Emission time scales for light charged particles from symmetric and asymmetric fission processes for $^{40}Ar+^{197}Au$ reactions at 25 MeV/nucleon

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(Received 7 February 1997)

Two-particle correlation functions at small relative momenta were measured in the binary fission processes for $^{40}Ar+^{197}Au$ reactions at 25 MeV/nucleon. Compared to trajectory calculations the mean emission times of light charged particles were determined from two-particle correlation functions. The emission times varied weakly with the mass of the particles, but strongly with the kinetic energy of the particles. A slightly shorter emission time was determined for the particles emitted in the fission plane compared to out of the fission plane due to preferential, in-plane preequilibrium emission with shorter emission time. The emission time of light particles was nearly independent of the mass asymmetry of the fission fragments, depending mainly on the degree of equilibration in the emitting nuclei. A very short emission time of less than 100 fm/c was deduced for the preequilibrium emission of high-energy particle pairs with kinetic energy $E \geqslant 20$ MeV/nucleon while a long emission time of about 600–1000 fm/c was deduced for emission of low-energy particles with $E \leqslant 9$ MeV/nucleon. Such a long time suggests evaporation for these low-energy particles from thermalized compound nuclei or fission fragments. [S0556-2813(98)03203-8]

PACS number(s): 25.70.Pq

I. INTRODUCTION

The disassembly of highly excited nuclear systems remains an open problem in the investigation of intermediate-energy nucleus-nucleus collisions. The time scales of the various disintegration models are of central importance for a complete understanding of the experimental observations. One very successful approach for measuring such time scales is to make correlation measurements between pairs of the light particles, light fragments, and heavy fragments emitted from highly excited nuclear systems. For example, the emission time scales of light particles have been deduced from two-particle correlation functions to probe the mean lifetime for particle emission from excited nuclear systems (e.g., [1–6]). At low energies of a few MeV/nucleon, a thermalized compound nuclear system is expected to be formed and then decay by particle evaporation on a long time scale of more than 300 fm/c [7]. The emission times of evaporated protons were determined to be in the range of 300–1500 fm/c by measuring two-proton correlation functions for the reaction 140 MeV $^{16}O+^{27}Al$ [2]. At intermediate energies of a few tens of MeV/nucleon the emission time scales for the light particles (p,d,t) were deduced by two-particle correlations to be in the range of 100–500 fm/c and to vary with the energies of the particles [6]. On the other hand, the emission times for intermediate-mass fragments (IMF's) with $Z \geqslant 3$ have also been extracted from two-fragment correlation functions to investigate the transition of IMF emission mechanisms from sequential binary disassembly to multifragmentation (e.g., [6,8–19]). Very short emission times for IMF were determined at bombarding energies of 50 MeV/nucleon or more [8–16], indicating that prompt multifragmentation occurred in this energy region; while a long emission time was determined at a bombarding energy of 25 MeV/nucleon [6], suggesting that a sequential binary disassembly occurred. The transitional beam energy appeared to be about 35–50 MeV/nucleon, which decreased with the increasing entrance-channel mass [6]. In addition, the emission times of heavy fragments can be deduced from correlation measurements among threefold- and fourfold-fragment coincidences [20–24].

However, how can one compare these measured emission time scales using various techniques and particle pairs? Recently determinations of the emission order and time delays between light particles and lithium fragments were performed using small-angle correlation methods [25]. The results suggested that the delay time between direct emission and fragmentation was 50 fm/c or less. This work is an attempt to provide further information on the competition between the emission of light particles and the fission process. Since fission of highly excited nuclei has been found to proceed faster for asymmetric mass splits than for symmetric ones, emphasis in this work is placed on the differences in emission times of particles between symmetric and asymmetric fissions. In Sec. II the experimental setup is described. The experimental results of the emission time scales for light particles with different masses, as well as light particles from in- and out-of-fission-plane emission, are described in Sec. III. The emission times of light particles in symmetric and asymmetric fission are reported in Sec. IV. Finally the important results are summarized in the last section.

