Extract neutron-neutron interaction strength and spatial-temporal dynamics of neutron emission from two-particle correlation function

Authors: Dawei Si, Sheng Xiao, Zhi Qin, Junhuai Xu, Baiting Tian, Boyuan Zhang, Haojie Zhang, Dong Guo, Yijie Wang, Wei Xiaobao, Yibo Hao, Zengxiang Wang, Tianren Zhuo, Chunwang Ma, Yuansheng Yang, Xianglun Wei, Herun Yang, Peng Ma, Limin Duan, Fangfang Duan, Kang Wang, Junbing Ma, Shiwei Xu, Zhen Bai, Guo Yang, Yanyun Yang, Zhigang Xiao, Yuhao Qin, Dawei Si, Yijie Wang, Zhigang Xiao

Date: 2025-01-17T00:00:00+00:00

Abstract

The neutron-neutron (nn) correlation function has been measured in 25 MeV/u ^{124}Sn+^{124}Sn reactions. Using the Lednick' y-Lyuboshitz approach, the nn scattering length and effective range (f_0^{nn}, d_0^{nn}), as well as the reduced space-time size $R^{(0)}$ of the neutron emission source are simultaneously extracted as ($18.9^{+1.3}_{-1.2}$ fm, $1.9^{+1.3}_{1.0}$ fm) and 4.12 ± 0.12 fm, respectively. The measured nn scattering length is consistent with the results obtained in the low-energy scattering $^2\mathrm{H}(\pi^-, \gamma)2n$, indicating heavy-ion collisions can serve as an effective approach for measuring nn interactions and further investigating the charge symmetry breaking of nuclear force. The space-time size extracted from momentum-gated correlation functions exhibits clear dependence on the pair momentum, with $R^{(0)}=2.8 ±0.1 $ fm and 4.9 ± 0.2 fm being determined for the high and low momentum neutrons, respectively.

Full Text

Preamble

Extracting Neutron-Neutron Interaction Strength and Spatiotemporal Dynamics of Neutron Emission from Two-Particle Correlation Functions

Dawei Si,[1],* Sheng Xiao,[1] Zhi Qin,[1] Yuhao Qin,[1] Junhuai Xu,[1] Baiting Tian,[1] Boyuan Zhang,[1] Haojie Zhang,[1] Dong Guo,[1] Yijie Wang,[1],† Xiaobao Wei,[2] Yibo Hao,[2] Zengxiang Wang,[2] Tianren Zhuo,[2] Chunwang Ma,[2],[3] Yuansheng Yang,[4] Xianglun Wei,[4] Herun Yang,[4] Peng Ma,[4] Limin Duan,[4] Fangfang Duan,[4] Kang Wang,[4] Junbing Ma,[4] Shiwei Xu,[4] Zhen Bai,[4] Guo Yang,[4] Yanyun Yang,[4] and Zhigang Xiao[1],[5],‡

[1]Department of Physics, Tsinghua University, Beijing 100084, China
[2]Institute of Particle and Nuclear Physics, Henan Normal University, Xinxiang 453007, China
[3]Institute of Nuclear Science and Technology, Henan Academy of Sciences, Zhengzhou 450015, China
[4]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[5]Center of High Energy Physics, Tsinghua University, Beijing 100084, China
(Dated: January 16, 2025)

The neutron-neutron (nn) correlation function has been measured in 25 MeV/u ^{124}Sn+^{124}Sn reactions. Using the Lednický-Lyuboshitz approach, the nn scattering length and effective range (f^0_{nn} and d^0_{nn}), as well as the reduced space-time size $R(0)$ of the neutron emission source are simultaneously extracted as ($18.9^{+1.3}_{-1.0}$ fm) and 4.12 ± 0.12 fm, respectively. The measured nn scattering length is consistent with results obtained from low-energy scattering experiments such as ^{2}H$(\pi^-,\gamma)^2$n, indicating that heavy-ion collisions can serve as an effective approach for measuring nn interactions and further investigating charge symmetry breaking of the nuclear force. The space-time size extracted from momentum-gated correlation functions exhibits clear dependence on the pair momentum, with $R(0) = 2.8 \pm 0.1$ fm and 4.9 ± 0.2 fm being determined for high- and low-momentum neutrons, respectively.

