Bremsstrahlung Gamma Ray as a Probe of Short-Range Correlations in Nuclei

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Abstract

The nucleons in nuclei form temporally correlated pairs in close proximity, called short range correlation (SRC), which plays a crucial role in understanding nuclear structure and the fundamental properties of dense nuclear matter. The consequence of SRC on heavy-ion collisions (HICs) has remained unexplored until now. In this paper, we identify neutron-proton bremsstrahlung γ-ray emission from HICs as a new indicator of SRC in nuclei. By observing the hardening of the bremsstrahlung γ-ray spectrum, which results from the increase of high-momentum components above the Fermi surface in nucleon momentum distributions, we precisely determine the SRC fraction in nuclei to be (21$±7) $ confidence levels. Our experiment identifies the first direct and accurate signature of SRC in low-energy HICs, providing a new method to study the parton momentum distribution of nucleons in nuclei.

Full Text

Preamble

Bremsstrahlung Gamma Ray as a Probe of Short-Range Correlations in Nuclei

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The nucleons in nuclei form temporally correlated pairs in close proximity, called short-range correlations (SRC), which play a crucial role in understanding nuclear structure and the fundamental properties of dense nuclear matter. The consequences of SRC on heavy-ion collisions (HICs) have remained unexplored until now. In this paper, we identify neutron-proton bremsstrahlung γ-ray emission from HICs as a new indicator of SRC in nuclei. By observing the hardening of the bremsstrahlung γ-ray spectrum, which results from the increase of high-momentum components above the Fermi surface in nucleon momentum distributions, we precisely determine the SRC fraction in nuclei to be $(21 \pm 7)\%$ at 3σ confidence levels. Our experiment identifies the first direct and accurate signature of SRC in low-energy HICs, providing a new method to study the parton momentum distribution of nucleons in nuclei.

Introduction

Nucleonic matter represents one of the strongly-interacting forms of matter across vastly different scales, from atomic nuclei to neutron stars in the Universe. Understanding how nucleons interact is of fundamental importance for reproducing the static and dynamical properties of nucleonic matter [1]. While protons and neutrons are composed of quarks, quark-level interactions are neglected in most nuclear models based on mean-field approaches, such as the nuclear shell model [2].

In the conventional picture, nucleon momenta are constrained below the Fermi momentum, and the partonic structure functions of bound and free nucleons are assumed identical. However, deep inelastic scattering (DIS) experiments conducted by the European Muon Collaboration (EMC) observed that the nucleon structure function in deuterons differs from that in heavy nuclei. This phenomenon, known as the EMC effect [3], indicates that the internal quark distribution plays a role in nuclear structure and that the nucleon momentum distribution deviates from shell model predictions [4–9].

To clarify the origin of this deviation from the Fermi distribution, scientists identified short-range correlations (SRC) between nucleons [4, 10], representing a temporal fluctuation effect beyond the mean-field approximation. Additional evidence demonstrates that the EMC effect and the presence of SRC are closely connected at the quark level, and that the abundance of SRC pairs influences the EMC effect across different nuclei [11–13]. This suggests that studying SRC may provide insights into the parton distribution functions (PDF) of nucleons in nuclei.

The majority of our current understanding of SRC in atomic nuclei comes from electron-nucleus scattering [10, 14–17] and proton-nucleus knockout experiments [18–20]. A recent global analysis based on QCD factorization scheme extracts the universal effective distribution of partons inside SRC pairs and the mean-field fraction using a variety of high-energy data [21]. Existing studies have found that SRC can be predominantly characterized by neutron-proton (np) pairing in the isosinglet (T=0) channel at short distances, which favors ud diquark isosinglet and spin-singlet pairing at the quark level [22]. SRC also enhances the high-momentum components of the nucleon momentum distribution above the Fermi surface in nuclei, forming a "high-momentum tail" (HMT) that is absent in the mean-field picture [10, 17]. The presence of HMT has strong implications for the properties of dense nucleonic matter, particularly the density dependence of the nuclear symmetry energy [23–25].

