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HBT Study of Reactions Induced by Neutron-Rich Nuclei at Intermediate Energy

MA Yu-Gang WEI Yi-Bin SHEN Wen-Qing CAI Xiang-Zhou CHEN Jin-Gen
FANG De-Qing GUO Wei MA Guo-Liang SU Qian-Min TIAN Wen-Dong
WANG Kun ZHONG Chen ZHOU Xing-Fei

(Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China)

Abstract Hanbury Brown-Twiss (HBT) results of the nucleon-nucleon correlation function have been presented for the nuclear reactions with neutron-rich projectiles (Be isotopes) using an event-generator, the Isospin-Dependent Quantum Molecular Dynamics model. We explore that the relationship between the strength of the neutron-proton HBT at small relative momentum and the binding energy of the projectiles. Moreover, we reveal the relationship between the strength of the proton-halo neutron HBT and the single neutron separation energy. Results show that neutron-proton HBT results are sensitive to binding energy or separation energy. The dependences of Equation of State (EOS) and in-medium nucleon-nucleon cross section of the HBT results are also presented.

Key words IDQMD, HBT, correlation function, binding energy, separation energy

1 Introduction

Intensity interferometry originates from the astrophysics in 1950's. It was developed by Hanbury-Brown and Twiss as a means of determining the dimension of distant astronomical objects and subsequently applied the method to a measurement of the angular diameter of Sirius[1]. Although the original application of the HBT effect used photons as the detected particles, it was rapidly realized that the method could be generalized to include correlation measurements for other bosons and fermions as well[2—7]. In 1960's, Goldhaber et al. applied this approach to the research of nuclear physics from a study of pion emission in proton-antiproton annihilation[8]. Recently, the two-particle interferometry in nuclear physics has been considered as a well established and powerful experimental procedure to determine the space-time extent of the particle emitting source.

Some groups have applied HBT technique to study the exotic nuclear reaction recently[9—11]. Studies have been performed for many years for exotic nuclei with the increasing availability of radioactive nuclear beams around the world. Among the various techniques to investigate on the exotic nuclei, the measurements of the total interaction cross section and the fragment momentum distribution of the projectile are the main methods to explore the exotic structure in the past years. However, in terms of the structure of the halo, integral measurements, such as total reaction cross sections, are only sensitive to the overall size. Dissociation reactions, in which the core and/or nucleons are detected in the final state, can provide some structure information[9,10]. So it is very interesting to investigate the exotic nuclei via HBT technique further.

As we know, the binding energy and the nucleon(s)-separation energy are important physical quantities for the structure of the nuclei. The former indicates the stable level of the nucleus and the nucleon-nucleon relationship among the nucleus, and the later is a good criterion to verify the possibility of the exotic nucleus. These two have been studied through the density calculation by RMF theory in the past years. Researches about these two factors via the nuclear collisions are needed. In this work, we shall explore the relationship between these two factors and the nucleon-nucleon correlation function value at very small relative momentum with help of Isospin-Dependent Quantum Molecular Dynamics (IDQMD) model which describes the reaction dynamics on event by event basis.

2 HBT Method

The wave function of relative motion of light identical particles, when emitted in close proximity in space-time, is modified by the final-state interaction (FSI) and quantum statistical symmetries (QSS), and this is the principle of the intensity interferometry, i.e. HBT. In standard Koonin-Pratt formalism[3,12,13], 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.,

$$C(\boldsymbol{P},\boldsymbol{q})=\frac{\int \mathrm{d}^4x_1\mathrm{d}^4x_2 g(\boldsymbol{P}/2,x_1)g(\boldsymbol{P}/2,x_2)|\varphi(\boldsymbol{q},\boldsymbol{r})|^2}{\int \mathrm{d}^4x_1 g(\boldsymbol{P}/2,x_1)\int \mathrm{d}^4x_2 g(\boldsymbol{P}/2,x_2)}$$

where $\boldsymbol{P}(=\boldsymbol{P}_1+\boldsymbol{P}_2)$ and $\boldsymbol{q}(=\frac{1}{2}(\boldsymbol{P}_1-\boldsymbol{P}_2))$ are the total and relative momenta of the particle pair respectively, and $\varphi(\boldsymbol{q},\boldsymbol{r})$ is the relative two-particle wave function with r being their relative position, i.e., $\boldsymbol{r}=(\boldsymbol{r}_2-\boldsymbol{r}_1)-\frac{1}{2}(t_2-t_1)$. This approach has been very useful in studying effects of nuclear equation of state (EOS) and in-medium nucleon-nucleon cross sections (σ_{nn}) on the reaction dynamics of intermediate energy heavy-ion collisions[13]. In this work, we use the Koonin-Pratt method to investigate the neutron-proton correlation function of a few isotope chains to explore the dependence of binding energies on the strength of the HBT in intermediate energy heavy-ion collisions.