Introduction

The neutron-neutron (nn) strong interaction is of fundamental significance for understanding charge symmetry breaking (CSB) of the nuclear force [1, 2]. However, direct measurement of the nn scattering length (f^0_{nn}) using free neutrons is not feasible because of the unavailability of a neutron target. Instead, the nn scattering length f^0_{nn} has been measured indirectly in few-body reactions with two neutrons in the final state, such as ^{2}H$(n,p)^2$n, ^{2}H$(\pi^-,\gamma)^2$n, and ^{3}H$(t,\alpha)^2$n [3–5]. Discrepancies in f^0_{nn} from these channels exist, indicating that three-body forces are at work and calling for further measurements.

Alternatively, Lednický and Lyuboshitz (LL) first proposed constraining the nn interaction from the correlation function (CF) of neutron pairs with low relative momentum [6], a method derived from the generalization of intensity interferometry invented by Hanbury-Brown and Twiss (HBT) [7, 8]. Since the formulation of the proton-proton (pp) CF in heavy-ion reactions [9], the LL method has been extensively employed to study final-state interactions of various baryon pairs, such as $\bar{p}\bar{p}$, $p\Lambda$, $p\Omega^-$, and $\Lambda\Lambda$ pairs [9–13]. Yet, the extraction of the nn scattering length from CF has not been reported since the LL approach was formulated.

The CF method can also be utilized to extract the spatiotemporal characteristics of the emission source [14–16]. Enormous experimental analyses have been performed using pions and kaons as probes to infer the spatial features of the source formed in relativistic and ultrarelativistic energy experiments [17–21]. Furthermore, the spatial information encoded in the CF has also been utilized to study the valence nucleon distribution of unstable nuclei [22–24]. More interestingly, moving down to intermediate- and low-energy heavy-ion reactions, the emission time scale, which is much longer, brings significant effects to the final CF [14, 25, 26]. Hence, the CF method applied to pp and nn offers the opportunity to differentiate the emission time difference between neutrons and protons, which may provide a new probe to constrain the stiffness of nuclear symmetry energy, currently under hot debate [27, 28].

Although experimental pp CFs are more copious, nn CFs are very scarce. So far, there have been mainly two heavy-ion experiments at intermediate and low energies reporting nn CFs measured over 20 years ago. Colonna et al. first observed the difference between transverse and longitudinal nn CFs in $^{18}\mathrm{O} + ^{26}\mathrm{Mg}$ at 130 MeV [29]. The CHIC Collaboration measured the nn CF in 45 MeV/u $^{58}\mathrm{Ni} + ^{27}\mathrm{Al}$, $^{\mathrm{nat}}\mathrm{Ni}$, and $^{197}\mathrm{Au}$ reactions, and observed increasing correlation strength with cuts on the total momentum of neutron pairs [30–32]. In these analyses, the emission source size and average emission time scale were determined by fixing the nn interaction parameters [33].

In this Letter, the nn CF in neutron-rich $^{124}\mathrm{Sn} + ^{124}\mathrm{Sn}$ reactions at 25 MeV/u is reported. A novel method to subtract the cross-talk effect is introduced to avoid significant distortion of the CF due to very strong cuts. The nn scattering length f^0_{nn} and effective range d^0_{nn}, as well as the reduced emission size $R(0)$, are simultaneously extracted based on LL fits. The extracted (f^0_{nn}, d^0_{nn}) are compared to results from scattering experiments, and the spatiotemporal features of the neutron emission source are discussed.

Experiment

The experiment was performed at the final focal plane of the Radioactive Ion Beam Line at Lanzhou (RIBLL1) with the Compact Spectrometer for Heavy Ion Experiments (CSHINE) [34–37]. The $^{124}\mathrm{Sn}$ beam was delivered by the cyclotron of the Heavy Ion Research Facility at Lanzhou (HIRFL), bombarding a $^{124}\mathrm{Sn}$ target with a thickness of 1.0 mg/cm^2. Neutrons were detected by a neutron array consisting of twenty $15 \times 15 \times 15$ cm^3 plastic scintillators coupled with 2-inch photomultiplier tubes, installed in 5 columns and 4 rows on a spherical surface at a distance of $L = 200$ cm from the target, covering laboratory polar angles $27^\circ < \theta_{\mathrm{lab}} < 53^\circ$. The relative angle between units varies from

6° to 30°, ensuring sufficient coverage of the relative momentum range for CF measurement. For more details of the neutron array, see [38].

