

Precise measurement of short-range correlations in nuclei from bremsstrahlung gamma-ray emission in low-energy heavy-ion collisions

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Atomic nuclei and dense nucleonic matter in neutron stars exhibit short-range correlations (SRCs), where nucleons form temporally correlated pairs in close proximity beyond mean-field approximation. It is essential to make precision measurement of the fraction of SRC since it carries the signature of underlying quark dynamics in nuclear medium. In this article, we present the first high-precision measurement of neutron-proton bremsstrahlung γ -ray emission from the symmetric $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions at 25 MeV/u. From the observed spectral hardening, the precise SRC fraction in the ^{124}Sn nucleus is extracted to be $(20 \pm 3)\%$. This result provides a statistically unambiguous evidence of SRCs and demonstrates that low-energy heavy-ion collisions offer an approach to studying nuclear structure in connection with quark-level dynamics.

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I. INTRODUCTION

As a typical strongly correlated system in nature, nucleonic matter, composed of protons and neutrons, exhibits extremely complex many-body dynamics. Among these, some nucleons form short-range correlations (SRCs) [1,2], which are temporal fluctuation effects that go beyond the mean-field approximation. SRCs in nuclei have been experimentally observed and provide an explanation for the high-momentum tail (HMT) observed beyond the Fermi surface in nucleon momentum distributions [1,3]. These high-momentum components significantly influence the properties of asymmetric nucleonic matter [4–7] created in neutron stars and heavy-ion collisions (HICs). Therefore, the precise measurement of SRCs is key to understand the dense nucleonic matter as well as the intrinsic nuclear structure.

Studies indicate that SRCs are primarily characterized by proton-neutron pairs in the isosinglet ($T = 0$) channel at short distances, favoring ud diquark isosinglet and spin-singlet configurations [8]. These structural features of SRCs have been shown to significantly influence the EMC effect in nuclei [9–12], establishing a direct link between short-range nucleon correlations and quark-level modifications of nuclear structure [2,13–17]. Furthermore, a recent global analysis based on the QCD factorization scheme has extracted the universal effective parton distribution function (PDF) within SRC pairs and the mean-field fraction using a variety of high-energy data [18]. These findings suggest that SRC can offer valuable insights into the quark dynamics in nuclei, serving as a potential bridge between nuclear structure and the underlying partonic degrees of freedom.

Heavy-ion collisions provide a means to study the manifestation of short-range nucleon correlations, complementing traditional probes such as electron- and proton-induced reactions [1,3,19–24], which have been the primary sources of our current understanding of SRCs. The insights gained from HICs regarding SRCs are crucial for understanding the microscopic properties of dense matter, for instance, the cooling mechanism of protoneutron stars [7]. During the collision of two heavy nuclei, two-body nucleon-nucleon collisions generate bremsstrahlung γ rays, primarily through neutron-proton scattering $np \rightarrow np\gamma$ [25–27]. SRCs modify the internal structure of nuclei by introducing an HMT in

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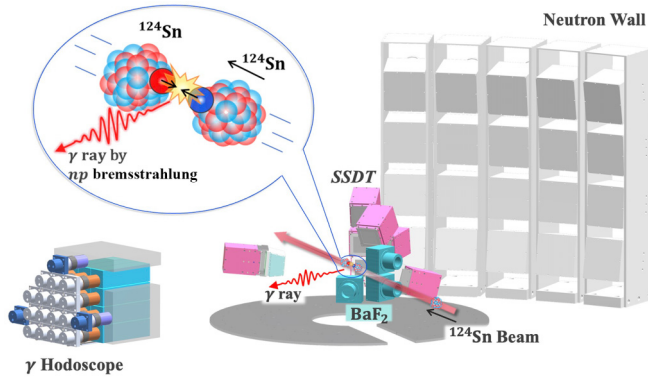


FIG. 1. An illustration of the CSHINE detector setup. A schematic view of an $^{124}\text{Sn} + ^{124}\text{Sn}$ event is plotted, involving the np collision that emits a bremsstrahlung γ ray, subsequently detected by the CsI(Tl) hodoscope with three surrounding plastic scintillators.

