The Emission Order of Hydrogen Isotopes via Correlation Functions in 30 MeV/u Ar+Au Reactions

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Date: 2023-11-25T00:00:00+00:00

Abstract

The intensity interferometry is applied as a chronometer of the particle emission of hydrogen isotopes from the intermediate velocity source formed in ^{40}Ar+^{197}Au reactions at 30 MeV/u. The dynamic emission order of \$ tau_{ rm p}> tau_{ rm d}> tau_{ rm t}\$ is evidenced via the correlation functions of nonidentical particle pairs. Assuming the similar source size, the same emission order is inferred from the correlation functions of identical particle pairs, where \$ tau_{ rm p} approx 100 { rm ~fm/c}\$ is extracted by the fit of Koonin-Pratt equation to p-p correlation function. Transport model simulations demonstrate that the dynamic emission order of light charged particles depends on the stiffness of the nuclear symmetry energy.

Full Text

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Abstract

Intensity interferometry is applied as a chronometer of particle emission for hydrogen isotopes from the intermediate velocity source formed in ^{40}Ar+^{197}Au reactions at 30 MeV/u. The dynamic emission order τ > τ_d > τ_t is evidenced via correlation functions of nonidentical particle pairs. Assuming similar source sizes, the same emission order is inferred from correlation functions of identical particle pairs, where τ 100 fm/c is extracted by fitting the Koonin-Pratt equation to the p-p correlation function. Transport model simulations demonstrate that the dynamic emission order of light charged particles depends on the stiffness of the nuclear symmetry energy.

Key words: Particle emission time scale, Small angle correlation function, Symmetry energy, Heavy ion reactions
PACS: 25.70.-z

Introduction

Hanbury-Brown and Twiss introduced intensity interferometry techniques using photons detected by telescopes located at short distances compared to the size of stars [1,2]. Since then, the HBT method has found numerous applications in various fields, ranging from quantum optics [3], cold atom physics [4,5] to nuclear

[6,7] and particle physics [8,9]. In nuclear physics, the correlation function (CF), usually at small relative momentum or small angle, has been widely explored to infer the space-time dimensions of the emitting source formed in heavy ion collisions (HIC) over a wide energy range.

Here, unlike in the original astronomical application, the temporal evolution of the source, as well as the final state interaction (FSI) between the correlated particles, affect the CFs [6]. For a review, one can refer to [10,11]. At relativistic energies, CF techniques have been developed to extract the spatial extent of the source [12,13,14] and to image the anisotropic shape of the fireball [15,16]. Besides studies on the space-time characteristics of relativistic HICs, CFs are also investigated extensively to deduce the interaction properties of particle pairs. For instance, the interaction between antiprotons has been confirmed to be the same as between protons [17], and $\Lambda - \Lambda$ interaction has been studied via CFs of Λ pairs [18]. An earlier review of CF studies at relativistic energies can be found in [11].

At Fermi energies, CFs of neutrons, light charged particles (LCPs), and intermediate mass fragments (IMFs) have been extensively measured as well. It has been found that the emission time of IMFs is about 100 fm/c [19,20,21,22], characterizing the time scale of multifragmentation [23,24]. It turns out that CFs depend on the emitting source. In ^{129}Xe+^{n} Sn at 50 MeV/u, the emission time of fast hot protons from an out-of-equilibrium source is much shorter than that from an equilibrium source [25]. The physical content of the pp (and other like-particle) CFs in the presence of fast dynamical and slow secondary decay emitting sources has been discussed, suggesting that the height and width of the CFs can be used to decompose the different sources [26]. CF analysis of massive fragments reveals the short time scale and dissipative feature of fragment emission in dynamic PLF fission in ^{124}Sn+^{64}Ni at 35 MeV/u [27].

With the ability to image femtoscopic nuclear systems created in HIC at subzeptosecond time scales, the HBT method may provide a novel opportunity to explore isospin dynamics. The transport of the isospin degree of freedom is the effect of the nuclear symmetry energy E_{sym}( ), which has attracted intense interest in both astrophysics and nuclear physics following the discovery of the neutron star merger event GW170817 [28,29,30,31,32,33,34,35,36]. Despite great experimental and theoretical progress, E_{sym}( ) remains one of the most unknown ingredients in the nuclear equation of state (EOS) [37,38,39]. More accurate constraints on E_{sym}( ) require further investigations of fine isospin effects originating from E_{sym}( ), for instance, the different transport behavior of neutrons and protons, either free or bound in light clusters, in heavy ion reactions [40,41,42].

