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Correlation function studies at intermediate energies at CSHINE

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Summary. — The isospin-dependent nuclear equation of state, *i.e.* symmetry energy $E_{sym}(\rho)$ plays an important role in the study of nuclear physics and astrophysics. In terrestrial lab, heavy-ion reaction provides a unique way to constrain $E_{sym}(\rho)$. So a compact spectrometer for heavy ion experiment (CSHINE) is built and particle correlation functions are measured. The HBT correlation function method is applied as an chronometer to extract the emission timescale and determine the emission order of hydrogen isotopes from the intermediate velocity source formed in $30MeV/u^{40}Ar +^{197}Au$. The proton emission timescale $\tau_p \approx 100$ fm/c is extracted by the fit of Koonin-Pratt equation with correlation after burner (CRAB) code. And the dynamic emission order of $\tau_p > \tau_d > \tau_t$ is evidenced via the correlation functions of nonidentical particle pairs, indicating that the neutron rich particles are emitted earlier. Meanwhile, transport model simulations demonstrate that the emission timescale of isospin dependent particles depends on the density slope parameter of the nuclear symmetry energy. And the isospin chronology provides a promising route to study the symmetry energy and isospin relaxation.

1. – Introduction

Nucleus is an important material level in the universe, and a complex quantum multibody system composed by protons and neutrons. In 1932, Heisenberg introduced the concept of isospin in nuclear force research to distinguish proton and neutron. When studying the binding energy of all nuclei in the world, people found that there is a part of energy that makes the proton number and neutron number tend to be equal, so-called symmetry energy. The symmetry energy is an important issue to understand neutron rich systems, such as neutron stars [1] and neutron rich exotic nucleus [2]. Heavy-ion reaction experiment is a good process in terrestrial lab to study the property of symmetry energy [3-5] and isospin dynamics [6, 7]. Previous theoretical results indicate that the emission timescales of neutrons and protons in heavy-ion reactions are related to the symmetry energy [8]. And with a simple estimation, the reaction time is in zeptosecond scale. Even with the atto-second technique from 2023's Nobel Prize, it is still impossible

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to visualize the heavy-ion reactions. Hence, we may ask the question, how to measure the isospin dependent particle emission timescale and order in the extremely fast process of heavy-ion reactions?

The HBT correlation function method is a good approach to extract spatial and temporal information of the emission source, which was first used by Hanbury Brown and Twiss to measure the angular diameter of star in astronomy [9]. Subsequently, this method was widely used in atomic physics [10], anti-matter physics [11], and nuclear physics researches [6]. For nuclear physics, the HBT correlation function is related to both the space-time properties of the emission source and the relative motion wave function between two particles [12]. Taking proton-proton correlation function as an example: due to the final state interaction, there will be an anti-correlation due to repulsive Coulomb force at the small relative momentum, and a positive correlation due to the attractive nuclear force, and the correlation strength is related to the space-time properties of the emission source [13]. Therefore, the HBT correlation function can be used to extract source radius, emission timescale and the interaction between particles. In this work, the research will be focused on the emission timescale and emission order of hydrogen isotopes in intermediate energy heavy-ion reactions.

Motivated by achieving the HBT correlation function measurements and visualizing the heavy-ion reactions in the isospin degree of freedom (IDOF), a compact spectrometer for heavy ion experiment (CSHINE) was built [14, 15]. CSHINE consists initially of silicon strip detector (SSD) telescopes, parallel-plate avalanche counters (PPACs) [16] and a high energy gamma array [17]. The charged particles, fission fragments and high energy gamma can be measured coincidentally. Recently a field-programmable gate arrays (FPGA) trigger system based on CAEN V2495 module is added [18]. And a neutron detector array will be added in the future. Benefiting by the high-precision relative momentum measurement ability and good isotopic resolution of CSHINE, the HBT correlation functions of hydrogen isotopes were studied.

In this article, the experiment setup and detector performance will be presented in sect. **2**. The results about emission timescale of proton and emission order of hydrogen isotopes will be discussed in sect. **3**. Meanwhile, the theory calculations indicate that the emission timescales of isospin dependent particles are good processes for symmetry energy and isospin dynamic studies. The last is a summary.

