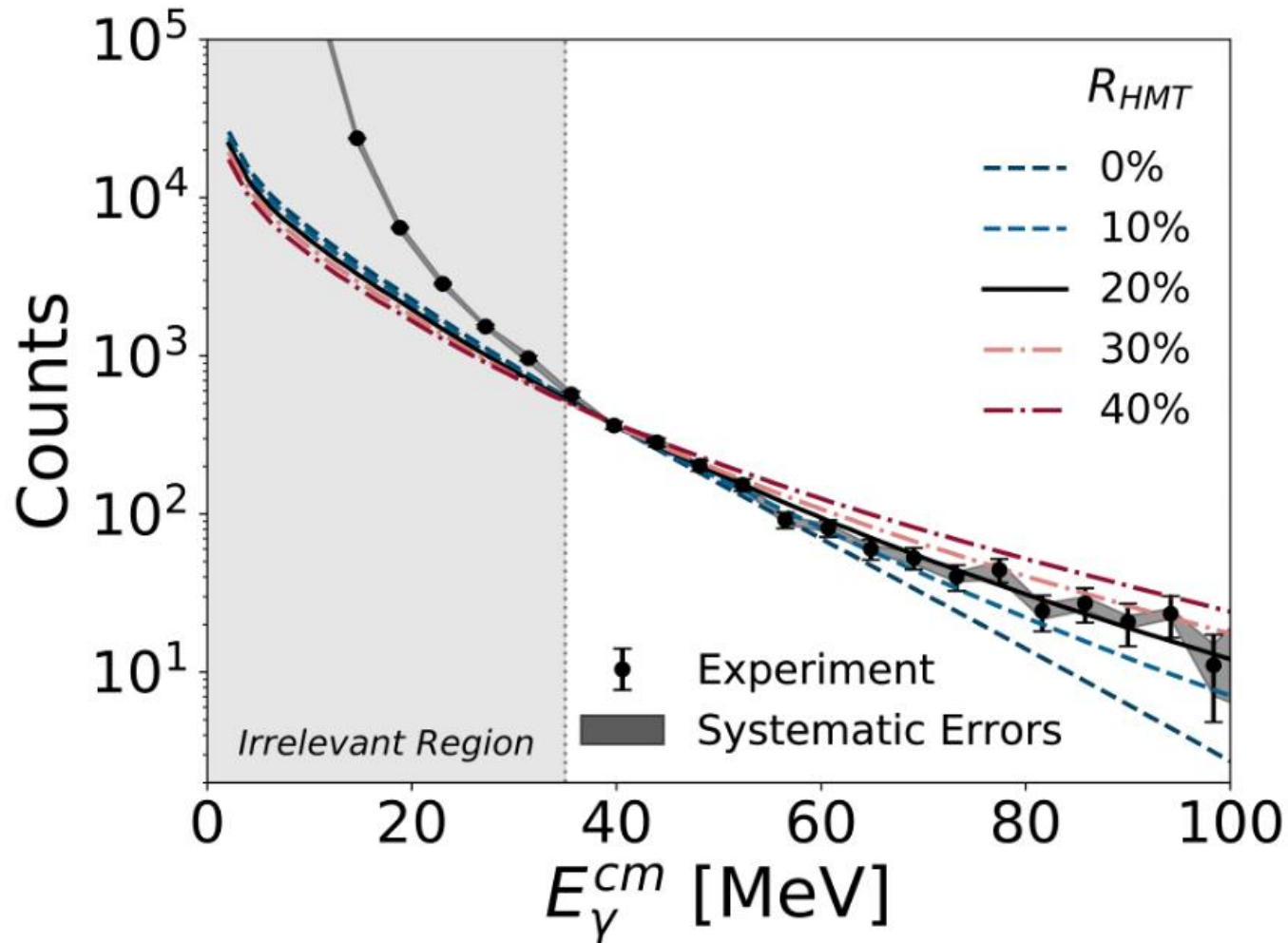
- **two kinds correction of typical response of higher energies with respect to linear**



(d) Spectra generated by events from different trigger modes

[Phys. Rev. C 113, 044613 \(2026\)](#)

Comparisons between Experimental and Theoretical Spectra



- Curves - IBUU simulation with detector filter
 - Dots – Experimental detected γ spectrum (statistical errors and systematic errors)
- ◆ Gamma rays <30 MeV are dominated by:
- collective resonances
 - statistical emissions
 - possibly residual radiation in the target chamber

◆ *Detector response matrix:*

$$D_{ij} = P_i(E_j)$$

- Obtained by Geant4 simulations
- The probability of a photon with a energy of E_j being detected as E_i