Such investigations require isospin chronology, for which the CF method provides a solution by quantitatively determining the emission time scale of light particles with different N/Z. The resolution of the CF method reaches a few fm/c. For instance, at SIS energies, the emission order of p, d, t, ^{3}He, and ^{4}He has been established by comparing correlations of particles with relative momenta parallel and anti-parallel to the center-of-mass velocity of the unlike particle pairs. It was found that the deduced space-time differences of LCP emitting sources allow two complementary scenarios attributed to the duality of space and time being indistinguishable from each other [43]. At Fermi energies, by measuring CFs of p-p, n-p, and p-d in ^{36}Ar+^{27}Al (N/Z = 1.03) at 61 MeV/u, it was shown that for dynamic emissions, the emission time constant satisfies τ_n < τ_d < τp *[44]. Besides, CFs of light particles as well as IMFs exhibit dependence on the initial N/Z of the reaction system, indicating that* E{sym}( ) is playing a role [45,46,47].

Despite this potential capability, using the CF method to quantify the effect of E_{sym}( ) is very difficult. Based on transport model simulations, it has been reported that the stiffness of E_{sym}( ) does affect CFs of n-p, p-p, and n-n pairs [48]. However, once the momentum-dependent interaction is taken into account, the effect of E_{sym}( ) is washed out significantly, as in the case of ^{52}Ca+^{48}Ca at 80 MeV/u according to the same transport model calculations [49], particularly for less energetic particles. Angular dependence in the laboratory frame of the CFs is reportedly stronger than the isospin effect [50]. Even more, radial expansion and secondary decay may further wash out the effect of E_{sym}( ) [51].

The above difficulties suggest that E_{sym}( ) is not the only unknown quantity in heavy ion reactions. It is intriguing to invest further systematic efforts in studies of CFs with an upgraded detection system. Our motivation here is to measure CFs of Z = 1 isotopes in a heavier system where the E_{sym}( ) effect can be enhanced because of the more neutron-rich environment created with larger space-time extension. In addition, it is also intended to clarify whether the positive d-d correlation peak exists, since some previous experimental results have negated the theoretical prediction.

In this letter, we present CFs of identical and nonidentical particle pairs of hydrogen isotopes in 30 MeV/u ^{40}Ar+^{197}Au reactions (N/Z = 1.44). An isospin-dependent sequence of particle emission has been confirmed. The Koonin-Pratt (K-P) equation, which connects the CF with the source function and the kernel function as shown by Eq. (3) later in section 3, has been applied to fit the p-p CF to extract the emission time constant τ_p. Positive correlations on d-d and t-t CFs are suggestively presented and discussed.

Experimental Setup

The experiment was performed with the Compact Spectrometer for Heavy IoN Experiment (CSHINE) installed at the final focal plane of the Radioactive Ion Beam Line at Lanzhou (RIBLL-1). The argon beam with 30 MeV/u incident energy was delivered by the Heavy Ion Research Facility at Lanzhou (HIRFL) bombarding a gold target with thickness of 1 mg/cm^2. The first phase setup of CSHINE was installed [52].

Fission fragments (FFs) were measured by three parallel plate avalanche counters (PPACs) with sensitive area 240 × 280 mm^2, delivering position and timing information of coincident FFs. The main PPAC was centered at _{lab} = 50°, while the other two coincident PPACs were centered at _{lab} = 40° and 95° on the other side of the beam. The perpendicular distances of the PPACs to the target were equally 427.5 mm and all centers of the sensitive areas were in the same horizontal level.