Among various experimental approaches, heavy-ion collisions (HICs) offer a unique opportunity to create bulk dense nucleonic matter in a terrestrial laboratory. Therefore, searching for signatures of SRC in HICs is of significant importance, as it not only bridges SRC and dense nucleonic matter but also helps determine the SRC fraction, thereby validating the accuracy and reliability of previous measurements. When two heavy nuclei collide, two-body np collisions produce bremsstrahlung γ-rays [26–28]. Due to the influence of HMT, the average nucleon kinetic energies of both projectile and target increase significantly, causing the emitted γ-ray spectrum to harden, particularly at high energies [29]. Advantageously, these high-energy γ-rays are largely unaffected by the nuclear medium, making them an effective and novel probe for detecting SRC effects [29–31].

Theoretical calculations using the Isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model [32], adopting Momentum-Dependent Interaction (MDI) [33], predict the bremsstrahlung γ-ray spectra produced in HICs by varying the HMT ratio (RHMT) [29]. This ratio represents the fraction of high-momentum components above the Fermi surface in the nucleon momentum distributions in nuclei [29]. By comparing model predictions with experimental γ-ray spectra, the HMT ratio can be constrained, potentially offering an innovative method to probe the parton momentum distributions in correlated np pairs in nuclei.

Experiments and Data Analysis

The Compact Spectrometer for Heavy Ion Experiment (CSHINE), located at the end of Radioactive Ion Beam Line 1 (RIBLL1) at the Heavy Ion Research Facility in Lanzhou (HIRFL), is designed to study HICs at Fermi energies [34, 35] (see Fig. 1). Charged particles produced in the final state are detected using silicon-strip telescopes (SSDTs) [36]. Neutrons are identified by an array of 20 plastic scintillators, while BaF2 γ-detectors surrounding the target provide starting time (T0) information [37]. To measure energetic bremsstrahlung γ-rays from reactions at the target, a 4 × 4 CsI(Tl)-based hodoscope has been installed [38], allowing detection of photons with energies up to 100 MeV. Each unit has dimensions of $7 \times 7 \times 25$ cm^3. The trigger system of CSHINE is implemented using field-programmable gate array (FPGA) technology [39].

In an experiment involving 86Kr+124Sn reactions at a beam energy of 25 MeV per nucleon, the bremsstrahlung γ-ray spectrum was successfully measured using CSHINE, revealing a high-momentum nucleon fraction of RHMT   15% in the γ energy range between 35 and 80 MeV. This was achieved through comparison with predictions from the IBUU-MDI transport model [40]. To mitigate the effects of detector filtering, a deblurring algorithm was developed to reconstruct the original γ spectrum, which further indicated the presence of high-momentum tails (HMT) with a ratio of RHMT   25% [41]. However, the limited energy range and low statistics restricted the accuracy of the result.

To overcome these limitations, a new experiment was conducted using 124Sn+124Sn reactions at 25 MeV per nucleon beam energy [37]. A plastic scintillator array was installed around the CsI(Tl) hodoscope to veto cosmic ray background as well as γ events with energy leakage to the outside. Additionally, the energy range of the individual scintillators was extended to reach the maximum detectable energy of 100 MeV for bremsstrahlung γ-rays. These advancements enabled a high-confidence determination of the RHMT associated with SRC, leveraging high-energy γ-ray emissions from HICs.

After calibrating the CsI(Tl) hodoscopes, the energy deposit in the hodoscope is reconstructed on an event-by-event basis. The reconstruction algorithm identifies clustered CsI(Tl) hits in each event and classifies them as either a γ-ray event or a penetrating cosmic muon. Figures 2(a) and (b) illustrate a typical γ-ray event and a penetrating cosmic ray event detected by the CsI(Tl) hodoscopes, respectively. The penetrating cosmic muon clearly results in a large spatial extension of the CsI(Tl) hits and likely leaves hits in the surrounding scintillators, demonstrating a significantly different pattern compared to the γ-ray event. To subtract the background, which mainly includes cosmic muons and low-energy residual γ-rays, the background spectrum is measured when the beam is off. Figure 2(c) shows the total γ spectrum (black histogram) and the background spectrum (red), which is scaled to match the total spectrum based on the counts above 110 MeV. The pure γ spectrum is then obtained by subtracting the scaled background spectrum from the total spectrum.

