High Energy Physics and Nuclear Physics

Volume 20, Number 1

Emission-Time Measurements of Light Particles from $^{40}Ar + ^{197}Au$ Collisions in Intermediate Energies

He Zhiyong, Duan Limin, Li Zuyu, Jin Genming, Luo Qingzheng, Wu Heyu, Zhang Baoguo, Wen Wanxin, Qi Yujin, Dang Bingrong, and Dai Guangxi

(Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China)

Particle-particle correlation functions have been measured for $^{40}Ar + ^{197}Au$ collisions at E/A = 25 MeV. Emission time of light particles has been extracted from correlation functions using the three-body trajectory model. The average emission time varies with the energy of particles. It decreases from about 300 fm/c for low energy particles to about 100 fm/c for energetic particles.

Key words: correlation function, three-body trajectory model, emission time.

1. INTRODUCTION

Emission times of the particles from nucleus-nucleus collision in intermediate energies can be used to test various reaction mechanisms, such as equilibrium emission from completely thermalized nuclei or pre-equilibrium emission from partially thermalized nuclei; sequential decay or multifragmentation of fragments from nuclei; emission order of particles, as well as lifetime and decay of hot nuclei. In 1970s, S.E. Koonin suggested to probe the spatial-temporal information of proton from nucleus-nucleus collisions by means of the p-p correlation measurements at small relative momenta [1]. Until now, two-proton correlation measurements are widely made to study the spatial extent of the emitting source and source radii are extracted to be less than 10 fm. However, to predict

Received on January 24, 1995. Supported by the National Natural Science Foundation of China and the Science Foundation of the Chinese Academy of Sciences.

the correlation function and emission times for heavier particles, such as d, t, α, and intermediate-mass fragments (IMF) ($Z \geq 3$), the Koonin model has its deficiency and difficulty. Only little data can be found for the emission time of d, t, and α particles. An adequate theoretical model is needed to study emission times of these particles.

Recently, a classical three-body trajectory model was used to study the correlation function of IMF [2,3]. This model evaluates the trajectories of particles by taking into account the Coulomb and nuclear interactions among three body (two emitted particles and the mother nucleus). Comparison between experimental measurements and model predictions suggests that the emission time of IMF is close to 100 fm/c in the heavy ion collisions at intermediate energies. This paper reports our studies of emission time of light particles at intermediate energies by comparing the experimental correlation measurements at small relative momenta with the three-body trajectory model calculations.

2. EXPERIMENTAL DETAILS

The experiment was carried out at Heavy Ion Research Facility at Lanzhou (HIRFL). A ^{40}Ar beam with beam energy of 25 MeV/u and beam intensity of 10 nA were used to irradiate ^{197}Au target. Two-particle correlations at small momenta were measured by a close-packed array of thirteen ΔE-E telescopes, each of which consists of a 300 μm thick silicon detector as ΔE measurement and a 50 mm thick BGO scintillator as E measurement. Each telescope was located at a distance of 580 mm from the target, and each telescope had a detective area of ϕ17 mm. The array axis was positioned at angle $\theta = 20°$ with respect to beam line. The angular separation between adjacent telescopes was 3°; the maximum relative angle between most distant two telescopes was 13.6°. Particle identifications were done by measuring both the energy loss in ΔE and energy in E. A clear identification for light elements (α, Li, Be, B, C, etc.), as well as all hydrogen isotopes (p, d, t), was obtained for all telescopes.

3. EXPERIMENTAL CORRELATION FUNCTION

The two-particle correlation function $1+R(q)$ is defined in terms of the coincidence yield, $Y_{12}(p_1, p_2)$, and the single particle yield, $Y_1(p_1)$ and $Y_2(p_2)$

$$\sum Y_{12}(p_1, p_2) = (1+R(q)) \sum Y_1(p_1) Y_2(p_2), \tag{1}$$

where p_1 and p_2 are the laboratory momenta of particles 1 and 2, q is the relative momentum given by $\mu | p_1/m_1 - p_2/m_2 |$. The normalization function, $\Sigma Y_1(p_1)Y_2(p_2)$, is obtained by the method of Ref. 4.

Figure 1 shows the correlation functions of light-charged particles measured at $\theta = 20°$ for ^{40}Ar+^{197}Au collisions at 25 MeV/u. The p-p correlation function is shown in Fig. 1(a). A maximum at $q \approx 20$ MeV/c is observed. This peak is caused by the attractive single S-wave interaction between the two detected protons. Roughly speaking, this peak can also be attributed to the decay of unstable ^{2}He nuclei. Comparison between experimental data and theoretical calculation also suggests that this maximum is due to the contribution of pre-equilibrium emission [5]. The peak in Fig. 1(a) indicates that pre-equilibrium emissions exist at the forward angle at 25 MeV/u.