LCPs at midrapidity were measured by two telescopes, each consisting of two silicon strip detectors (SSDs) and one layer of CsI(Tl) array containing 3$×$3 units read out by photodiode (PD). The first layer of the SSD was a single-sided silicon strip detector (SSSSD) of 32 strips with thickness 65 µm. The second layer, with thickness 1540 µm, was a double-sided silicon strip detector (DSSSD) of 32 strips on both sides. The sensitive area S_a, distance d, polar angle _{lab}, and azimuth ϕ{lab} *of the two SSD telescopes are listed in Table I. Three small silicon telescopes consisting of two Si(Au) barrier detectors and one CsI(Tl) unit were placed at large angles with* {lab} = 90°, 120°, and 128° to measure evaporated LCPs. The geometry of detectors was determined by mechanical machining, and the overall accuracy is better than 1.

The correlation functions of LCPs are measured by the SSD telescopes, as schematically displayed in Fig. 1(a). The strip widths of both SSDs are 2 mm and the interstrip distance is 0.1 mm. With pixel size 2 × 2 mm^2, angular resolution of 0.7° for LCPs was achieved in the experiment. The SSDs were calibrated by combining a precise pulser generator and a ^{239}Pu α source. The thicknesses of the mylar foil (4 µm) and the dead layer (0.6 µm [53]) of the SSD detector are corrected. After the SSDs with well-defined thickness were calibrated, the energy deposit in CsI(Tl) units could be calculated using the program LISE++ [54] and then calibrated through the ΔE_2 − E_{CsI} band for each isotope. For each telescope, the total uncertainty of the energy of LCPs, which was largely contributed by the CsI(Tl) unit, was estimated to be 2% according to Monte-Carlo simulation studies reproducing the width of the isotope bands on the ΔE_2 − E_{CsI} plot. The mass resolution ΔM = 0.1 for α particles was then obtained [52]. Fig. 1(b) presents the ΔE_2 − E_{CsI} scattering plot of one CsI(Tl) unit in SSD telescope 2, showing that isotopes of Z = 1 and 2 are clearly identified.

Here the non-uniformity of the thin SSSSD is not corrected. Fig. 1(c) presents the energy spectra of p, d, and t. The low-energy parts for each isotope are undetected because the high voltage for the first layer of the SSD telescopes did not work during the experiment, and only particles penetrating through the second layer were analyzed.

Table 1 Geometric parameters of SSD telescope 1 and 2.

SSD Tele.	S_a (mm^2)	d (mm)	_{lab} (°)	ϕ_{lab} (°)
1	64 × 64			

SSD Tele.	S_a (mm^2)	d (mm)	_{lab} (°)	ϕ_{lab} (°)
2	64 × 64			

In data analysis, we focus on track recognition and reconstruction in events with multiple hits in SSD telescopes. One first counts the fire multiplicity in the CsI(Tl) array, then looks for fired strips crossing the area that matches geometrically to each individual fired CsI(Tl) unit. The pixel of 2 × 2 mm^2 at the crossing point of the front strip and rear strip of the DSSSD defines the hit position. Special check of signal sharing is conducted. In case two neighboring strips are fired, the energies are summed to form a single hit if the smaller signal is below a given ratio (85% in the analysis) of the larger one on the neighboring strips. A good track (hit) on the DSSSD requires that the relative difference of signal amplitude between front and rear strips is less than 20%. On average, 6% of total exclusive events are abandoned because two or more DSSSD hits are recognized in the area corresponding to one single CsI(Tl) unit.

Considering the current angular range 20°–60° and high energy threshold in the current experiment, LCPs originate mainly from the intermediate velocity source. According to moving-source fits in previous experiments of the same reaction, where the low-energy part of spectra was well covered, target-like (TL) evaporation contributes less than 10% in the phase space covered by the SSD telescopes [41,55]. The projectile-like (PL) source may contribute to the CF in the region of large relative momentum if one particle from the PL source is measured, as discussed later in Fig. 2.

