Systematic studies of binding energy dependence of neutron-proton momentum correlation function

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Abstract. Hanbury Brown-Twiss (HBT) results of the neutron-proton correlation function have been systematically investigated for a series nuclear reactions with light projectiles with help of Isospin-Dependent Quantum Molecular Dynamics model. The relationship between the binding energy per nucleon of the projectiles and the strength of the neutron-proton HBT at small relative momentum has been obtained. Results show that neutron-proton HBT results are sensitive to the binding energy per nucleon.

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1. INTRODUCTION

The intensity interferometry was developed by Hanbury-Brown and Twiss [1, 2, 3] in the 1950s, as a means of determining the dimension of distant astronomical objects. After a number of terrestrial experiments were performed to confirm this technique, the method of intensity interferometry is now commonly referred to as the Hanbury-Brown/Twiss (HBT) effect. HBT interferometry differs from ordinary amplitude interferometry in that it comprises intensities, rather than amplitudes, at different points. It indicates the effects of Bose or Fermi statistics even if the phase of the (light or matter) wave is disturbed by uncontrollable random fluctuations or if the counting rate is very low [4]. It has also become an important tool in high energy heavy ion collision region since it can be utilized to measure the evolving geometry of the interaction zone while being applied to the studies to search for a possible quark-gluon plasma and study the properties of the predicted new state of matter [5, 6, 7, 8].

In the applications of experimental and theoretical heavy ion reactions, various aspects have been investigated via the HBT correlation functions (for the review, e.g., see Refs. [4, 5]). Overlooking the literatures [9, 10, 11, 12, 13], more studies on HBT with unstable nuclear beam can be explored. In terms of the structure of the nuclei,
integral measurements, such as total reaction cross sections \[1, 15, 16, 17\], are only sensitive to the overall size. However, the dissociation reactions, in which the core and/or nucleons are detected in the final state, can provide some structure information \[18\]. The major difficulty is the relationship between the initial and final states as dictated by the distorting effects of the reaction \[19, 20\]. It is very interesting to investigate the nuclear structure via HBT technique further.

The binding energy is very important for the structure of nuclei and it indicates of the stable level of nucleus and nucleon-nucleon relationship among nucleus. It has been studied through the density calculation with the Relativistic Mean Field theory in the past years. In this paper, we will make a systematical study of the relationship between the binding energy per nucleon and the strength of neutron-proton correlation function at very small relative momentum with help of Isospin-Dependent Quantum Molecular Dynamics (IDQMD) model which can describe the reaction dynamics on the event-by-event basis.

2. MODEL DESCRIPTION

Firstly, we would like to recall the HBT technique. As we know the wavefunction of relative motion of light identical particle, when emitted in close proximity in space-time, is modified by the final-state interaction and quantum statistical symmetries, and this is the principle of the intensity interferometry, i.e. HBT. In standard Koonin-Pratt formalism \[3, 21, 22\], the two-particle correlation function is obtained by convoluting the emission function \(g(p, x)\), i.e., the probability for emitting a particle with momentum \(p\) from the space-time point \(x = (r, t)\), with the relative wave function of the two particles, i.e.,

\[
C(P, q) = \frac{\int d^4x_1d^4x_2g(P/2, x_1)g(P/2, x_2)|\phi(q, r)|^2}{\int d^4x_1g(P/2, x_1)\int d^4x_2g(P/2, x_2)}.
\]

(1)

where \(P = p_1 + p_2\) and \(q = \frac{1}{2}(p_1 - p_2)\) are the total and relative momenta of the particle pair respectively, and \(\phi(q, r)\) is the relative two-particle wave function with \(r\) being their relative position, i.e., \(r = (r_2-r_1) - \frac{1}{2}(v_1 + v_2)(t_2 - t_1)\). This approach has been very useful in studying effects of nuclear equation of state and nucleon-nucleon cross sections on the reaction dynamics of intermediate energy heavy-ion collisions \[23\]. In this work, we use the Koonin-Pratt method to investigate the neutron-proton correlation function of a few isotope chains to explore the binding energy dependence of the HBT strength in intermediate energy heavy-ion collisions.

Using the computation code Correlation After Burner of Pratt \[24\], which takes into account final-state nucleon-nucleon interactions, we have constructed two-nucleon correlation functions from the emission phase space given by the IDQMD model.

Interpretation of correlation functions measured in heavy-ion collisions requires understanding the relationship of the parameters extracted from fitting the data and the true single-particle distributions at the freeze-out. This relationship can be established by using an event generator that models the collision dynamics, particle production,
and then construct a two-particle correlation function. The event-generator correlation functions are constructed from the positions and momenta representing the single-particle emission distribution at the time of the last strong interaction, i.e. at freeze-out. The event-generator used in our work is the Isospin-dependent Quantum Molecular Dynamics transport model, which has been applied successfully to the studies of the heavy-ion collisions process \cite{25, 26, 27}. For completeness, we would like to give a brief sketch of the model in following.