2. – Experiment

The experiment was performed in Radioactive Ion Beam Line at Lanzhou (RIBLL-I) [19]. The ^{40}Ar ions were accelerated to 30 MeV/u, bombarding on a gold target with the thickness of 1 mg/cm^2. There are two SSD telescopes and three PPACs in this experiment (fig. 1 (a)). The isotopes of hydrogen were detected by SSD telescopes, which consist of one single-sided silicon strip detector, one double-sided silicon strip detector and a 3×3 CsI(Tl) crystal array [14,15]. The signal sharing effect and track recognition are analysed carefully [20]. The hydrogen isotopes were identified clearly via the $\Delta E - E$ method (fig. 1 (b)). Due to the high granularity and good energy resolution, the relative momentum of two coincident particles were measured precisely. The data set for HBT correlation functions is triggered by the multiplicity of light charged particles larger than two. And the angular coverage of SSD telescopes are located in the forward angle range ($20° < \theta_{lab} < 60°$) to focus on the dynamic emission timescale of the particles.

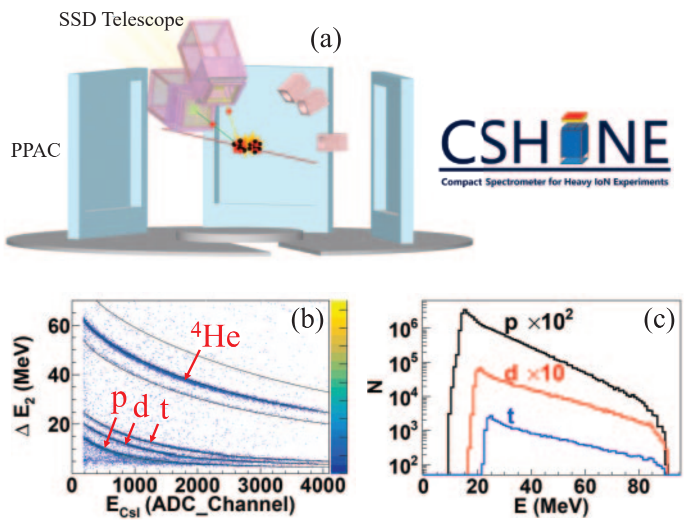

Fig. 1. – (a) Experiment configuration. (b) $\Delta E - E$ scattering plot. (c)The energy spectra of proton, deuteron and triton in the analyzed event set. The data is from [6].

3. – Results and discussion

3˙1. *Emission timescale of proton.* – The emission timescale of particles can be obtained via the HBT correlation function method. To understand the relationship between the HBT correlation function and the emission timescale, let's consider a simplified picture focusing on a pair of charged particles. If the emission timescale is shorter, the initial distance between two charged particles will be smaller, and then the Coulomb repulsion will be stronger, causing finally a larger anti-correlation at small relative momentum.

The experimental correlation functions are generated with the relative momentum spectrum from the coincident events, divided by the mixing event spectrum, and normalized at high relative momentum range. The correlation function can be expressed as:

$$1 + R(q) = C_{\mathrm{N}} \frac{Y_{\mathrm{con}}(\mathbf{p}_1, \mathbf{p}_2)}{Y_{\mathrm{mix}}(\mathbf{p}_1, \mathbf{p}_2)} \tag{1}$$

where q is one particle momentum in the particle pair frame, the numerator Y_{con} is the yield of two particles with momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ from coincident events, while the denominator $Y_{\mathrm{mix}}(\mathbf{p}_1, \mathbf{p}_2)$ is the yield of two particles generated by mixing event method in the same data set. C_{N} is the normalization parameter to keep $R(\mathbf{q}) = 0$ at relatively large q.

To obtain the emission timescale of particles, the angle-averaged Koonin-Pratt equation is used to fit the experiment correlation function results [13]. The theoretical correlation functions are the convolution of the space-time distribution of the emission source and the relative motion wave function in correlation after burner (CRAB) code [21]:

$$(2) \qquad 1 + R(q) = 1 + 4\pi \int S(r,t) \cdot K(r,q) \mathrm{d}r\mathrm{d}t$$

where S is the source function which includes the radius of emission source and the emission timescale of particles and K is the Kernel function including the final state interaction. The source function can be express as Gaussian form:

$$(3) \qquad S(r,t) = c \cdot \exp\left(-r^2/2\sigma_r^2 - t^2/2\tau^2\right)$$

where σ_r is the source radius and τ is the emission timescale.