Results and Discussions

Since event statistics for 4-body coincidence (2 LCPs in SSD telescopes and 2 FFs in PPACs) are insufficient, only LCP-LCP two-body coincidence events are presented. When two LCPs were identified in the SSD telescopes, the reduced relative momentum q can be approximated to the non-relativistic form as q = (p$_1$/m$_1$ − p$_2$/m$_2$), where m_i and p_i represent the mass and momentum of the two particles marked by i = 1 and 2, respectively, and is the reduced mass. The CF is constructed by

1 + R(q) = C_N Y_{con}(p$_1$, p$_2$) / Y_{mix}(p$_1$, p$_2$)

where the numerator Y_{con} is the coincident yield with the particle pair flying with momenta p$_1$ and p$_2$, respectively, while the denominator Y_{mix}(p$_1$, p$_2$) is the yield product of particles 1 and 2 taken from mixing events in the same data sample. C_N is the normalization factor to ensure R(q) = 0 at sufficiently large q.

To extract the space-time extension of the source, the correlation function can be fitted using the angle-averaged Koonin-Pratt equation [61] as follows:

$1 + R(q) = 1 + 4\pi \quad S(r, t) \cdot K(r, q)\, dr\, dt$

where S is the source function characterizing the space-time extension of the source and K is the kernel function carrying all information about the wave function of the particle pair and the mutual Coulomb and nuclear FSI. Applying a Gaussian form to both size and time evolution, the source function is written as

$S(r, t) = c \cdot \exp(-r^2/2\sigma\_r^2 - t^2/2\tau^2)$

where σ_r is the width of the source size and τ is the emission time constant.

The scheme to construct mixing event spectra is essential in correlation function analysis, as summarized in Fig. 2. Panel (a) presents the scattering plot of total momentum P and relative momentum q of correlated proton pairs. Two main bands are visible: the upper one, with larger P in clearer coincidence with q, represents events with two protons recorded in the same SSD telescope, while the lower one, with smaller P but larger q, represents those recorded by the two SSD telescopes respectively. The light gap between the bands is due to the dead area between the telescopes. Panel (b) presents the P−q scattering plot by randomly mixing pairs from two successive events in the same data sample as in panel (a), showing similar features. Panel (c) presents the P−q scattering plot by picking two protons from different events in the inclusive one-body measurement. Compared with mixing spectra in panel (b), the distribution shows more complicated components. An obvious component appears at very large q but relatively lower total momentum P, suggesting one proton may come from PL emission which has higher probability of being recorded in inclusive events. In our analysis, the same data sample is used to construct the yield product $Y\_\{mix\}(p_1, p_2)$ in the denominator of Eq. (2). The validity of this scheme has been verified in [56,57].

Fig. 2. (Color online) (a) P−q scattering plot of correlated proton pairs. (b) P−q scattering plot of protons picked in mixing events in the same data sample of two-body events. (c) P−q scattering plot of protons from mixing inclusive events.

CFs of α-α and d-α are constructed to verify the scheme of event mixing and detector calibration, as presented in Fig. 3(a). The three peaks at q 15, 42, and 100 MeV/c, corresponding to the ^{8}Be ground state and excited states at E = 2.43 MeV in ^{9}Be and E = 3.04 MeV in ^{8}Be, are clearly observed. Similarly, the q 39 MeV/c peak corresponding to the 2.19 MeV excited state of ^{6}Li in d-α CF is presented in Fig. 3(b). The position of the d-α peak (expected at q = 42 MeV/c) is slightly shifted left by about 1 bin, possibly due to calibration inaccuracy and collective motion [51]. The relative yield of the first peak of the ^{8}Be ground state is not as enhanced as in literature because only α particles at high energy are measured. Besides, the CF strength 1+R(q) remains constant at unity at large relative momentum q, indicating the feasibility of the mixing event scheme, and energy-momentum conservation induced correlations (EMCIC) may bring insignificant influence [58].

Fig. 3. (Color online) $\alpha-\alpha$ (a) and d$-\alpha$ (b) correlation functions in 30 MeV/u ^{40}Ar+^{197}Au reactions. Individual peaks corresponding to different states are indicated.