Neutron energy was measured using the time-of-flight (TOF) method, with BaF_2 as the start timing detector. The overall time resolution in the beam experiment is 0.74 ns, resulting from the inherent time resolution (0.2 ns) and the variation of the neutron interaction position in the scintillator (0.7 ns). Fig. 1 Figure 1: see original paper illustrates the experimental TOF distribution. Besides neutrons and γ-rays from triggered events, secondary and accidental coincidence backgrounds also exist. Fig. 1(b) presents the neutron energy spectra at different angles θ_{lab}. The inverse slope parameters of the spectra vary from 13.0 ± 0.1 to 22.9 ± 0.1 MeV depending on θ_{lab} [38]. To reduce background influence, events within the TOF range from 20 ns to 87.5 ns, corresponding to neutron kinetic energies of 3 MeV to 76 MeV, are selected to generate the nn CF.

The CF was constructed from the relative momentum $k^* = |p_1 - p_2|/2$ of the two particles in the pair rest frame (PRF), where p_1 and p_2 are the momenta of the two particles. The experimental CF is defined as

$$C_{\text{exp}}(k^*) = A\frac{N_{\text{same}}(k^*)}{N_{\text{mix}}(k^*)}$$

where $N_{\text{same}}(k^*)$ is the relative momentum distribution with two particles from the same event, and $N_{\text{mix}}(k^*)$ is the reference distribution generated by event mixing. The normalization parameter A is determined by requiring $C_{\text{exp}}(k^*) = 1$ at large relative momenta ($k^* > 40$ MeV/c).

The most important effect to be corrected is cross-talk. It arises from a single neutron scattering within the neutron array and forms pseudo two-neutron events that are encompassed in the measured raw CF $C_{\text{exp}}(k^*)$. Additionally, a background component of accidental coincidences is also convoluted, which exhibits a uniform distribution in the TOF spectrum [38]. Hence, the genuine nn CF $C_{nn}(k^*)$ can be obtained by subtracting these two additional components from the experimental CF as

$$C_{nn}(k^*) = A_{nn}\left[\frac{1-\lambda_{ct}-\lambda_{ac}}{A_{\text{exp}}}C_{\text{exp}}(k^*) - \lambda_{ct}\frac{N^{\text{ct}}_{\text{same}}(k^*)}{N^{\text{exp}}_{\text{same}}(k^*)} - \lambda_{ac}\frac{N^{\text{ac}}_{\text{same}}(k^*)}{N^{\text{exp}}_{\text{same}}(k^*)}\right]$$

where A_{nn} and A_{exp} refer to the normalization parameters of the genuine nn CF and the measured raw CF, respectively. $N^{\text{ct}}_{\text{same}}(k^*)$ and $N^{\text{ac}}_{\text{same}}(k^*)$ are the relative momentum distributions of cross-talk events and accidental coincidence events, and λ_{ct} and λ_{ac} represent the corresponding proportions. λ_{ac} is obtained by fitting the TOF spectrum [38], and λ_{ct} can be derived from the TOF difference spectrum of experimental two-body events, as illustrated below.

To correct the cross-talk effect, we consider two primary configurations: the secondary particle produced by a single incident neutron fires an adjacent unit (adjacent configuration) or fires a diagonally neighboring unit (diagonal configuration). Figure 2 Figure 2: see original paper presents the TOF difference between the two fired units in Geant4 simulations for adjacent configuration (a) and diagonal configuration (b), respectively. Two separate peaks are visible. The left narrow one is associated with secondary γ rays, while the wider peak corresponds to scattered neutrons featuring a longer flight time. In the diagonal configuration (b), the neutron peak shifts further rightward due to the longer flight distance. The distribution can be described by a double asymmetric Gaussian function.