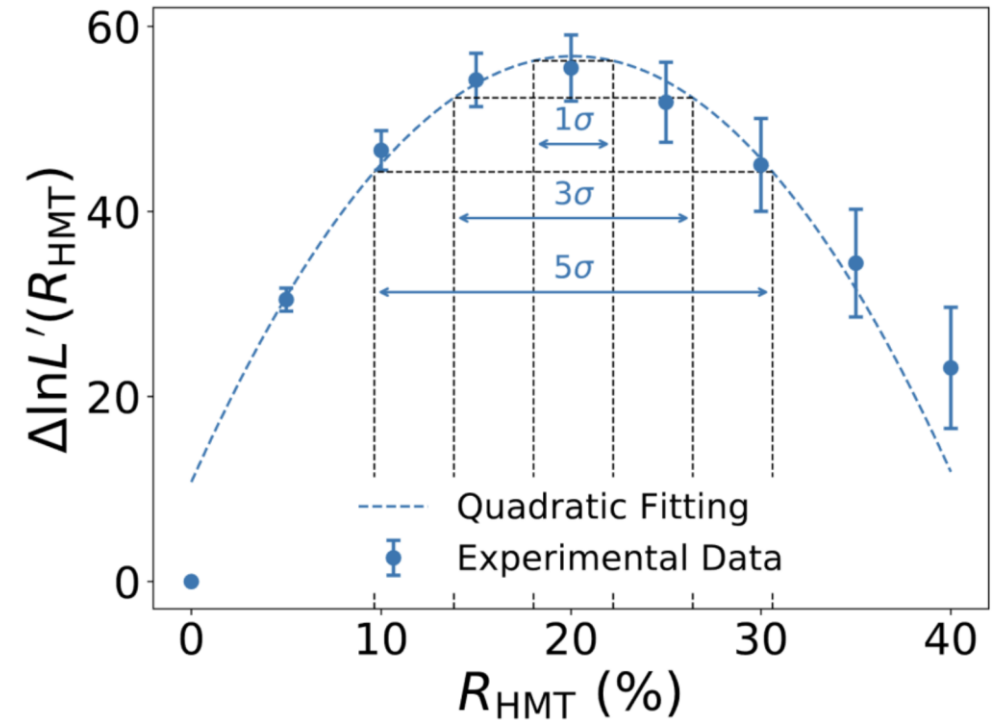
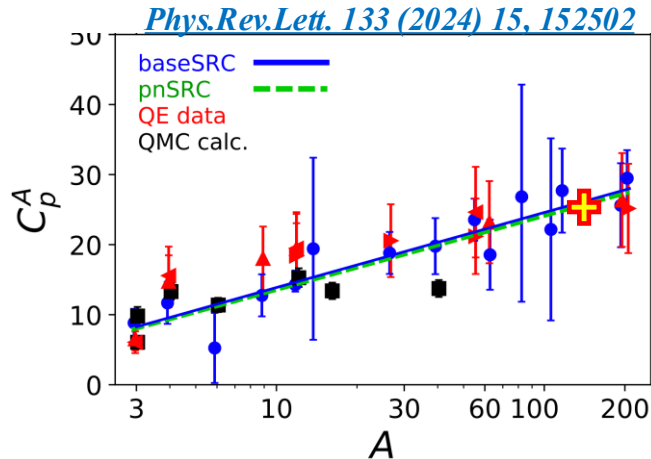
Extraction of R_{HMT} in nuclei through Maximum Likelihood Tests

➤ Likelihood function definition:

$$\ln L'(R_{\text{HMT}}) = \sum_i^{\text{range}} n_i \ln p_i(R_{\text{HMT}})$$

- n_i : counts of i th experimental data point
- p_i : probability (theoretical model predictions falling within the corresponding histogram bin of the experimental data)

➤ Energy range for analysis: 35 MeV – 100 MeV



■ The results of R_{HMT} (all systematic errors have been considered):