We now investigate the emission sequence of hydrogen isotopes. With less space-time ambiguity, the emission sequence of different particles can be inferred by comparing CFs of nonidentical particle pairs with different velocity gates [59]. Considering two unlike particles marked 1 and 2 in a classical view, as shown schematically in Fig. 4(a), if particle 1 is emitted on average later than particle 2 (i.e., $\tau_1 > \tau_2$), the (anti)correlation will be stronger for events with $v_1 > v_2$ where v denotes velocity, because particle 1 catches up with particle 2 during flight and final-state interaction (FSI) between the pair is then expected to be strong. Conversely, the (anti)correlation is reduced with $v_1 < v_2$ because the distance between them increases with time. If $\tau_1 < \tau_2$, the (anti)correlation will be stronger with $v_1 < v_2$. We note that analysis is not done for 4-body correlations due to insufficient statistics. It is assumed that different particle pairs do not differentiate fine division of reaction centrality.

Fig. 4. (Color online) (a) Principle of using velocity-gated CF to determine emission order, assuming $\tau_1 > \tau_2$. Panels (b–d) present velocity-gated CFs of p-d, p-t, and d-t pairs respectively. Velocity conditions are indicated in each panel.

Figures 4(b–d) present velocity-gated CFs of p-d, p-t, and d-t pairs respectively. The velocity gate conditions are indicated in each panel. For p-d pairs, in the v_p > v_d group, Coulomb anti-correlation is stronger at lower q and positive correlation appears in the vicinity of q = 50 MeV/c. In the v_p < v_d group, however, Coulomb anti-correlation is weaker at lower q and the positive correlation disappears. The discernible difference in correlation strength between the two groups suggests protons are emitted on average later, i.e., τ_d < τ_p, in accordance with earlier experimental results in Ar+Ag at 34 MeV/u [60]. A very similar trend is found for p-t pairs, where the difference between the two CFs is more pronounced, similarly supporting τ_t < τ_p. For d-t pairs, the position of the peak near q = 70 MeV/c shown in the v_d > v_t group accords with contribution originating from loosely bound ^{5}He. Similarly, correlation is stronger in the v_d > v_t group, and τ_t < τ_d is correspondingly inferred. Combined, the emission sequence τ_t < τ_d < τ_p is evidenced, in agreement with the order of dynamic emission τ_n < τ_d < τ_p established in ^{36}Ar+^{27}Al (N/Z = 1.03) where the neutron emission time constant was also extracted [44].

The emission time constant of a certain species can be extracted from the correlation function of identical particle pairs. Fig. 5 presents the p-p correlation function compared with calculations using the Correlation After Burner code (CRAB). The positive correlation peak at q 20 MeV/c is attributed to S-wave nuclear attraction between protons. It is well known that space-time ambiguity exists since source size r and particle emission time constant τ are correlated [62]. Such ambiguity can be partly discriminated by directional cut analysis on relative velocity [63], but the statistics here do not allow fine analysis. Therefore, before inferring the space-time extension of the source—which is assumed to be the intermediate velocity source (midrapidity source) since high-energy protons are mainly measured—we first estimate the size of the source containing transferred projectile nucleons and target nucleons of the same amount. The mass number of the source reads $A_s = 2 \times A_p \times LMT$ where LMT is the linear momentum transfer. Assuming the most probable momentum transfer of 75%, one obtains $A_s = 60$ and static radius r 4.8 fm.

Fig. 5(a) first presents comparison of p-p CF to CRAB calculation [64,65] by fixing emission time constant at $\tau = 0$. The fit with Gaussian standard width $\sigma_r = 3.2$ fm reproduces CF height but the shape is slightly off. Then, releasing the $\tau = 0$ condition, one expects to obtain smaller source size and finite emission time. Panels (b–d) present results by varying τ at given geometric size parameters $\sigma_r = 1.2$, 1.6, and 2.0 fm respectively. As shown, at all σ_r settings, calculations reproduce experimental CF reasonably well. Surveying more carefully, at $\sigma_r = 2.0$ fm the fit shape starts to deviate from the right descent of experimental CF although height coincides with data points. With Gaussian standard width $\sigma_r = 1.6$ fm, the best fit situates at $\tau_p = 100$ fm/c. An uncertainty of $\pm$50 fm/c is allowed if variation of size parameter is taken into account. The τ_p value is consistent with predictions of transport model simulations based on coalescence scheme of clustering [66]. In addition, τ_p is comparable to the time for the projectile to traverse the target region, suggesting again that contributions from PL and TL evaporation are insignificant because these two sources experience mainly evaporation processes characterized by much larger time scales. We recall that Eq. (4) is a simplified way to characterize space-time extension of the source. Possible mixing of different emitting sources and collective motion of the participant zone may bring some influence to modeling of the source, but magnitude of τ is unlikely changed dramatically. Alternatively, imaging technique extracts source profile by numerical inversion of K-P equation without introducing a priori assumptions on source shape [26].