Since the detected γ-ray spectrum is influenced by detector efficiency, theoretical curves must be processed through the detector filter before comparing them to experimental data. Using Geant4 simulations, the CsI array' s response to γ-rays of varying energies was modeled to generate a detector filter matrix in the laboratory frame [38]. Each element of the matrix represents the probability, P (E), of a photon with energy E producing a response E in the detector. For spectra limited to energies E $\leq$ 100 MeV, the matrix is a 100\$×\$100 array, with energy ranging from 1 to 100 MeV in 1 MeV steps. To enable direct comparison with experimental data, the theoretical curves are transformed into the laboratory frame, processed using the detector filter matrix, and then converted back to the center-of-mass (c.m.) frame. During the conversion of the spectrum between the laboratory and c.m. frames, the photon Doppler effect is taken into account, which causes a slight softening of the energy spectrum.

The statistical uncertainties in the γ spectrum follow a Poisson distribution. The Poisson error for each bin is calculated based on the counts in the original spectrum and is propagated through all subsequent operations performed on the spectrum. The most significant systematic uncertainty arises from the calibration process. Since the maximum energy of the radioactive source used for calibration is below 3 MeV, additional high-energy γ beam tests were conducted to characterize the detector' s response at higher γ energies [42]. These tests resulted in two typical detector response correction functions.

To evaluate the systematic uncertainties, nine distinct γ spectra were generated using the two detector response correction functions in conjunction with linear calibration, along with three calibration datasets from radioactive sources that account for the time shift of the detector and electronics. Of these, the spectrum derived from the calibration datasets with the highest statistics and the initial two-range linear calibration method [42] was designated as the central spectrum. The remaining spectra were then used to estimate the systematic uncertainties by calculating the standard deviation of their values in each energy bin.

Results and Discussions

Fig. 3 [Figure 3: see original paper] illustrates the rebinned experimental γ spectrum in the c.m. frame. The black dots represent the central spectrum, with statistical uncertainties indicated by error bars, and the gray shaded regions denote the systematic uncertainties at each energy point. Several key theoretical curves, processed with the detector filter, are presented for comparison. Unlike in our previous experiment [40, 41], in this experiment the γ detector array was operated in active triggering mode, preventing the determination of the number of np collisions in heavy-ion reactions as a normalization factor for the γ spectrum. Consequently, the comparison between experimental data and theoretical curves predicted by the IBUU model focused on spectral shape similarities rather than absolute normalization. To align the range of the theoretical curves with the experimental spectrum, the theoretical values were uniformly scaled by a factor of 2.5×10^9, which had no impact on determining the RHMT, as it did not affect the comparison of shape differences between the experimental and model-predicted spectra.

The comparison between the IBUU model and the experimental data was performed using the maximum likelihood analysis method. The likelihood function was defined as [40]

$$\ln L'(R_{\mathrm{HMT}}) = \sum_i n_i \ln p_i(R_{\mathrm{HMT}}),$$

where i denotes the sum of experimental points within a certain statistical analysis interval, n represents the counts of the i-th experimental data point, and p represents the probability that the theoretical model predictions fall into the corresponding histogram bin of the experimental data under the specified statistical analysis interval for a given R_{HMT}. Energies below 30 MeV are primarily influenced by collective resonance and statistical emissions. Therefore, we selected an energy range of 35 < E_{cm}^γ < 100 MeV as the central analysis interval and calculated the likelihood function between the experimental γ spectrum at each point within this range and various IBUU theoretical curves.

The results are presented as blue dots with error bars in Fig. 4 Figure 4: see original paper, where the central values are derived from the central γ spectrum. To standardize the likelihood function values obtained from different γ spectra, the likelihood corresponding to the theoretical curve with R_{HMT} = 0% was selected as the reference point (ln L' (R_{HMT} = 0%) = 0). The relative likelihood values, Δ ln L' (R_{HMT}), for all other points were calculated relative to this baseline. The error bars at each R_{HMT} represent the standard deviations of the relative likelihood values obtained from the other γ spectra with the corresponding R_{HMT}.