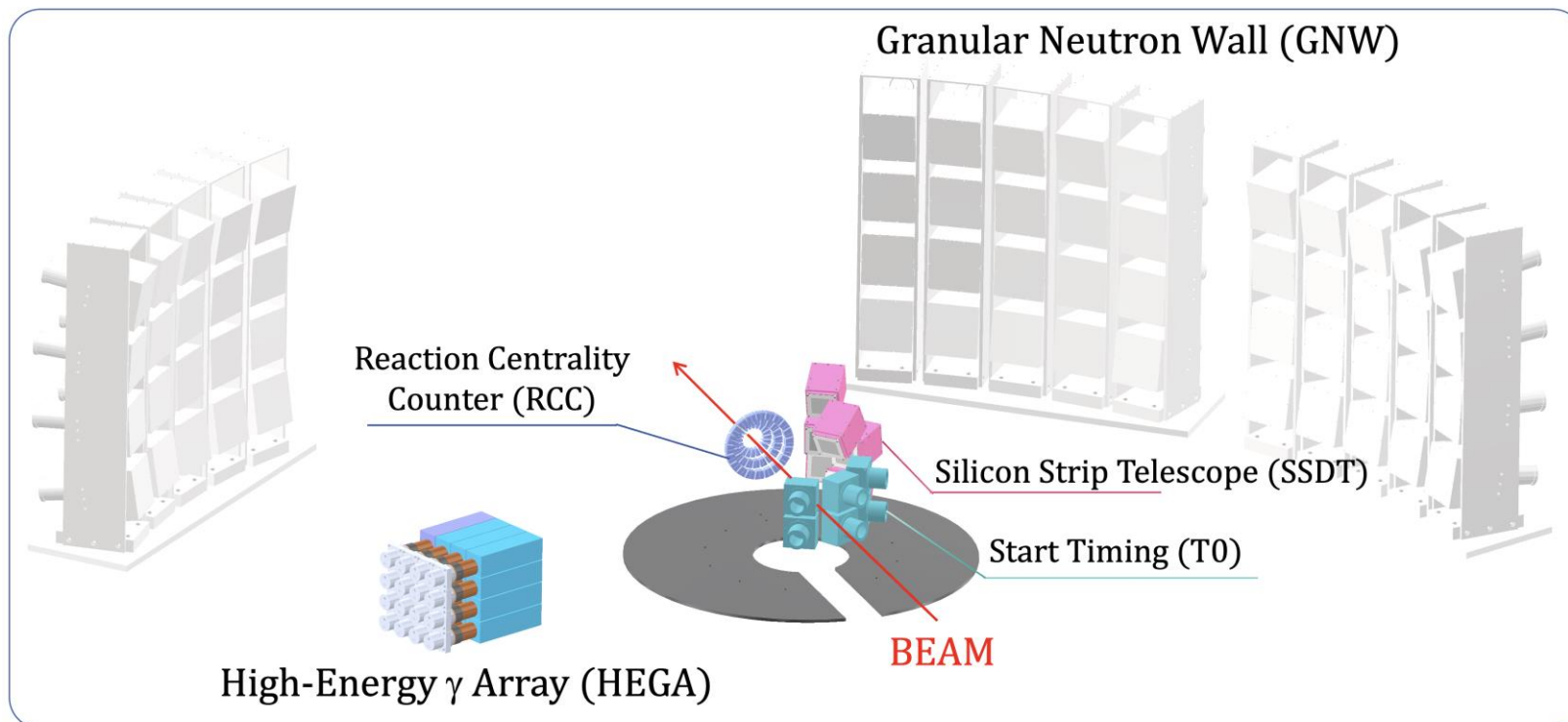
$$R_{\text{HMT}} = (20 \pm 3)\%$$

✓ consistent with the SRC scale established by electron scattering in heavy nuclei:

In ^{124}Sn ($A=124, \delta=0.194$), $C_n^{124}=16\%$, $C_p^{124}=24\%$, respectively!

CSHINE⁺ in the Future

CSHINE⁺ : Combinatory Spectrometer for Heavy Ion Experiment



◆ Main Research Goals

- Upgrade of neutron and SSDT arrays to measure $n - n$ and $p - p$ correlation functions

[*Phys.Rev.Lett.* 134 \(2025\) 22, 222301](#)

- Bremsstrahlung γ and SRC

[*Phys.Lett.B* 850 \(2024\) 138514](#)

[*Phys.Lett.B* 857 \(2024\) 139009](#)