Fig. 5. (Color online) CF of p-p compared with predictions of CRAB code calculations by varying emission time constant τ_p with different Gaussian parameter σ_r of spatial extension of source. Panel (a) presents calculation results with different source sizes assuming zero emission time scale. Panels (b–d) present results by varying τ_p at $\sigma_r = 1.2$, 1.6, and 2.0 fm respectively.

Fig. 6 presents experimental CFs of d-d and t-t compared to p-p. It is clear that Coulomb anti-correlation at small q, visible for all pairs, increases successively from proton to deuteron and triton. Given that Coulomb force between particle pairs is the same for p-p, d-d, and t-t (all Z = 1 isotopes), evolution of Coulomb anti-correlation strength is consistent with particle emission hierarchy that neutron-rich tritons are emitted with shorter average time constant than deuterons and protons, in agreement with observation in Fig. 5. The increasing anti-correlation from p-p to d-d and t-t pairs is consistent with experimental observation in ^{40}Ar+Ag at lower beam energy, where faster emission of t and d was also suggested [67]. One should remain cautious that the above inference from Fig. 6 relies on assumption that p, d, and t emissions are characterized by the same geometrical source size. A more convincing picture would be possible if matrix analysis could be done with relative momentum q perpendicular and parallel to sum momentum P of the source [63].

Another feature worth noticing in Fig. 6 is positive correlation peaks near 45 MeV/c (60 MeV/c) on d-d (t-t) correlation functions slightly beyond statistical uncertainty. This is at variance with earlier experimental results [68,69,70] where positive correlation was not observed, possibly due to low detector granularity. In addition, CRAB calculation does not reproduce positive correlation if simplified Woods-Saxon d-d potential is adopted, as shown by the curve in Fig. 6 for which source-size parameter σ_r = 1.6 fm and temperature obtained from deuteron energy spectrum are used. On the other hand, presence of positive correlation is qualitatively consistent with theoretical prediction of resonating group (RG) method taking into account form factor of deuteron nucleus [68,71]. Interestingly, positive correlations have also been experimentally indicated, although not discussed, at the same positions of d-d and t-t CFs in ^{40}Ar+Ag at 17 MeV/u [67]. Compared to t-t correlation, which exhibits an even more pronounced positive peak, d-d positive correlation is weaker. If presence of positive peaks in d-d and t-t CFs is true, it suggests nuclear FSI may be playing a role, and weaker d-d positive correlation is consistent with effect of α formation from two deuterons at small distance in phase space. We checked possible effects of cluster recognition algorithms in neighboring strips, as well as $\alpha-\alpha$ correlation function, which did not show such wide positive correlation except for known peaks corresponding to ^{8}Be and ^{9}Be states [52]; thus the positive correlation could not be excluded. Further studies are called for to understand presence of positive peaks in d-d and t-t CFs.

The observed emission sequence of Z = 1 isotopes (i.e., an N/Z effect on CFs) may or may not be evidence that E_{sym}( ) is at work. Different emitting sources, secondary decay, collective motions [26,50,51], as well as different transport behavior of neutrons and protons, could all cause isospin-dependent hierarchy. More efforts are required to extract convincing isospin effects from isotope-resolved CFs. As a starting attempt, we inspect relaxation of the isospin degree of freedom (IDOF) with transport model calculations since we are measuring energetic LCPs in current phase space insignificantly contributed by evaporation according to previous moving-source analysis [41,55]. In an intuitive picture, neutrons (protons) experience repulsion (attraction) due to isovector nuclear potential, thus neutrons are driven more easily to gas phase causing isospin fractionation [72]. With stiffer E_{sym}( ), the neutron-proton difference in emission time constant is larger.