Figures 1(b)-(d) show p-d, d-d, and t-t correlation functions. These correlation functions do not exhibit maxima since these particle pairs are not due to the decay of unstable nuclei. The anti-correlations are observed at small relative momenta, i.e., correlation functions exhibit a minimum at small q. At small relative momenta, the two emitted particles have a small separate distance and a short time interval. The strong Coulomb repulsive interaction between two particles results in this anti-correlation.

Figure 2 shows the dependence of the t-t correlation function on the energy of the outgoing particles. Three constraints on the total energy, $E_1 + E_2$, of the two coincidence particles are

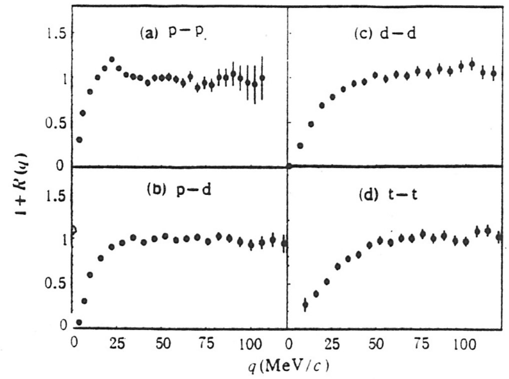

Fig. 1
The correlation function of light particles for $^{40}Ar + ^{197}Au$ reaction at 25 MeV/u.

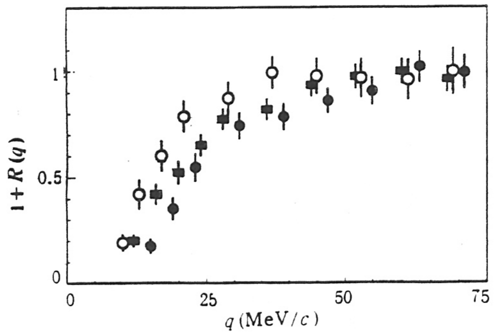

Fig. 2
t-t correlation functions with different constraints on the total energy of the two coincident tritons: $E_1 + E_2$ = 20—60 MeV (○), 60—100 MeV (■), and 100—170 MeV (●).

performed: $E_1 + E_2$ = 20—60 MeV (○), 60—100 MeV (■), and 100—170 MeV (●). The anti-correlation at small relative momenta becomes more pronounced with increasing total energy of the coincident particles, indicating that more energetic particles are emitted more quickly and the repulsive Coulomb interaction is stronger.

4. EXTRACTION OF EMISSION TIME

To extract the emission time of the light particle, the experimental correlation functions are compared with the theoretical calculations of the three-body trajectory code MENEKA [2,7,8]. This code considers that the particles are emitted from the surface of a source with a radius of R. The time delay (t) between the two emitted particles is characterized by an exponential probability distribution $P(t) \propto e^{-t/\tau}$, where τ is the mean emission time. The emitted energy is given by sampling the experimental energy spectrum. The code takes into account the Coulomb and nuclear interactions among two emitted particles and the source. In addition, it also takes into account the acceptance of the detector array.

Figure 3 shows the d-d correlation functions with different constraints on the total energy of the two coincident deuterons: $E_1 + E_2$ = 20—56 MeV, 56—90 MeV, and 90—150 MeV, respectively. The five curves represent calculated d-d correlation with a mean emission time τ = 30, 100, 200, 300, and 600 fm/c, respectively. Figure 3(a) shows the d-d correlation function with the high total energy constraint, $E_1 + E_2$ = 90—150 MeV. This constraint selects energetic deuterons which mainly come from rapid pre-equilibrium emission contributions and contributions from projectile-fragments. Comparing the experimental data with calculated curves, a mean emission time of 100 fm/c is obtained for these energetic deuterons. The transit time (target radius/projectile velocity) for $^{40}Ar + ^{197}Au$ collisions at 25 MeV/u is about 30 fm/c (1×10^{-22} sec). This mean emission time is close to the transit time.

The d-d correlation function with the lowest total energy constraint, $E_1 + E_2$ = 20—56 MeV, is shown in Fig. 3(c). This constraint selects low energy deuterons which mainly come from equilibrated target residues [5]. For these low energy deuterons a mean emission time of over 300 fm/c (1×10^{-21} sec) is observed. This emission time is longer than the evaporation time of light particles