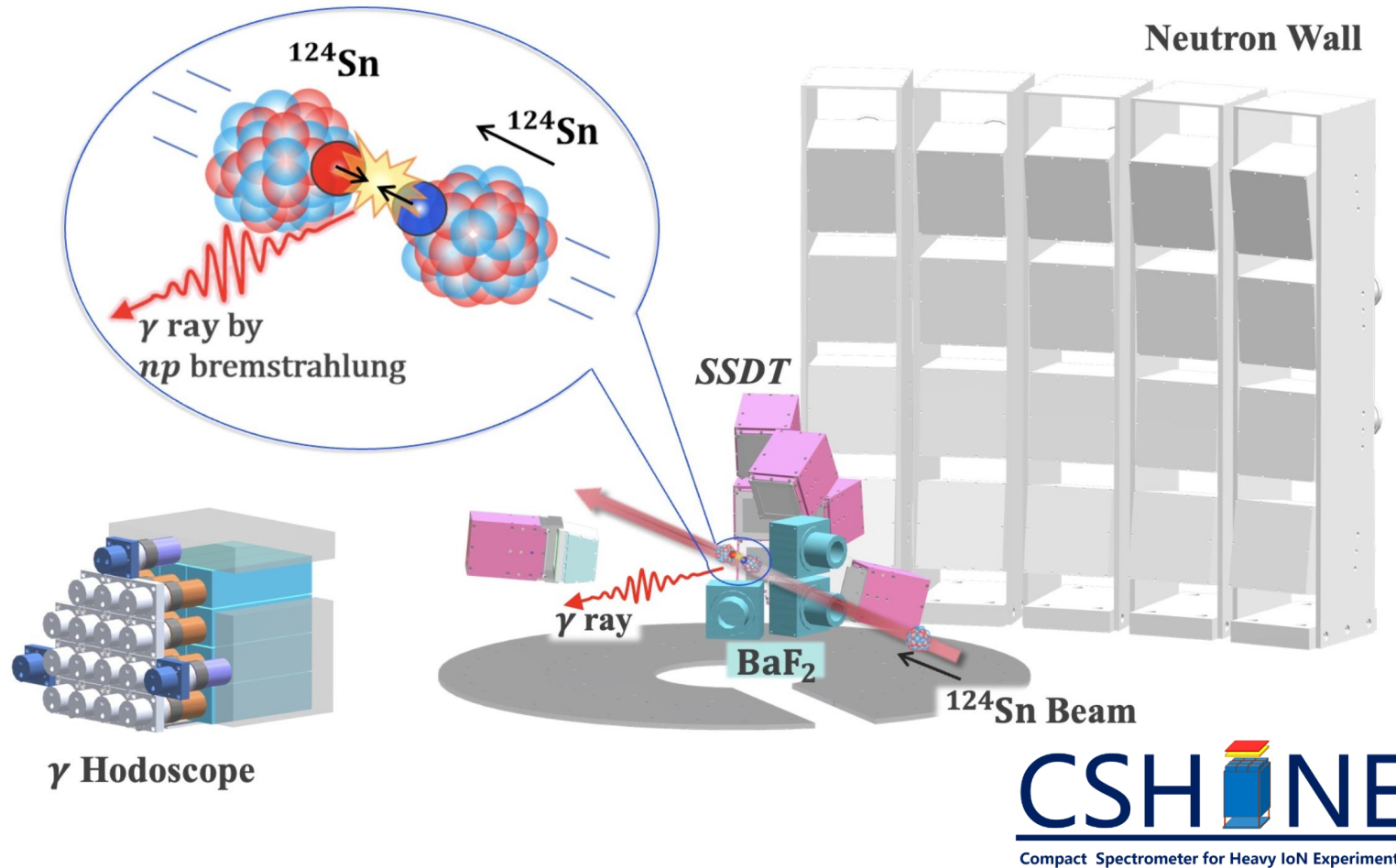
[*Phys. Rev. Research* 7 \(2025\), 043174](#)

[*Phys. Rev. C* 113 \(2026\), 044613](#)

- Precise measurement of **isospin dependence** of SRC in two symmetric collision systems
 - $^{124}\text{Sn}+^{124}\text{Sn}$
 - $^{112}\text{Sn}+^{112}\text{Sn}$
- $\gamma - \gamma$ correlation functions

Conclusions

- Low-energy heavy-ion collisions provide a novel method to measure SRC in nuclei
- Bremsstrahlung γ spectra reveal high-momentum components in nucleon momentum distributions beyond the Fermi surface
- IBUU simulations confirm that high-energy γ spectra are a sensitive probe of SRC.



- CSHINE experiment established the existence of SRC in nuclei with significance far exceeding 5σ , precisely measured the high-momentum component fraction in ^{124}Sn :

$$R_{\text{HMT}} = (20 \pm 3)\%$$

- Opens a new experimental approach to study nucleon structure and quark-level dynamics

- **Future work:** systematic measurements with symmetric systems $^{124}\text{Sn}+^{124}\text{Sn}$ and $^{112}\text{Sn}+^{112}\text{Sn}$