It is of interest to reproduce IDOF relaxation process with an Improved Quantum Molecular Dynamics (ImQMD) model incorporating density dependence of nuclear symmetry energy E_{sym}( ). Instead of pursuing quantitative comparison with experimental emission time constant, we aim at revealing characteristics of IDOF relaxation qualitatively by inspecting time distribution of emission of coalescence invariant neutrons (CINs) and protons (CIPs). Here CINs (CIPs) refers to total neutron (proton) numbers in light particles with $Z < 3$. Details of ImQMD calculations with IQ3 interaction potential for the same reactions can be found in [73,74]. Fig. 7 presents time evolution of emission rates of CINs and CIPs during dynamic emission stage within $t < 600$ fm/c, where t = 100 fm/c corresponds to time when projectile and target start to contact on surface. To see effect of E_{sym}( ), two types of density dependence with slope parameter γi = *0.6 (a) and 1.0 (b) are simulated, representing soft and stiff E*{sym}( ) respectively. Energy cut of E_k/A > 10 MeV is applied approximately as in experiment. Calculation is done by weighting impact parameter in range b = 1–5 fm. It is shown that after production peak, emission rate of CINs descends more rapidly than CIPs, suggesting neutrons experience faster dynamic emission than protons, either free or bound in clusters. We fit descent with exponential decay function $\exp(-t/\tau)$, where superscript differentiates it from Gaussian extension in Eq. (4). For γi = *1.0, time difference* τ {CIP} $-$ τ _{CIN} is larger than at γi = *0.6, indicating faster IDOF relaxation with stiffer E*{sym}( ), in agreement with picture obtained from angular distribution of N/Z of LCPs in the same reaction [41].

Qualitative agreement of ImQMD simulation with experiment suggests that precise measurement of isospin chronology in whole phase space, including neutrons which have not been measured here, raises further scientific interest for experimental and theoretical endeavors toward comprehending effect of E_{sym}( ) on CFs in heavy ion reactions.

Fig. 7. (Color online) Emission rate of CIN (red) and CIP (blue) as function of time in ImQMD simulation of 30 MeV/u Ar+Au by averaging impact parameter over b = 1–5 fm. Two slope parameters of E_{sym}( ), γi = *0.6 (a) and 1.0 (b), are adopted representing soft and stiff E*{sym}( ) respectively. Dashed curves are exponential fits to decaying points with time constants τ *{CIN} and* τ {CIP} listed.

Summary

In summary, with Phase-I CSHINE detector appended to RIBLL-1, we have measured CFs of like and unlike particle pairs of hydrogen isotopes in ^{40}Ar+^{197}Au at 30 MeV/u. Velocity-gated CFs of p-d, p-t, and d-t pairs support emission sequence τ_p > τ_d > τ_t. For identical particle pairs, p-p CF is reproduced by K-P equation with τp *100 fm/c. Besides, anti-correlation at small q becomes increasingly pronounced from p-p to d-d and t-t pairs, consistent with emission hierarchy that neutron-rich particles are emitted relatively faster under assumption that p, d, and t emissions are characterized by same spatial parameter. A positive peak is observed on both d-d and t-t CFs, at variance with earlier experiments but in qualitative agreement with theoretical prediction of* *resonating group method, requiring further confirmation in future experiments. Quantitative determination of isospin chronology can potentially be used to probe isospin dynamics. Nevertheless, such task is not yet straightforward since various conditions intertwine in reaction process, including beam energy, reaction geometry, collective motion, and convolution of different emitting sources. In addition, neutrons carrying first-order isospin effects need to be detected with high accuracy. Therefore further efforts, both theoretical and experimental, are called for to better understand effect of* E\{sym\}( ) at $\leq$ $_0$ on intensity interferometry in heavy ion reactions.

Acknowledgment

This work has been supported by National Natural Science Foundation of China under Grant Nos. 11875174, 11890712, 11961131010, and U1732135, and by Ministry of Science and Technology under Grant No. 2020YFE0202001. The work is also supported by Initiative Scientific Research Program and Center of High Performance Computing of Tsinghua University and by Heavy Ion Research Facility at Lanzhou (HIRFL). The authors acknowledge machine staff for delivering beam.

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