The Quantum Molecular Dynamics (QMD) approach is an n-body theory to describe heavy ion reactions from intermediate energy to 2 GeV/n. It includes five important parts: the initialization of the target and the projectile; the propagation in the effective potential; the collisions between the nucleons; the Pauli blocking effect and the numerical tests. A general review about the QMD model can be found in \cite{25}.

As we know, the dynamics in heavy-ion collisions at intermediate energies is mainly governed by three components, namely the mean field, two-body collisions, and Pauli blocking. Therefore, for an isospin-dependent reaction dynamics model it is important for these three components to include isospin degrees of freedom. What is more essential, in the initialization of projectile and target nuclei, the samples of neutrons and protons in phase space should be treated separately because there exists a large difference between neutron and proton density distributions for nuclei far from the $\beta$-stability line. Particularly, for light neutron-rich nucleus one should sample a stable initialized nucleus with neutron-skin structure and therefore one can directly explore the nuclear structure effects through a microscopic transport model. The IDQMD model has been improved based on the above ideas.

The nuclear size and density distribution are important bulk properties of nuclei that are mainly determined by the nuclear potential, single-particle orbits and wave function \cite{28}. In the IDQMD model, the neutrons and protons are distinguished from each other in the initialization of projectile and target nuclei. The references of neutron and proton density distributions for the initial projectile and target nuclei in IDQMD are taken from the Skyrme-Hartree-Fock (SHF) method with parameter set SKM* and they can be obtained through Monte-Carlo sampling technique in IDQMD which gives the similar distributions to the input ones from SHF. The input density distributions of B-isotopes which are used as the references of the IDQMD initialization of the projectiles by Monte-Carlo sampling in our calculation are shown in Fig. 1(a). From the figure, we can see, with the increasing mass number, the total density distribution extends a larger range. In general, it is known that the radius of the isotopes becomes larger with the rising of neutron number. Our calculated density distribution reproduces this tendency very well. The relationship between the RMS radius and the binding energy per nucleon is shown in Fig. 1(b). It is obvious that the radius tends to be small with the increasing binding energy per nucleon. In this figure, we plot three-set values of RMS radius, namely SHF radius from our calculations (solid squares), the experimental data \cite{29} and the deduced values from Glauber model \cite{30}. As we know, the binding energy per nucleon indicates of the compactness among nucleons. While, HBT can give us the
spatial information, such as source size. Therefore it is very interesting to investigate the tightness of the nuclei through HBT. With these suitable nuclear density distributions we could get the coordinate of nucleons in the initial nuclei in terms of the Monte-Carlo sampling method. The momentum distribution of nucleons is generated by means of the local Fermi gas approximation.

It is well known that the binding energy ($E_{\text{binding}}$) of the nuclei incarnates the stability level of the nucleus and the relationship among the nucleons. With higher $E_{\text{binding}}$ per nucleon, normally, the nuclear stability is higher too. It is an important way to study the inner structure of the nuclei. In some simulation models $E_{\text{binding}}$ is considered as a benchmark so that the most suitable results can be obtained. In this
In the IDQMD model in zero temperature, $E_{\text{binding}}$ per nucleon of the nuclei can be obtained and its stability can be checked till a longer time. During the evolution process lasted till 200 fm/c, the transport process of the nucleons are governed by the initialization, the Pauli blocking effects, nucleon-nucleon collisions and nuclear mean field etc. In our calculations, only those events which keep good stability according to their radii and $E_{\text{binding}}$ per nucleon are selected. From these events we can choose the most suitable initialization phase space. For instance, for isotopes $^{11-14}B$ which we will use in our simulation calculation, the time evolution of the binding energy in zero temperature are shown in Fig. 2. The dots are the simulation results of the binding energy per nucleon of the isotopes with the time. The numbers behind the labels are the experimental $E_{\text{binding}}$ values of the isotopes. From Fig. 2 it is clearly that the values of the binding energy per nucleon are almost the same as the experimental value and the nucleus keeps its own stability throughout the simulation process in the case of no thermal excitation.

3. RESULTS AND DISCUSSION

The approach of HBT with IDQMD has been applied in reproducing the halo neutron-halo neutron correlation function of HBT results in IDQMD [31]. In our work [31], the nucleons are defined as emitted if they do not belong to any clusters ($A \geq 2$) which are recognized by a simple coalescence model: i.e. nucleons are considered to be part of a
cluster if in the end at least one other nucleon is closer than \( r_{\text{min}} \leq 3.5 \text{ fm} \) in coordinate space and \( p_{\text{min}} \leq 300 \text{MeV/c} \) in momentum space in the final state. With this approach, the experimental data could be reproduced well.