In the experiment, since the neutron detectors are placed equidistantly in both x and y directions, the flight time of secondary particles generated by cross-talk is relatively fixed, resulting in peak structures in the time difference spectra of two-body events for both adjacent and diagonal configurations, as shown in Fig. 2(c) and (d). The double-peaked structure of the ΔT spectra can be used to quantify the contribution of the cross-talk effect. Assuming the cross-talk distribution maintains the shape obtained from Geant4 simulations and using an exponential distribution to describe the true neutron pair time difference, one can decompose the experimental TOF difference spectra with λ_{ct} as a fitting parameter. This method allows derivation of λ_{ct} while avoiding strict rejection strategies that may introduce large distortions to the two-neutron CF [39].

The nn CF is analyzed using the LL approach [6, 23, 40]. Theoretically, the CF can be expressed as

$$C(k^*) = \int S(r,t,p)|\Phi(k^*,r)|^2 d^{3r}$$

where r is the relative distance between the particle pair, $S(r,t,p)$ is the distribution of this relative distance for particles emitted in the collision, which is sampled by the single-particle emission function parameterized as $g(r,t,p) \propto \exp(-r^2/R^2 - t^2/\tau^2)Y(p)$. Here R and τ are two parameters characterizing the spatial and temporal features of the source. The variables r, p, and t in Eq. (4) refer to the rest frame of the source. To incorporate the resolution and detection efficiency of the apparatus, the neutron momenta were selected by randomly sampling the experimental yield $Y(p)$. Phase-space points generated in the rest frame of the source were Lorentz-boosted into the PRF. The relative wave function $\Phi(k^*,r)$ is obtained from the effective range expansion [6, 41].

The fitting curve using the LL model reproduces the corrected nn CF well, as plotted in Fig. 3 Figure 3: see original paper.

Results

Fig. 3 presents the experimental nn CF. The measured raw CF $C_{\mathrm{exp}}(k^*)$ obtained from Eq. (1) is shown by the blue triangles. Systematic uncertainties, depicted by the squares, stem from the uncertainty of the TOF used to calculate neutron kinetic energy. The genuine nn CF $C_{nn}(k^*)$ is presented by the red circles after subtracting cross-talk and accidental coincidences using Eq. (2). Fig. 3(b) presents the relative momentum distributions of cross-talk and accidental coincidence events. The cross-talk distribution is significantly enhanced at small relative momenta, resulting in an overestimation of the CF, while the accidental coincidence distribution decreases at small relative momenta and partly cancels the cross-talk effect. For the genuine nn CF in panel (a), the uncertainty was calculated bin by bin according to Eq. (2), including uncertainties from experimental statistics, flight distance, Monte Carlo simulation in panel (b), and the fitting uncertainty of λ_{ct}.

The nn interaction parameters (f^0_{nn}, d^0_{nn}) and source parameters (R, τ) can now be extracted using the LL model [42]. In the Fermi energy region, both spatial and temporal extensions influence the CF. To avoid the impact of space-time ambiguity [43] on the interaction parameters, we first fix $\tau = 0$. The best-fit values of $f^0_{nn} = 18.9^{+1.3}_{-1.0}$ fm and $d^0_{nn} = 1.9^{+1.3}_{-1.2}$ fm are obtained and plotted in Fig. 4 Figure 4: see original paper with the combined 68% confidence level contour. For comparison, f^0_{nn} measured in reactions $^2\mathrm{H}(n,p)^2\mathrm{n}$ [3, 44], $^2\mathrm{H}(\pi^-,\gamma)^2\mathrm{n}$ [4, 45, 46], and $^3\mathrm{H}(t,\alpha)^2\mathrm{n}$ [5] are also shown. The blue band represents the widely adopted value of f^0_{nn} [47], while the red band indicates the recommended value of d^0_{nn} [48]. Remarkably, the measured (f^0_{nn}, d^0_{nn}) from the current CF method is consistent with previous determinations from low-energy scattering experiments, demonstrating the validity of the LL method for studying nn interactions by measuring CFs in heavy-ion reactions. It is worth mentioning that since the uncertainty is comparable to the CSB amplitude, more precise measurements will definitely be required in the future to address CSB using the CF method.