*Thanks !
Any Questions?*

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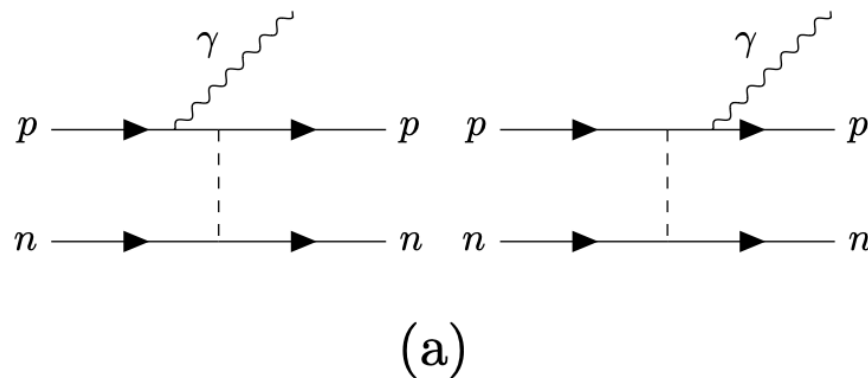
Back up

Bremsstrahlung process

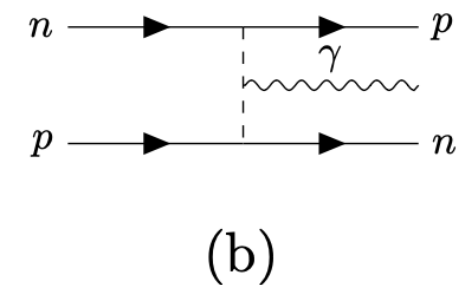
The bremsstrahlung reaction channel is incorporated into the collision processes within the IBUU model, which employs the **Bertsch criterion** and **Pauli exclusion principle** to determine whether a NN collision occurs.

1. proton-proton collisions ($pp\gamma$): dominates as the dipole moment in a charge-symmetric pp system vanishes. The **lowest-order multipole radiation** in the pp collisions is of **quadrupole type**, whose intensity is much lower compared to the dipole radiation in the np collisions

2. neutron-proton collisions ($np\gamma$):

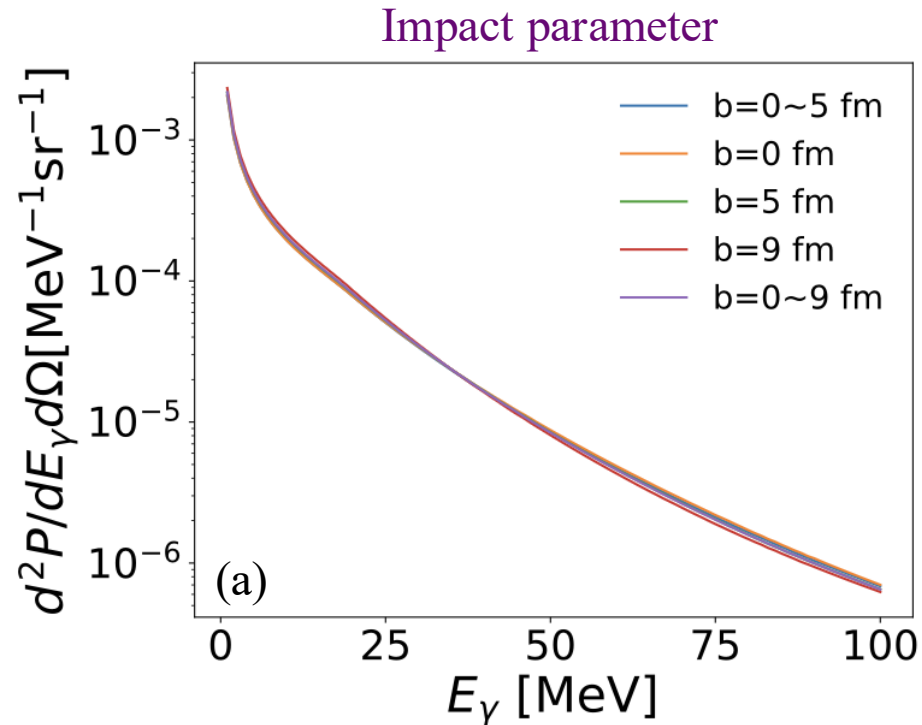


(a) In the intermediate energy range, we adopt the neutral scalar σ meson exchange model, in which the photons are emitted via the **external processes**