Based on the above success to fit the data, we further made a prediction for the \( E_{\text{binding}} \) dependence of n-p HBT strength for Be-isotopes in [31]. Here we wonder its applicability for other light isotopes. To the end, we select that the target is \(^{12}\text{C}\) and the projectiles are \( \text{Li, B, N and C-isotopes, respectively.} \) The incident energy is 800 MeV/n. The emitted nucleons which are taken into account in the HBT calculation are all from the projectiles.

The calculated results are shown in Fig. 3 at 200 fm/c which is well later than the freeze-out time for the central collisions at 800 MeV/n. The soft potential (an incompressibility of \( K = 200 \text{ MeV} \)) and the asymmetrical strength \( C_{\text{sym}} = 32 \text{ MeV} \) between the neutron and the proton is used in IDQMD simulation. Fig. 3(a) shows the n-p correlation function which peaks at \( q \approx 0 \text{ MeV/c} \). The deviation of \( C(q) \) from 1 thus reflects the information of the emission source. Fig. 3(b) shows the relationship between the strength of n-p correlation function \( C_{\text{PN}} \) at 5 MeV/c versus the binding energy per nucleon of the projectile \( E_{\text{binding}} \). The solid line is just a linear fit to guide the eyes.

From the figure, it is clearly that the strength of HBT at very small relative momentum shows a distinct dependence on the neutron number and the tendency of \( C_{\text{PN}} \) rises with the increasing of \( E_{\text{binding}} \). Among the projectiles we studied, the number of the protons is five and that of the neutron is gradually increasing. With the increasing of the mass number, the mean relationship among the nucleons changes weaker in general. Since the strength \( C_{\text{PN}} \) of correlation function reflects the mean relationship among the emitted neutrons and protons and the binding energy associates with the tightness among the nucleons, it is reasonable to exist such a relationship between these two parameters. Actually, the tendency shown in Fig. 3 indicates that \( C_{\text{PN}} \) can reveal the compactness of the nuclei.

Considering that the correlation function is influenced by the spatio-temporal information of the emitted particles, it is necessary to investigate the HBT results in different evolution time. The results are shown in Fig. 4. For our systems at 800 MeV/n the freeze-out time is less than 100 fm/c in IDQMD model. From Fig. 4 one can find that the HBT strength has the strong dependence with the \( E_{\text{binding}} \) at the different evolution time. Generally speaking, the strength of HBT becomes weak in late stage of time evolution which is a natural result since the system tends more dilute which reduces the spatial correlation between nucleons. However, the tendency of relationship between the HBT strength and the \( E_{\text{binding}} \) does not change despite the different value of \( C_{\text{PN}} \) reveals when the different evolution time is used. As a result, it is reliable to investigate qualitatively the behavior of HBT strength at a certain evolution time which is later than the freeze-out one. This is a reason why we choose \( t = 200 \text{ fm/c} \) to extract the correlation function as shown in Fig. 3.

In addition, we investigated the relationship of \( C_{\text{PN}} \) versus \( E_{\text{binding}} \) in other three
isotopes of $Li$, $C$ and $N$. The calculated results are shown in Fig. 5. Again the HBT results are extracted at $t = 200$ fm/c. The calculation condition is the same as that of $B$-isotopes. From Fig. 3 one can find that the nearly linear relationship between the $E_{binding}$ per nucleon and the strength of proton-neutron correlation function $C_{PN}$ at 5 MeV/c exists in these different isotopes.

4. SUMMARY

In summary, the intensity interferometry technique has been used to investigate systematically its sensitivity to the binding energy of light nuclei from the break-up of nuclei by convoluting the phase-space distribution generated with the IDQMD model. Firstly, we use SHF to determine the reasonable initial density distributions
Figure 4. The comparison of the n-p HBT strength at different evolution time. The stars, filled circles and opened circles are the results at the evolution time of 100fm/c, 200fm/c and 400fm/c. The dotted lines are linear fits to guide the eyes.

which are taken as the references of IDQMD initialization of projectile and target by the Monte-carlo sampling. The stability has been checked by the time evolution of binding energy in IDQMD at zero temperature and the good stable initial phase space has been selected for the simulation of the event-generator IDQMD model afterwards. The dependence of the proton-neutron correlation functions ($C_{PN}$) at small relative momentum with the binding energy ($E_{binding}$) for four isotope chains ($Li$, $B$, $C$ and $N$) has been systematically explored. It was found that the correlation strength of $C_{PN}$ at small relative momentum rises with the binding energy per nucleon. It is of particular interest if one can explore experimentally.

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Figure 5. The similar results with Fig.3(b) but for different isotopes.

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