the single-nucleon momentum distribution. When two such nuclei collide, these high-momentum nucleons participate in the reaction with higher average kinetic energies than those in a pure mean-field configuration. As a result, the nucleon-nucleon bremsstrahlung photons generated via $np \rightarrow np\gamma$ during the collisions exhibit a harder γ -ray spectrum, especially at high-energy end [28]. In comparison to the hadron probes [29–33], the high-energy γ rays are minimally affected by the nuclear medium, making them a clean and sensitive probe for detecting SRC effects in HICs [28,34,35].

The bremsstrahlung photon production in HICs can be simulated by isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [36], adopting momentum-dependent interaction (MDI) [37]. The proportion of nucleons with momenta above the Fermi surface is measured by HMT fraction (R_{HMT}) [28]. By comparing model predictions with experimental γ -ray spectrum, the value of R_{HMT} can be effectively constrained. In our previous experiment involving $^{86}\text{Kr} + ^{124}\text{Sn}$ collisions, the bremsstrahlung γ -ray spectrum was measured, suggesting a nonzero R_{HMT} induced by SRCs [38,39]. The results showcased the potential of bremsstrahlung γ -ray emission as a probe of SRC in nuclei.

This article reports on a statistically precise measurement of bremsstrahlung γ rays from $^{124}\text{Sn} + ^{124}\text{Sn}$ at 25 MeV/u with significantly enhanced statistics and extended high-energy end of the spectrum. The γ -ray spectrum is analyzed using the IBUU-MDI transport model incorporating the $np \rightarrow np\gamma$ process. The use of a symmetric reaction allows for an unambiguous extraction of R_{HMT} in the ^{124}Sn nucleus.

II. EXPERIMENT

The experiment [40] was performed on Radioactive Ion Beam Line 1 at the Heavy Ion Research Facility in Lanzhou (HIRFL). The products from the reaction of 25 MeV/u $^{124}\text{Sn} + ^{124}\text{Sn}$ were measured by the Compact Spectrometer for Heavy Ion Experiment (CSHINE) [41–44]. Figure 1 presents the detector setup. The charged isotopes of $Z \leq 5$ were identified by six silicon-strip detector telescopes covering $20^\circ < \theta_{\text{lab}} < 60^\circ$ in partial azimuth [45,46]. Neutrons are

detected by a 4×5 array of plastic scintillator installed at 2.0 m to the target. With four fast BaF_2 γ detectors surrounding the target delivering starting time (T_0) information, neutrons can be discriminated from the γ rays [41,47]. Besides, a liquid scintillator neutron detector of $\phi 348 \text{ mm} \times 1020 \text{ mm}$ is mounted at 513 cm to the target (not shown in Fig. 1).

To measure the energetic bremsstrahlung γ rays from the reactions on the target, a 4×4 CsI(Tl)-based hodoscope has been mounted [48]. Each unit has a dimension of $70 \times 70 \times 250 \text{ mm}^3$. Three plastic scintillators were installed surrounding the CsI(Tl) hodoscope to veto the cosmic ray background as well as the γ events with energy leaking to the outside. A dual-range amplifier was applied to record the small and large energy signals, and then the response of each CsI(Tl) unit was calibrated by a dual-range method [49].

The data acquisition was triggered by requiring that at least two particles be recorded by the detectors in six different combinations, enabling a cross-check of the γ spectrum under various trigger conditions and with different background-subtraction methods. For further details, please refer to an upcoming comprehensive paper [40].

After calibrating the CsI(Tl) hodoscope, the energy deposits are reconstructed event by event. In each triggered event, the reconstruction algorithm identifies the clustered CsI(Tl) hits coincided in a $|\Delta T| < 50 \text{ ns}$ time window and led by a “core” corresponding to the largest energy deposit. The energy range of each individual CsI(Tl) unit was optimized in order to reach the maximum γ -ray energy deposit of 100 MeV in the hodoscope. The background, which mainly includes cosmic-ray muons and residual γ radiation at low energies, was measured when the beam was off.