Using the computation code Correlation after Burner of Pratt[14], which takes into account final-state nucleon-nucleon interactions, we have evaluated two-nucleon correlation functions from the emission function 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 freeze-out. This relationship can be established by using an event generator that models the collision dynamics, particle production, and then constructing 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 in this work is the IDQMD, which has been applied successfully to the studies of the heavy-ion collisions which includes the simulation of the reaction process[15]. The Quantum Molecular Dynamics (QMD) approach is an n-body theory to describe heavy ion reactions from intermediate energy to 2GeV/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 Ref. [15].

3 Results and discussions

In order to check the reliability of QMD with the HBT approach, we first analyze the reaction of ^{14}Be fragments into ^{12}Be+2n at 35MeV/n with the target ^{12}C. ^{14}Be nucleus, which has been studied both theoretically and experimentally, has been approved as a halo nucleus with two halo neutrons[11,16,17]. Fig. 1

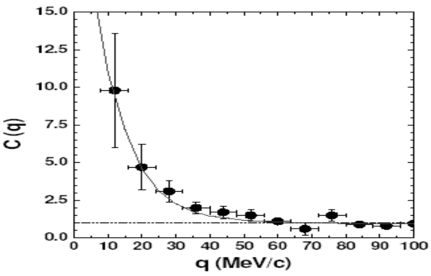

Fig. 1. The solid circles with error bars are the experimental data for the two halo-neutron correlation functions in the reaction of ^{14}Be fragmented into ^{12}Be+2n at 35MeV/n and the target is ^{12}C [11]. The solid line is the calculated two-halo neutrons correlation function.

shows the experimental and the calculated correlation functions between two halo neutrons. The two halo neutrons in calculation are defined as the emitted neutrons in coincidence with ^{12}Be core. The solid line is the calculated two halo neutron correlation function. It shows clearly that the correlation function between the two halo neutrons reproduces the experimental data excellently, which is consistent with the small two neutron separation energy. More information could be found in Ref. [18].

Now we move to study the binding energy dependence of the proton and neutron correlation function. The target is ^{12}C and the projectiles are Be isotopes. Only those events in which the neutron and the proton are emitted in the same event are accepted. The calculated results are shown in Fig. 2. The figure shows the proton-neutron correlation function for different Be isotopes and the insert of Fig. 2. shows the relationship between the strength of proton-neutron correlation function C_{PN} at 5MeV/ c and the binding energy per nucleon of the projectile $E_{binding}$. The solid line of the insert is just a linear fit to guide the eyes. It is obvious that the correlation function between proton and neutron increases with binding energy in Fig. 2.

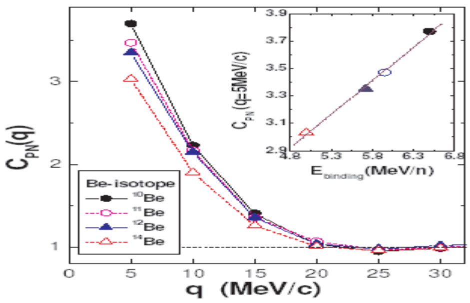

Fig. 2. The proton-neutron correlation function for different Be isotopes. The symbols are illustrated in left bottom corner of Figure. The insert shows the relationship between the strength of proton-neutron correlation function C_{PN} at 5MeV/ c and the binding energy per nucleon of the projectile $E_{binding}$. The collisions were simulated at 800MeV/n of the incident energy and head-on collisions. The target is ^{12}C.

Furthermore, we studied the correlation functions between the proton and the most outside neutron (halo neutron). The relationship between the strength of proton-halo neutron correlation function C_{PH} at 5MeV/ c and the single-neutron separation energy of the projectile E_{sep} was almost linear (see Fig. 3.). Results are similar with those of C_{PN} of Fig. 2.