II. EXPERIMENTAL SETUP

The experiment was performed using the separated-sector cyclotron at the Heavy Ion Research Facility at Lanzhou (HIRFL). A 1.4 mg/cm^2 gold target was bombarded with 25 MeV/nucleon ^{40}Ar ions. Two-particle correlations at small relative angles were measured using a close-packed array of 13 ΔE-E telescopes, each consisting of a 300-μm-thick silicon detector for measuring the particle energy loss ΔE and a

5-cm-thick bismuth germanate (BGO) scintillator for measuring the particle energies E [26]. Clear particle identifications, including for all hydrogen isotopes, could then be made from the combination of the E and ΔE signals from each telescope, each located 58 cm from the target. The center of the array was positioned at 20° to the beam axis, an angle significantly larger than the calculated grazing angle of 6° for our reaction partners. The angular separation between adjacent telescopes was 3.3°; the maximum relative angle between distant telescopes was 13.6°. The energy calibrations of the ΔE silicon detectors were made using the α particles of a ThC-ThC$'$ source and a precise pulse generator. For a certain type of charged particle, the energy deposited in a BGO scintillator can be determined using an energy-loss table from the energy corresponding to the measured energy loss in a ΔE detector. In the offline analyses, the thresholds of 6, 8, 10, 24, and 49 MeV were used for p, d, t, α, and Li, respectively.

In addition, two fission fragments in coincidence with light particles were detected by four, 25×20 cm^2, parallel-plate avalanche counters (PPAC's), each with two-dimensional position sensitivity. The four PPAC's were especially placed with azimuthal angles 0° or $\pm 90°$ relative to those of the telescopes to measure the in- and out-of-fission-plane emission of the particles in coincidence with the fission fragments. The four PPAC's were centered at azimuthally symmetric angles around the beam axis and subtended the polar angles 32°–90°. Position resolution of 4 mm for each PPAC led to an angular resolution of 0.7°. The thresholds of the PPAC's were adjusted to suppress fragments with mass numbers below $A=20$. The signals were recorded on tape event by event with an online data acquisition system supported by a micro VAX-II computer. Only fourfold coincident events in which two fission fragments detected in two different PPAC's and two light particles detected in two different detector telescopes were used in the offline analysis.

III. EXCLUSIVE TWO-PARTICLE CORRELATION FUNCTIONS AND THE EMISSION TIMES OF LIGHT PARTICLES

The two-particle correlation function $R(q)$ is defined in terms of the coincidence yield $Y_{12}(P_1,P_2)$ and the single particle yields $Y_1(P_1)$ and $Y_2(P_2)$:

$$\Sigma Y_{12}(P_1,P_2)=C_{12}[1+R(q)]\Sigma Y_1(P_1)Y_2(P_2). \quad (1)$$

Here P_1 and P_2 are the laboratory momenta of the particles 1 and 2; q is the relative momentum of the correlated pair given by $(P_2/m_2-P_1/m_1)\mu$, where $\mu=m_1m_2/(m_1+m_2)$ is the reduced mass. In our case the correlation function is determined only as a function of $q=|q|$. The normalization constant C_{12} was determined by the requirement that $R(q)=0$ for large relative momenta, where correlations due to final-state interactions should have vanished. For each gating condition, the sums on both sides of Eq. (1) were extracted over all energies and detector combinations corresponding to the given bins of q.

In order to extract the emission times, the experimental correlation functions were compared with theoretical calculations using the three-body trajectory code MENEKA [27]. The code takes into account the Coulomb and nuclear interactions among the two emitted particles and the source. The time interval t between the two emitted particles is characterized by an exponential probability distribution $P(t)\sim e^{-t/\tau}$, where τ is the emission time and freely given. This code considers the particles to be emitted from the surface of a source. The radius of the emitting system (R) is given by $R=rA^{1/3}$, where A is the mass number and r is nuclear density quantity and can be given freely if nuclear expansion is important. Reduction of 20–30 % in A has only a small effect on the calculated correlation functions [10,25]. Use of a smaller nuclear density (i.e., an expanded source) would lead to smaller assignments of τ for cases of short τ values. But the influence of the nuclear density (or the emitter size) on the calculated correlation functions is very small for $\tau\geqslant 150$ fm/c [25,28]. In our calculations normal nuclear radii were used to assign the initial distance between emitter and ejector; therefore, these τ values can be taken as upper limits for cases of $\tau\leqslant 100$ fm/c.

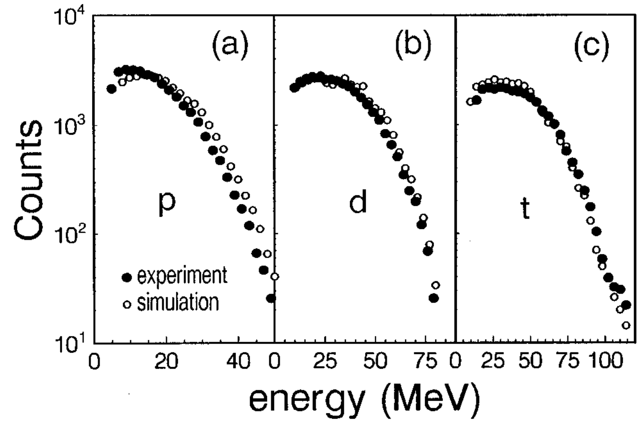

FIG. 1. Experimental and calculated energy spectra for (a) protons, (b) deuterons, and (c) tritons.