The γ events and the penetrating cosmic muon events can be distinguished by their topological characteristics. Generally, an incident high-energy γ ray loses most of the energy in the “core” unit with possibly small leakage to the neighboring units, while a cosmic-ray muon fires multiple units in row with similarly large energy deposit and leaves a long “track” along the flying path. Figures 2(a) and 2(b) present a typical γ -ray event and a penetrating cosmic muon event, respectively.

Specifically, one can further distinguish these two by inspecting the spatial spread of the signal distribution δ_y and the energy deposit in the event core E_{core} . Here, $\delta_y = \sum E_i |y_i - \bar{y}| / E_{\text{tot}}$ denotes the variance of the spatial distribution of the fired units in vertical direction [48]. E_i and y_i are the energy deposit and the vertical position of the i th fired unit, respectively. E_{tot} is the total reconstructed energy and $\bar{y}$ is the signal centroid of the fired units. Figures 2(c)–2(f) illustrate the scattering plots of δ_y [panels (c) and (d)] and E_{core} [panels (e) and (f)] as a function of E_{tot} in beam-on (left) and beam-off (right) measurements. For the beam-on events [panels (a) and (c)], two dominant components are clearly visible. One is the γ event in small spatial extension δ_y and in the vicinity of $E_{\text{core}} \approx E_{\text{tot}}$. The other is dominated by the cosmic muon characterized by large δ_y and $E_{\text{tot}} > E_{\text{core}}$. The latter exhibit similarity with those observed in the beam-off measurement shown in panels (d) and (f), in accordance with the picture that the cosmic-ray muon fires multiple units in row with similar energy loss. Low-energy events ($E_{\text{tot}} < 30 \text{ MeV}$) with multiple hits mainly result from statistical residual γ emission.

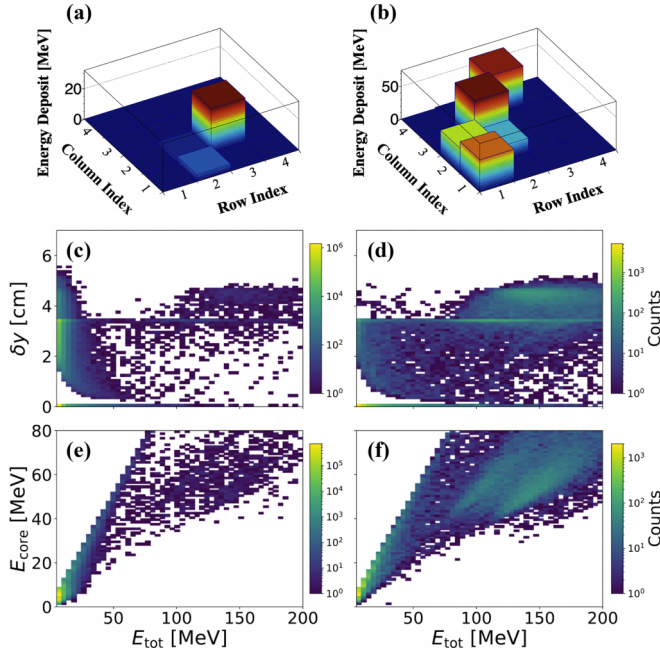


FIG. 2. Topological features of the γ event and the cosmic-ray muon event. A typical event display of a high-energy γ from the reaction [panel (a)] and of a cosmic muon penetrating through the γ hodoscope [panel (b)]. Vertical spatial spreading δ_y as a function of the total reconstructed energy E_{tot} for beam on (c) and beam off (d). Correlation between the energy deposit in the event core E_{core} and E_{tot} for beam on (e) and beam off (f).