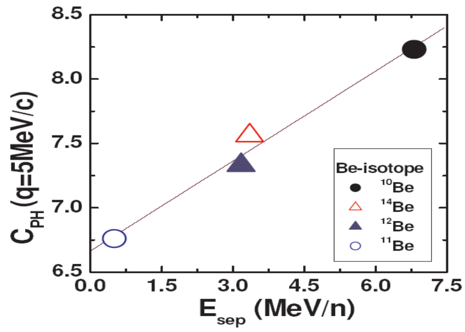

Fig. 3. The relationship between the proton-halo neutron correlation function C_{PH} at 5MeV/ c and the single-neutron separation energy for Be isotopes. The solid line is just a linear fit. The collisions were simulated at 800MeV/n of the incident energy and head-on collisions. The target is ^{12}C.

In addition, we present the HBT results with different aspects including the following three parts: gate of the total momenta of the emission particles, soft and stiff EOS, in-medium nucleon-nucleon cross section and the different impact parameters of the collision. Except for the especial note, the collisions are head-on at 100MeV/n of the incident energy. The target is ^{12}C and the projectile is ^{18}C.

Considering the important role of the emission time in HBT, it is interesting to discuss the influence of total momentum of the emitted nucleons which decides the emission time on HBT. In general, the higher total momentum induces the earlier emission time which consequently induces the stronger correlation. We proceed on the calculation with the different momentum-gated nucleons pairs. The results are shown in Fig. 4 for the HBT strength of neutron-neutron (C_{NN}) at 5MeV/ c, proton-proton (C_{PP}) at 20MeV/ c and neutron-proton (C_{NP}) at 5MeV/ c, respectively, with the soft (open circles) and hard (filled circles) momentum-dependent EOS.

From the figure, we find that with the stiff momentum-dependent potential in EOS, the strength is higher than that with the soft one. The influence of the different potential in EOS will be discussed in the next part in details. It is clearly that the strength of two-nucleon of lower momentum is smaller than that of higher momentum. This is due to the nucleons are emitted on a slow time scale with low total momenta in comparison with higher total momenta.

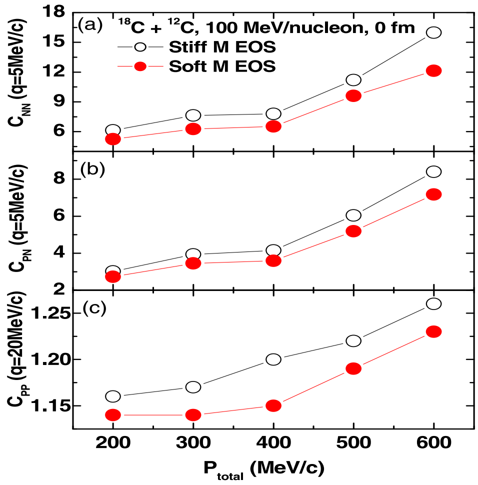

Fig. 4. The relationship between the two-nucleon correlation function at 5MeV/ c ($C_{\rm NN}, C_{\rm NP}$) or at 20MeV/ c ($C_{\rm PP}$) and the gate of the total momentum of the nucleons in the collisions. The collisions were simulated at 100MeV/n of the incident energy. The impact parameter is 0 fm. The projectile is ^{18}C and the target is ^{12}C.

The influence of the in-medium cross section is also investigated. The results are shown in Fig. 5. It is clear that the HBT strength increases with $\sigma_{\rm nn}$. This can be understood in the following way: with bigger nucleon-nucleon cross section, the collision system induces some nucleons emit earlier which make the strength of the correlation function stronger.

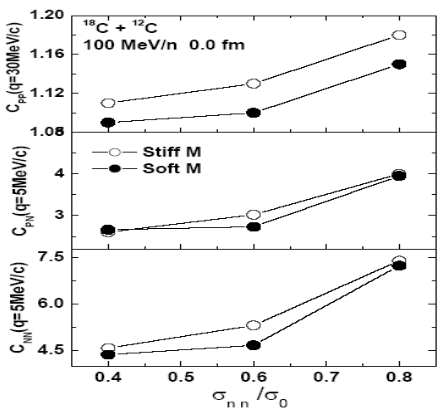

Fig. 5. HBT results with the different $\sigma_{\rm nn}/\sigma_0$ for $C_{\rm PP}$, $C_{\rm PN}$ and $C_{\rm NN}$, Calculation condition is similar to the case of Fig.3. σ_0 is the free nucleon-nucleon cross section.