The likelihood function reaches its maximum near R_{HMT} = 20% and follows an approximately quadratic distribution. This trend was fitted with a quadratic function, depicted as the blue dashed curve in the figure, which yielded a maximum value at R_{HMT}   21%. Based on the likelihood function distribution, the confidence intervals for the R_{HMT} are indicated by the black dashed lines in the figure. Therefore, based on the experimentally measured γ spectrum, the R_{HMT} value can be determined at a 3σ confidence level, yielding R_{HMT} = (21 ± 7)%.

To compare the experimental result with theoretical predictions without detector filtering, the original γ spectrum was reconstructed from the measured spectrum using the Richardson-Lucy (RL) algorithm [41]. The best value of R_{HMT} was determined by minimizing the ^{2}(R_{HMT}), which compares the reconstructed spectrum to the theoretical predictions. The ^{2}(R_{HMT}) is given by the following expression [41]:

$$\chi^2(R_{\mathrm{HMT}}) = \sum_i \frac{(n_i^{\mathrm{exp}} - n_i^{R_{\mathrm{HMT}}})^2}{\sigma_i^2},$$

where n_i^{exp} represents the experimental data counts in the i-th energy bin, n_i^{R_{HMT}} is the theoretical counts at a given R_{HMT} in the same bin, and σ is the uncertainty in the reconstructed spectrum for the i-th energy bin.

In the energy range of interest, the ^{2}(R_{HMT}) distribution is shown as red dots with error bars in Fig. 4(b). A quadratic fit to this distribution, represented by the red dashed line, reveals that the minimum occurs at R_{HMT} 22%. The confidence intervals for R_{HMT} were determined based on the ^{2} distribution, as indicated by the black dashed lines in the figure. Therefore, the optimal value of R_{HMT} determined from the reconstructed spectrum at the 3σ confidence level is R_{HMT} = (22 ± 6)%. This result is consistent with the forward analysis within the error margin.

Combining both the forward and inverse analysis results, it is concluded that the fraction of HMT components in the nucleon momentum distribution at the 3σ confidence level is R_{HMT} = (21 ± 7)%. The look-elsewhere effect, namely the variation caused by changing the lower limit of the energy range of interest, is well covered by the quoted uncertainty.

Last but not least, the result has important implications for studies of binary neutron star mergers (BNSM), which serve as an astrophysical analog of HICs. Bremsstrahlung γ-ray emission in the range of tens of MeV or higher from HICs can serve as a signature of accelerated nuclei interacting with the surrounding environment during the violent process of BNSM. Hydrodynamic simulations indicate that nuclear matter at the collision interface of BNSM events is heated to tens of MeV [43], where intense nucleus-nucleus collisions with high-energy γ-ray emission are expected. In addition, a recent study predicts that ultra-high-energy cosmic rays may originate from BNSM [44], and similarly high-energy γ-rays are emitted when the accelerating nuclei collide with surrounding matter. However, negative reports regarding high-energy γ-rays in follow-up observations of GW170817 [45] contradict these speculations and highlight the need for more detailed quantitative modeling of BNSM dynamics.

Summary

To summarize, the precise measurement of np bremsstrahlung γ rays in 124Sn+124Sn at 25 MeV/u not only resolves the puzzle that emerged in the 1980s regarding the origin of high-energy γ-rays in HICs [46], but also identifies a new indicator of SRC, which is a significant phenomenon relevant to nuclear structure as well as to the properties of dense nucleonic matter.

We leverage the advantage of HICs, where the bremsstrahlung γ-ray energy spectrum is hardened due to the HMT of nucleons resulting from SRC. By comparing the experimental γ-ray spectrum with theoretical predictions from the IBUU-MDI transport model, we have precisely determined the ratio of the high-momentum component of the np momentum distribution, R_{HMT} = (21 ± 7)% at a 3σ confidence level. Both forward and inverse methods yielded consistent results within the uncertainty range, confirming the robustness and reliability of our findings. IBUU-MDI simulations show that bremsstrahlung γ-ray production becomes increasingly sensitive to R_{HMT} induced by SRCs in the colliding nuclei, particularly at the high-energy end of the γ-ray spectrum. This underscores the need for further systematic experimental studies of higher-energy γ rays in HICs.

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Note: Figure translations are in progress. See original paper for figures.