Figure 3 presents the total energy spectra in beam-on (black) and beam-off (red) measurements. The minimum multiplicity condition $M = 2$ defines a nuclear reaction on the target with peripheral events well suppressed [50]. No further fine selection on the impact parameter b is done, since the spectrum shape shows insignificant dependence on b [38]. The beam-off background is scaled to match the beam-on spectrum using the counts above 110 MeV. The pure γ -ray spectrum in laboratory can be obtained by subtracting the scaled background spectrum from the total spectrum, as

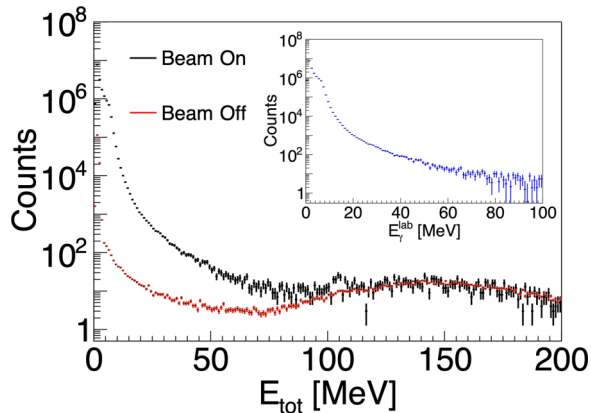


FIG. 3. The experimental γ energy spectrum in laboratory measured with beam on (black), compared to the background spectrum with beam off (red), normalized to the counts above 110 MeV. The inset displays the background-subtracted γ spectrum in laboratory.

displayed in the inset. It is noted here that the spectrum is affected by detector efficiency, and hence the theoretical spectra must be filtered by the detector response before comparison can be made (see next). The detector filter matrix, describing the response of the CsI(Tl) hodoscope to γ rays of varying energies in laboratory, was generated using Geant4 simulations [48].

The main systematic uncertainty of the spectrum originates from detector calibration with the linear response assumption, as the radioactive sources cover energies below 3 MeV, while the bremsstrahlung γ rays may deposit tens of MeV in a single CsI(Tl) unit. Higher-energy γ -ray beam test was conducted to characterize the nonlinearity of the CsI(Tl). As a result, the detector response correction functions were obtained to quantify the deviations from linear calibration. The uncertainty brought by the linear calibration is within 4% [49].

III. RESULTS AND DISCUSSIONS

The IBUU transport model [51–53] simulates nucleus-nucleus collisions and has been extended to include isospin degrees of freedom [54] and momentum-dependent nucleon interaction potential (MDI) [37]. The SRC and HMT effects are merely introduced in the initialization of single-nucleon momentum distribution $\rho(k)$ [28,54], provided that inclusion of SRC effect during the collision process is extremely challenging in the transport model. It has been shown that the high-momentum components with $k > 2 \text{ fm}^{-1}$ in the nucleon momentum distributions for different nuclei from ^3He to ^{208}Pb are proportional to that of deuteron [55], which roughly exhibits a $1/k^4$ tail [1,5,56,57]. In a simplified scheme, for the asymmetric nuclear matter (ANM), the high-momentum component depends linearly on the isospin asymmetry δ [6,58,59]. Counting all the possible correlated pairs (np , pp , and nn), the single-nucleon momentum distribution $\rho(k)$ for ANM is parameterized as

$$\rho_N(k) = \begin{cases} B_N, & k \leq k_F^N, \\ \eta(1 + s\delta)/k^4, & k_F^N < k \leq \lambda k_F^N, \\ 0, & k > \lambda k_F^N, \end{cases} \quad (1)$$

where the subscript or superscript N denotes either a proton ($s = +1$) or a neutron ($s = -1$), k is the single-nucleon momentum, k_F is the Fermi momentum, and λ is the high-momentum cutoff [28]. The Fermi momenta are calculated by the local Thomas-Fermi relation, yielding $k_F^p \approx 1.3 \text{ fm}^{-1}$ for protons and $k_F^n \approx 1.4 \text{ fm}^{-1}$ for neutrons. Given the HMT fraction R_{HMT} , the constants B_N and η are determined by $4\pi \int_0^\infty \rho_N(k) k^2 dk = 1$ and $4\pi \int_{k_F}^\infty \rho_N(k) k^2 dk = R_{\text{HMT}}$, respectively. Based on Eq. (1), the momentum distribution of finite nuclei is then obtained by applying the local density approximation.