Details of the Wigner function should depend on the impact parameter of the collision. Considering the importance of the Wigner function in the collisions, we try to explore the character of the collisions with different impact parameter with HBT method. First we calculate the nucleon-nucleon correlation function using the IDQMD model with the different impact parameter. Results are shown in Fig. 6.

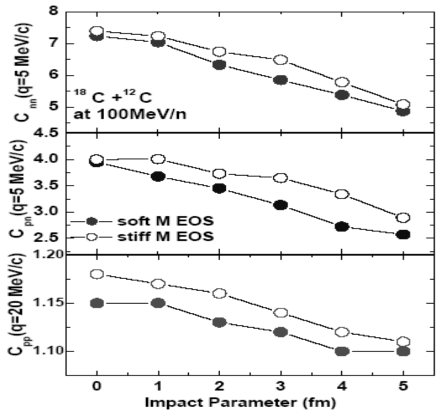

Fig. 6. The relationship of the two-nucleon correlation function at 5MeV/ c for neutron-neutron pair and neutron-proton pair or at 20MeV/ c for proton-proton pair to the impact parameter of the collision. The collisions were simulated at 800MeV/n of the incident energy. The projectile is ^{18}C and the target is ^{12}C.

In the former work[19], some explanations have been introduced. As known, the strength of the correlation function mainly depends on the emission time and the source size. In the collisions, we construct the intensity interferometry with all nucleons emitted with all the total momentum range. One could find the difference of the HBT strength with the soft potential from stiff potential easily. Secondly, the tendency of the strength of HBT becomes weaker with the increasing of the impact parameter in both soft and stiff momentum-dependent potential in EOS. This indicates that the type of the potential in the IDQMD will not change the tendency of the strength of HBT with the increasing impact parameter. On the other hand, the tendency of the HBT strength might stem from the changeable size of the emission source and the reaction violence. In the central collisions, the nucleon-nucleon collisions are very strong and the emitted nucleons are from a hot and squeezed region. This induces higher strength of correlation directly because of smaller source and earlier emission time of nucleons in comparison to that of the peripheral collisions. Also some other reasons including Fermi jets may contribute to it too.

In summary, the HBT intensity interferometry technique has been applied to investigate its sensitivity to the binding energy and separation energy of neutron-rich nuclei from the break-up of nuclei by convoluting the phase-space distribution generated with the IDQMD model. We explore the dependence of the proton-neutron correlation function (C_{PN}) at small relative momentum with the binding energy (E_{binding}) for Be isotopes. It was found that the correlation strength of C_{PN} at small relative momentum rises with the binding energy. Moreover, there exists the similar relationship between the proton-halo neutron correlation function (C_{PH}) at small relative momentum and the separation energy (E_{sep}) of Be isotopes as the relationship of C_{PN} to E_{binding}. From theoretical point of view, E_{sep} dependence of C_{PH} at small relative momentum can be attributed to the spatial extension level of the neutron which is most far away the center of the nucleus. The influence to the HBT results with different nucleon-nucleon cross section, the impact parameters and the gate of the total momenta have also been investigated. Results show that the HBT strength could reveal some details of the collisions at intermediate energy.

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丰中子核反应的HBT效应研究

马余刚　魏义彬　沈文庆　蔡翔舟　陈金根　方德清　郭威

马国亮　苏前敏　田文栋　王鲲　钟晨　周星飞

(中国科学院上海应用物理研究所　上海　201800)

摘要　用同位旋相关的量子分子动力学模型模拟了丰中子弹核引起(Be同位素)的核反应的中子–质子动量关联函数(即HBT), 我们发现在小相对动量的中子–质子的HBT敏感于弹核的结合能, 同时质子–晕中子的HBT依赖于核的单中子分离能. 我们还研究了核态方程和介质中核子–核子截面的对HBT的影响.

关键词　同位旋相关的量子分子动力学模型　HBT　关联函数　结合能　分离能