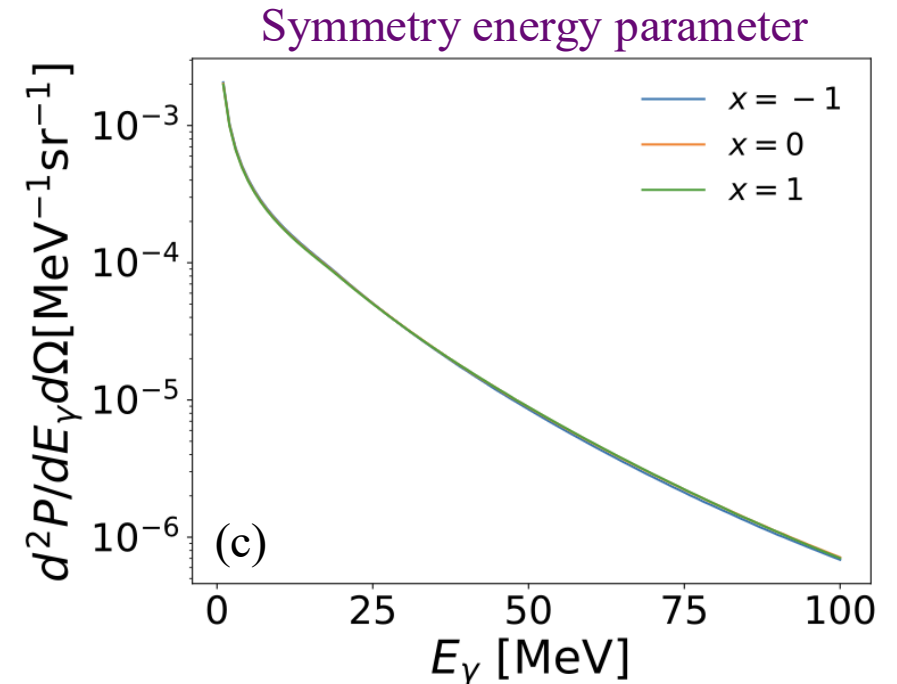
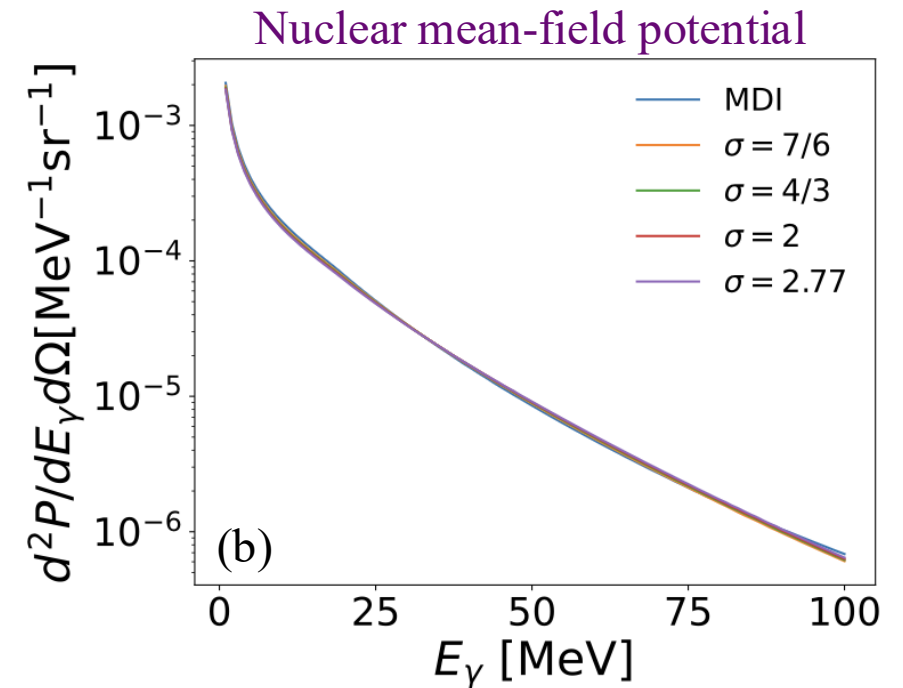


(b) At higher energies, consider charged meson exchange processes. The photons can also be emitted from the **internal mesons**, to which the electromagnetic field also couples

Parameter influence test of IBUU



Result: **Spectrum shape remains unchanged** — bremsstrahlung photons interact with nucleons purely electromagnetically, making them insensitive to both isoscalar and isovector components of nuclear interactions.