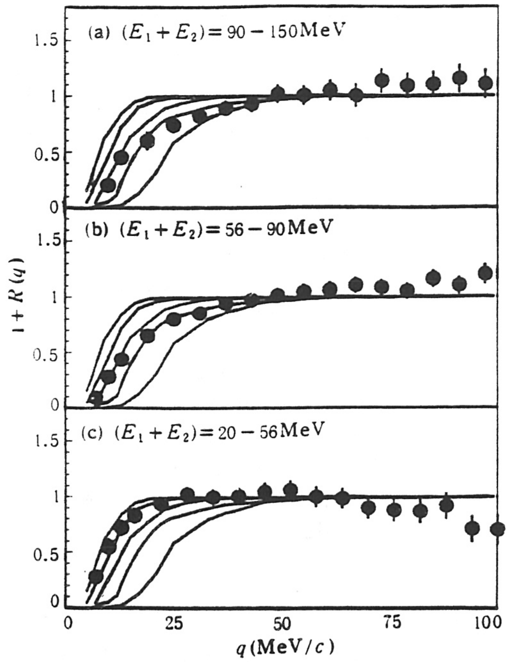

Fig. 3

d-d correlation function and emission time as a function of $E_1 + E_2$. The five curves represent calculated d-d correlation with a mean emission time (from left to right) τ = 600, 300, 200, 100, and 30 fm/c, respectively.

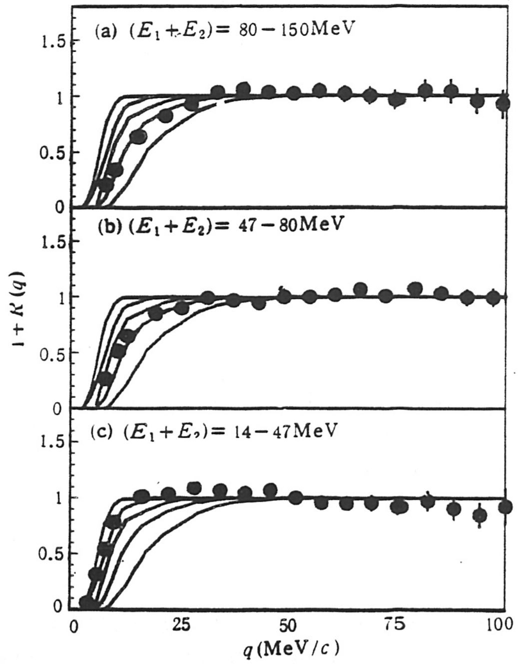

Fig. 4

Same as Fig. 3 but for p-d correlation.

from compound nuclei in low-energy heavy ion reactions: the emission time of protons was measured to be 300—1500 fm/c for $^{16}O+^{27}Al$ reaction at 140 MeV [6]. The d-d correlation function with the medium constraint, $E_1 + E_2$ = 56—90 MeV, is shown in Fig. 3(b). A mean emission time between 100 and 200 fm/c is observed. It is clearly shown in Fig. 3 that the emission time of particles decreases with the increasing energy of particles. It decreases from over 300 fm/c for low energy particles to about 100 fm/c for energetic particles.

Figure 4 shows p-d correlation functions with three energy constraints, $E_1 + E_2$ = 14—47 MeV, 47—80 MeV, and 80—150 MeV, respectively. Similar to d-d correlation, an average emission time of 100 fm/c is obtained for the energetic particles, $E_1 + E_2$ = 80—150 MeV. The emission time becomes longer with the decreasing energy of particles. For the low energy particles with energy constraints $E_1 + E_2$ = 14—47 MeV, a mean emission time of 300 fm/c is observed (Fig. 4(c)). The t-t correlation function and emission time of tritons were also studied as a function of particle energy. Very similar results as p-d and d-d correlation were obtained [9]. This suggests that the emission time of particles varies strongly with the energy of particles and weakly with the mass of particles. It is difficult to identify what kinds of particles are emitted earlier and what kinds are emitted later using this method.

5. CONCLUSION

This paper reports the experimental results of p-p, p-d, d-d, and t-t correlation functions for $^{40}Ar+^{197}Au$ reaction at 25 MeV/u. A maximum at $q \approx 20$ MeV/c is observed for p-p correlation function, indicating that these protons are due to the pre-equilibrium emission in the early stage of collision. The anti-correlation is observed at small relative momenta for p-d, d-d, and t-t correlation functions. Comparing with the three-body trajectory model, the mean emission time of particles is obtained from these correlation function. The mean emission time of particles decrease with the increasing energy of particles. For the energetic particles emission, the pre-equilibrium emission contribution and contribution from projectile-like fragments dominate, the mean emission time is measured to be as short as 100 fm/c. For the low energy particles emission, the contributions from equilibrated hot nuclei are important, the mean emission time is observed to be as long as over 300 fm/c. The average energy of emitted particles increases with the increasing excitation energy of hot nuclei. The mean emission times obtained from our measurements can provide important information on the lifetime and decay of hot nuclei. Particle-particle correlation measurements are a powerful tool to probe the time scale of nuclear reaction.

ACKNOWLEDGMENTS

The authors (especially He Zhiyong) would like to acknowledge A. Elmaani, E. Bauge, and Weidong Jiang for providing the trajectory code MENEKA which made determinations of emission times possible.

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