The space-time size of the neutron emission source is simultaneously inferred. As shown in the inset of Fig. 4(b), the reduced space-time volume (at $\tau = 0$) is obtained to be $R(0) = 4.12 \pm 0.12$ fm, which should be considered as the upper limit for the actual source size and is comparable to results obtained under similar experimental conditions [49–51].

To further investigate the space-time correlation, we release the condition $\tau = 0$ in the LL fit. Fig. 4(b) presents contour plots of emission source parameters (R, τ) at the 99% confidence level. It can be seen that R and τ are mutually coupled, and the slope of the distribution is determined by the average relative velocity of the particle pair. At the 99% confidence level, the emission time scale varies in the range of $0 - 150$ fm/c. The R-τ distribution reveals the space-time ambiguity of the angle-averaged CF in low-energy heavy-ion collisions [52].

Despite the difficulty in simultaneously extracting the emission time scale and source size through angle-averaged CF, the total-momentum-gated CF provides a complementary way to study the interplay between dynamical and statistical effects in particle emission [30, 53, 54]. Fig. 5 Figure 5: see original paper presents the nn CF with high (red) and low (blue) total momentum gates in comparison with the ungated one (gray). Enhancement (suppression) at low k^* is clearly shown in the high- (low-) momentum-gated CFs. To focus on the space-time variation with pair momentum, we fix the physically reasonable values $f^0_{nn} = 18.9$ fm and $d^0_{nn} = 1.9$ fm but keep R and τ as free parameters when fitting the momentum-gated CFs. The 99% confidence level contour plots are shown in Fig. 5(b). Significant momentum dependence is observed. For the high-momentum-gated CF corresponding to the early dynamic stage, the space-time ambiguity is well confined to a small space-time volume with a short time constant τ, while for the low-momentum-gated CF, the neutron pairs experience larger space-time separation. Fitting the momentum-gated CFs, we obtain reduced space-time sizes of $R(0) = 2.8 \pm 0.1$ fm and 4.9 ± 0.2 fm, corresponding to early and late stages of emission, respectively. This phenomenon is consistent with experimental observations in momentum-gated pp CF [55]. Given that the analysis framework is well established for pp CF (see, for instance, [14]), the upcoming combined analysis of nn and pp CFs in the same system will offer the opportunity to unravel the difference in emission timescales between neutrons and protons, providing novel insights into the effect of nuclear symmetry energy.

Summary

The nn CF in $^{124}\text{Sn} +^{124} \text{Sn}$ reactions at 25 MeV/u has been measured with CSHINE. The TOF difference between two fired neutron detectors is reproduced using Geant4 simulations to fit the cross-talk effect. For the first time, the nn scattering length and effective range (f^0_{nn}, d^0_{nn}), as well as the space-time size $R(0)$ of the neutron emission source, are simultaneously extracted using the Lednický-Lyuboshitz approach in neutron-rich heavy-ion reactions. The results for (f^0_{nn}, d^0_{nn}) are consistent with scattering experiments, which proves the validity of the LL method in describing the nn CF and demonstrates that fine femtoscopic techniques in heavy-ion experiments can be facilitated to study nn interactions and shed light on CSB of the nuclear force by reducing uncertainties in future measurements. In addition, we have respectively observed the space-time ambiguity through momentum-averaged CF and the evolution of the space-time size of the neutron emission source through momentum-gated CFs. This provides new perspectives for understanding isospin dynamics in heavy-ion reactions.

Acknowledgements

This work is supported by the Ministry of Science and Technology under Grant Nos. 2022YFE0103400 and 2020YFE0202001, by the National Natural Science

Foundation of China under Grant Nos. 12335008 and 12205160, and by the Center for High Performance Computing and Initiative Scientific Research Program at Tsinghua University. The authors thank Prof. Nu Xu and Bao-An Li for valuable discussions.

- Electronic address: sdw21@mails.tsinghua.edu.cn
  † Electronic address: yj-wang15@tsinghua.org.cn
  ‡ Electronic address: xiaozg@tsinghua.edu.cn

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