Definition of High-momentum Components

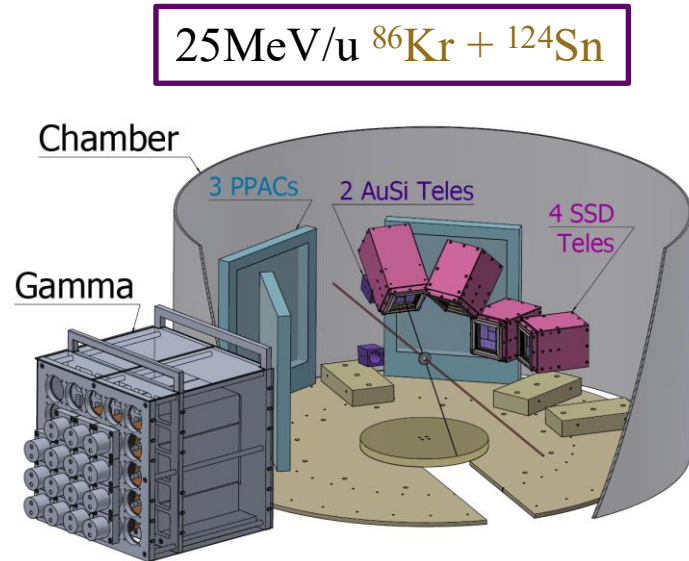
For asymmetric nuclear matter (ANM), the high-momentum component is linearly dependent on the isospin asymmetry. The $n(k)$ for ANM is parametrized as

$$n_{\text{ANM}}(k)_p = \begin{cases} B, & k \leq k_F^p, \\ C(1 + \delta)/k^4, & k_F^p < k \leq \lambda k_F^p, \\ 0, & k > \lambda k_F^p, \end{cases}$$
$$n_{\text{ANM}}(k)_n = \begin{cases} B', & k \leq k_F^n, \\ C(1 - \delta)/k^4, & k_F^n < k \leq \lambda k_F^n, \\ 0, & k > \lambda k_F^n, \end{cases}$$

where k represents the single nucleon momentum. k_F is Fermi momentum and λ is the high-momentum cutoff, and the parameters B and B' are determined by the normalization condition,

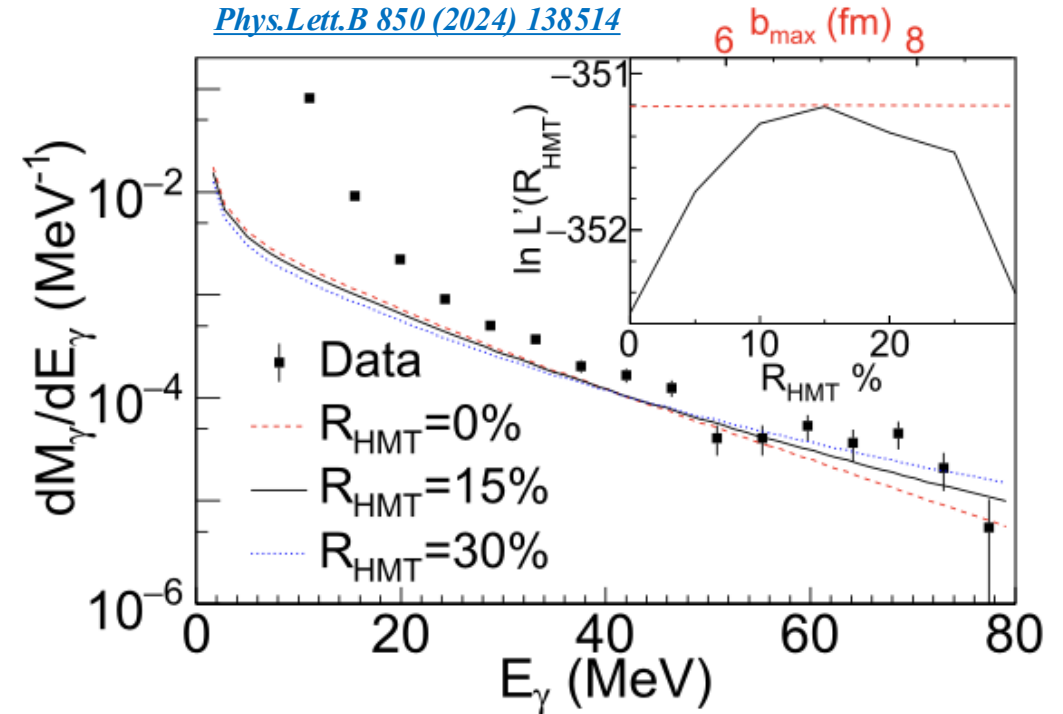
$$4\pi \int_0^\infty n_{\text{ANM}}(k)_{p(n)} k^2 dk = 1.$$

Previous Experiment Results



[Nucl.Instrum.Meth.A 1053 \(2023\) 168330](#)

- ✓ Successfully measured bremsstrahlung γ -ray spectrum
- ✓ $R_{\text{HMT}} \sim 15\%$ (35–80 MeV) from IBUU-MDI model comparison [Phys.Lett.B 850 \(2024\) 138514](#)
- ✓ Reconstructed original spectrum without detector effects, suggesting $R_{\text{HMT}} \sim 25\%$ [Phys.Lett.B 857 \(2024\) 139009](#)