It is worth noting that, in the present study, the low-momentum component is approximated by a step-function distribution, while the high-momentum component is modeled as a $1/k^4$ tail. These two components are joined at the Fermi momentum. While this simplified parametrization captures the essential physical features of the single-nucleon momentum distribution, the region near the Fermi surface—where both long-range and short-range correlations

contribute—could be further refined. Microscopic frameworks, such as the generalized contact formalism [60,61] and the low-order correlation operator approximation [62], could be applied in future studies to provide a more consistent description of the nucleon momentum distribution. Currently, the step-function approximation only minimally affects the results, as only a small fraction of nucleons near the Fermi surface are sampled in the Monte Carlo simulations.

The bremsstrahlung γ production channel is incorporated in the N - N collision processes governed by the Bertsch criterion [63] and Pauli exclusion principle. Due to the low production rate of the bremsstrahlung γ , its impact on the nucleon kinematics is negligible. Perturbation method is then employed to calculate the photon production probability in each np collision. Based on the one boson exchange model, a well-fitted formula is applied to calculate the elementary double differential γ production probability [27],

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

Here, E_γ represents the energy of produced photons and $E_{\max}$ is the total available energy in the center-of-mass (CM) frame of the colliding np pair. The coefficient α reads $\alpha = 0.7319 - 0.5898\beta_i$, where β_i is the nucleon velocity. The total γ yield per event is obtained by summing over all photon-producing np collisions during the reaction. The γ spectrum shows minimal dependence on the nuclear mean field, impact parameter, and symmetry energy in the test, as expected because bremsstrahlung photons are predominantly emitted in the early stages and interact only electromagnetically.

Figure 4(a) illustrates the rebinned experimental γ spectrum in CM frame. The black dots indicate the central values with statistical errors, while gray bands represent systematic uncertainties. Several key theoretical curves, filtered by the detector response matrix, are presented for comparison. Unlike our previous experiment [38,39], the γ detector array was operated here in active triggering mode, preventing the determination of the number of np collisions in HICs for normalizing the γ spectrum. Therefore, the comparisons with model predictions focus on spectral shape rather than absolute yield. Theoretical spectra were uniformly scaled by 2.5×10^9 to match the data range, without affecting R_{HMT} extraction based on the maximum likelihood analysis (MLA) (see below).

The MLA was performed to compare the model prediction with the experimental data, using the likelihood function [38] defined as

$$\ln L'(R_{\text{HMT}}) = \sum_i^{\text{range}} n_i \ln p_i(R_{\text{HMT}}), \quad (3)$$

where n_i denotes the count in the i th experimental bin and i sums over the bins within the statistical analysis interval. The quantity p_i represents the probability that the theoretical model predictions fall into the corresponding histogram bin under the specified statistical analysis interval for a given R_{HMT} . The γ rays below 30 MeV are dominated by collective resonances, statistical emissions, and possibly residual radiation in the target chamber. Accordingly, the analysis was restricted to the range of interest $35 < E_\gamma^{\text{cm}} < 100$ MeV