The emission timescale of proton is obtained by fitting the correlation function with CRAB calculations in fig. 2. In the theoretic calculation, the initial temperature was set as 11.5 MeV which is extracted from the proton energy spectrum (fig. 1 (c)), and the interaction between two proton is described with Reid form [22]. When changing the radius of emission source and the particle emission timescale, it was found that the best fitting parameters are the Gaussian source radius $\sigma_{\mathrm{r}} = 1.6$ fm and proton emission timescale $\tau_{\mathrm{p}} = 100$ fm/c.

The original plan is to obtain the emission timescales of deuteron and triton with CRAB code similarly as proton. Then the emission order of hydrogen isotopes could be determined directly. However, the deuteron-deuteron correlation function can not be reproduced via CRAB with a Woods-Saxon potential for deuteron-deuteron interaction. Hence, via the identical particle correlation function method, only the dynamic emission timescale of the proton has been determined as $\tau_{\mathrm{p}} = 100$ fm/c.

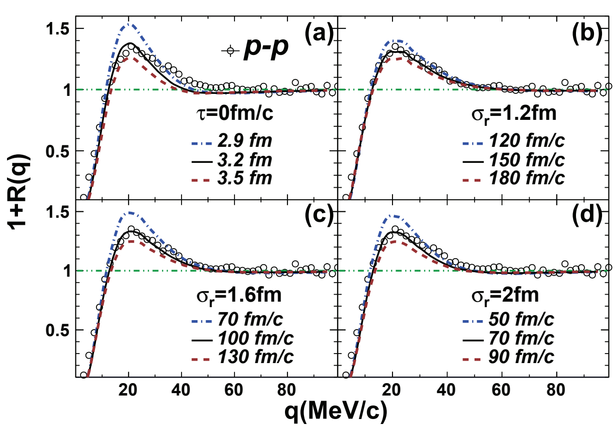

Fig. 2. – The proton-proton correlation function. The experimental result is expressed with open circles, and the theoretical results with different source radius and emission timescale are drawn with lines. The figure is from [6].

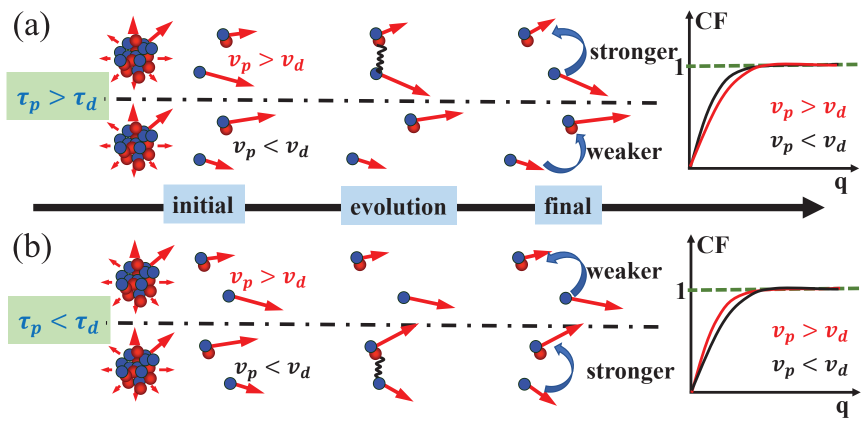

Fig. 3. – The velocity-gated non-identical particles correlation function method, taking proton and deuteron as an example.

3·2. *Emission order of hydrogen isotopes.* – To answer the question that how to determine the emission order of proton, deuteron and triton, the velocity-gated non-identical particles correlation function method is used [23, 24]. The principle is described as following. Taking proton and deuteron as an example (fig. 3), if the timescale of deuteron is shorter (fig. 3 (a)), it means that deuteron is emitted earlier in the initial stage. When the speed of proton is higher, the proton will catch up with the deuteron. Then, a strong interaction will occur in the evolution process, causing a stronger correlation result at final state, as drawn with the red curve. When the speed of proton is slower, the correlation is weaker as drawn with the black curve. And if the emission order is reversed (fig. 3 (b)), the correlation function behavior will change accordingly. And hence, qualitatively speaking, the particle with higher speed shows a stronger correlation result, indicating that this particle is emitted averagely later.