Experimental limitations:

- Low statistics \rightarrow large uncertainties in the γ spectrum
- Limited energy detection range \rightarrow reduced ability to distinguish between theoretical curves
- Asymmetric collision system \rightarrow cannot determine nucleon SRC fraction in a specific nucleus

Calibration method and its systematic errors

- Lack of high-energy γ -ray sources
- Risk in low-energy calibration extrapolation
- Need to cover a wide dynamic range

- ✓ Radioactive calibration with the high gain (**ADC-XE**)
- ✓ Calibrate the high-energy γ -ray with the low gain (**ADC-E**)

□ Calibration Step:

- Step1: Linear calibration of ADC-XE with ^{60}Co (1.17MeV, 1.33MeV) and ^{232}Th (2.61MeV):

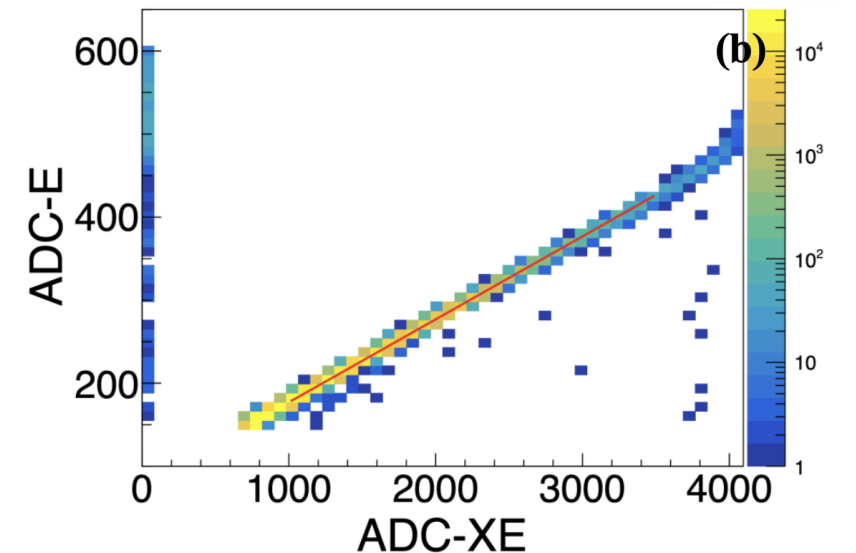
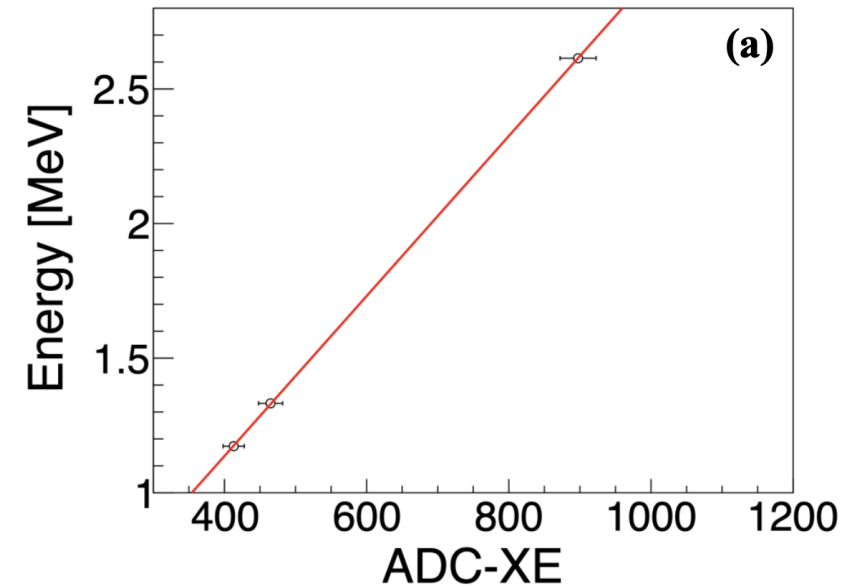
$$E_{\gamma} = a\text{CH}_{\text{XE}} + b$$

- Step2: Bridge the linear relationship between **ADC-E** and **ADC-XE**:

$$\text{CH}_{\text{E}} = \alpha\text{CH}_{\text{XE}} + \beta$$

- Step3: Combine results to link E_{γ} with CH_{E} , enabling detection of high-energy γ signals with the low gain

$$E_{\gamma} = \frac{a}{\alpha}\text{CH}_{\text{E}} + \frac{b\alpha - a\beta}{\alpha}$$



- The calibration method introduces about 2%~4% nonlinear **systematic errors**