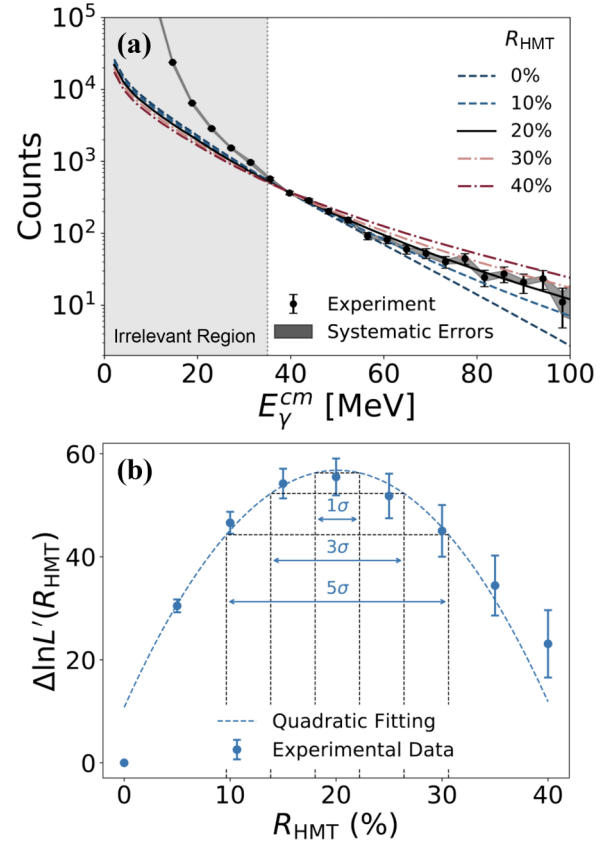


FIG. 4. (a) Comparison of the rebinned experimental γ spectrum (black dots) in CM reference with various detector-filtered theoretical curves. Statistical (systematic) uncertainties are denoted by vertical bars (gray bands). (b) Likelihood distribution as a function of R_{HMT} with quadratic fit (dashed curve). The error bars represent the standard deviation of likelihood values by varying the calibration and detector response data sets. Several main confidence levels are indicated.

to evaluate the likelihood between experimental spectra and IBUU-MDI predictions for different R_{HMT} values.

The results are shown in Fig. 4(b). The likelihood corresponding to the theoretical curve with $R_{\text{HMT}} = 0\%$ was selected as the reference point ($\ln L'(R_{\text{HMT}} = 0\%) = 0$). The relative likelihood values, $\Delta \ln L'(R_{\text{HMT}})$, for all other points were calculated relative to this baseline. A quadratic fit over $R_{\text{HMT}} = 5\% - 35\%$ is conducted as shown by the blue dashed curve. The optimal value $R_{\text{HMT}} = (20.1 \pm 2.1)\%$ is extracted. Considering the variation brought by fitting procedure and by using different scheme of background subtraction, the final constraint writes $R_{\text{HMT}} = (20 \pm 3)\%$. As a test of the look-elsewhere effect, the optimal R_{HMT} value is unchanged against the variation of the low limit of E_γ^{cm} from 33 to 44 MeV.

The result reveals a potential paradigm to probe the PDF of nucleon in nuclei (nPDF) via low-energy HICs. According to the collinear factorization scheme [18], the nPDF parametrization is composed of a linear combination of PDFs of free nucleons and of SRC pairs, with the fraction fully encapsulated in the ratio of neutrons (protons) in SRC pairs C_n^A (C_p^A). With $R_{\text{HMT}} = 20\%$ in ^{124}Sn ($A = 124$, $\delta = 0.194$), one writes $C_n^{124} = 16\%$ and $C_p^{124} = 24\%$, respectively, in

accordance with the results obtained from high-energy data [18]. The result also underscores the need for further systematic experimental studies of higher-energy γ -ray production in HICs. Interestingly, based on very similar mechanism of the presence of HMT, subthreshold particle production in proton-nucleus collisions is proposed recently as a probe of SRC in nuclei [64].

IV. SUMMARY

This work presents the first quantitative evidence of short-range correlations in low-energy heavy-ion collisions, based on the highest-quality measurement to date of neutron-proton bremsstrahlung γ rays up to 100 MeV in symmetric $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions at 25 MeV/u. This resolves a long-standing puzzle from the 1980s regarding the origin of high-energy γ rays in such collisions [65] and establishes bremsstrahlung emission as a sensitive probe of SRCs in nuclei. By analyzing the spectral hardening caused by high-momentum nucleons with IBUU-MDI transport model, we determine the SRC fraction in ^{124}Sn to be $R_{\text{HMT}} = (20 \pm 3)\%$.

This result surpasses the previous experimental attempts in both precision and clarity. Our findings open an avenue for studying nucleon SRCs and their possible connection to partonic dynamics in nuclei through low-energy heavy-ion collisions.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [66] embargo periods may apply.

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