When using this method to proton-deuteron correlation function, the data shows that proton with higher speed shows a stronger correlation result, which means that proton is emitted later than deuteron (fig. 4(a)). Via this method, the emission order of

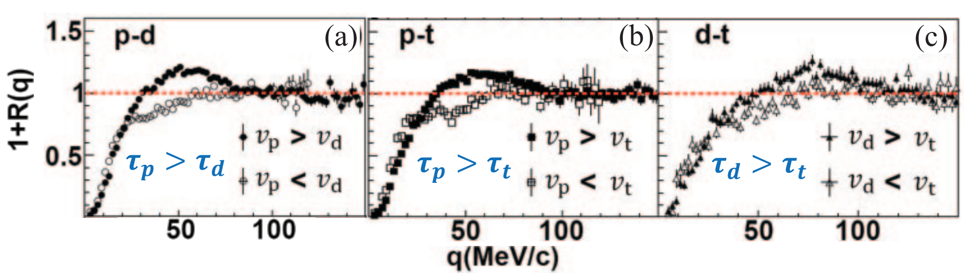

Fig. 4. – The velocity-gated correlation function of proton-deuteron(a), proton-triton(b) and deuteron-triton(c). The data is from [6].

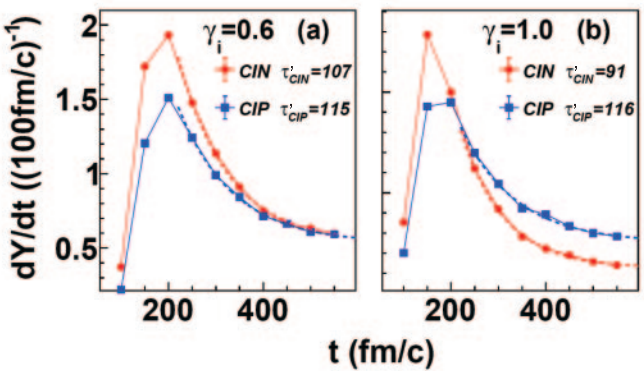

Fig. 5. – The emission rate over evolution time of CINs and CIPs. Two density dependent slope parameters $\gamma_{\rm i} = 0.6$ (a) and 1.0 (b) are used in the calculations. The emission timescales are obtained by fitting the data. And the fitting results are drawn with dash lines. The figure is from [6].

proton, deuteron and triton is obtained similarly (fig. 4). It suggests that neutron rich particles are emitted earlier in the dynamic emission process, which is consistent with the conclusion obtained in a lighter reaction system [23].

3·3. *Transport theory calculation.* – The emission timescale of particles reflects the integration effect of the potential during the particle emission process. To characterize the relaxation of the IDOF, the coalescence invariant neutrons (CINs) and protons (CIPs) emission rates over evolution time are explored with an Improved Quantum Molecular Dynamics (ImQMD) [25]. The CINs (CIPs) are the total neutron (proton) numbers summed over the light charged particles with $Z < 3$. The detail interaction potential and calculation process of the ImQMD which is used in the same reaction, can be found in [26]. To explore the relationship between particle emission timescale and symmetry energy, two density dependent slope parameters $\gamma_{\rm i} = 0.6$ (fig. 5(a)) and 1.0 (fig. 5(b)) are simulated. After fitting the descent data points with an exponential decay function $\exp(-t/\tau')$ in fig. 5 , the emission timescales of CINs and CIPs were obtained, as indicated in the panels. The results indicate that the difference of emission timescales between CINs and CIPs is dependent on the density dependent slope parameter of the symmetry energy. It suggests that the isospin dependent particle emission timescale may be a new way to explore the symmetry energy and isospin dynamics.

4. – Summary

The isospin chronology of hydrogen isotops is studied via HBT correlation function method in $30 MeV/u ^{40}Ar + ^{197} Au$ with CSHINE. The dynamic emission timescale of proton is extracted as $\tau_p \approx 100$ fm/c by fitting the correlation function with Koonin-Pratt equation. The emission order of hydrogen isotops is evidenced as $\tau_p > \tau_d > \tau_t$ by using the velocity-gated non-identical particles correlation function method, in accordance with the picture that the neutron rich particles are emitted earlier for the $Z = 1$ isotopes. For deeply understanding the relaxation in IDOF, the relationship between isospin dependent particle emission timescale and nuclear symmetry energy are explored with ImQMD transport modal. The simulation results show that the difference of emission timescale between CINs and CIPs is related to the slope parameter L of the symmetry energy $E_{\rm sym}(\rho)$. Hence, the isospin chronology may be a promising route to study the properties of symmetry energy and isospin dynamics. More experimental and theoretical explorations are called for in the future.

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