The kinetic energy for an emitted particle is sampled from the experimental energy spectrum of the emitted particles in the MENEKA code. This minimizes the effect of errors in the energy calibrations as well as items such as the emitter velocity, its temperature, etc. The solid circles in Fig. 1 represent the experimental kinetic energy spectra for protons, deuterons, and tritons particles. MENEKA calculations give an analytical expression for the spectral shapes in which three Maxwellian distributions are superposed to generate the energy spectrum of the observed particles. The trajectory energy spectra in MENEKA are also shown in Fig. 1 with open circles. In addition, the code also takes into account the acceptance of the detector array.

A. The emission times of different particle pairs

The p-d, d-d, and t-t correlations in coincidence with two fission fragments are shown in Fig. 2 for ^{40}Ar$+^{197}$Au reactions at 25 MeV/nucleon. These correlations exhibit pronounced deficits or anticorrelations at small relative momenta. The anticorrelations are the manifestations of the repulsive, final-state, Coulomb interactions between the emitted particles. A compact source that quickly emits par-

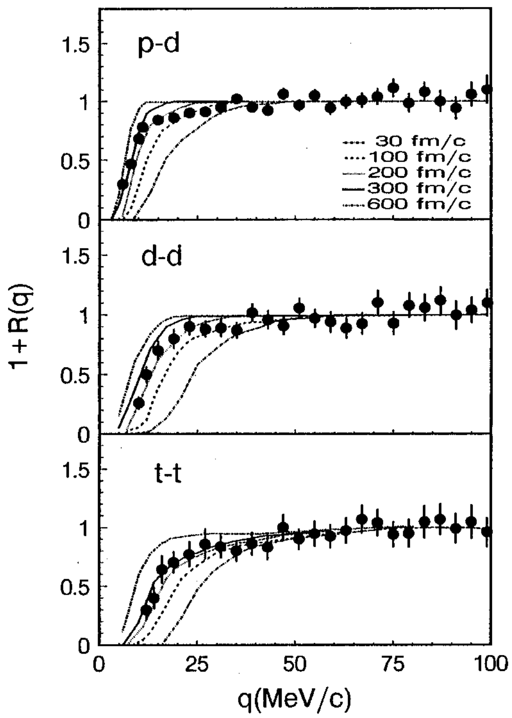

FIG. 2. The p-d, d-d, and t-t correlation functions of the relative momentum q in coincidence with two fission fragments in the reaction 25 MeV/nucleon ^{40}Ar+^{197}Au. The curves show calculations using the three-body trajectory code MENEKA [27] with various values of emission time.

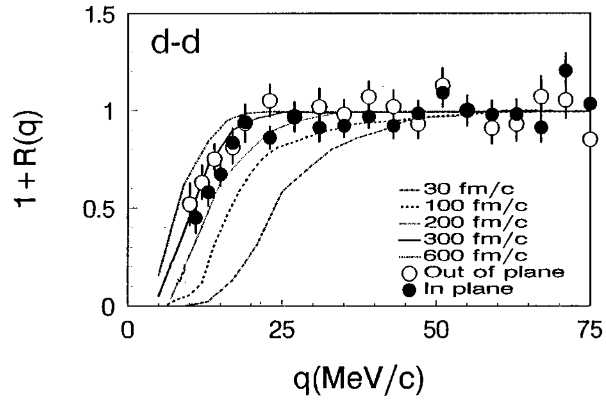

FIG. 3. The d-d correlation functions for in- and out-of-fission-plane emission in the reaction 25 MeV/nucleon ^{40}Ar+^{197}Au. The curves show calculations using the trajectory code MENEKA with various values of emission time.

ticles results in larger Coulomb interactions between the emitted particles than a larger source that emits particles more slowly. Consequently, the emission times of the particles can be determined from the strengths of the anticorrelation valleys near $q=0$ in Fig. 2.

The curves in Fig. 2 represent the calculated correlation functions with emission times τ=30–600 fm/c. The anticorrelations at small q in the calculated correlation functions become more pronounced with decreasing emission time, since the repulsive Coulomb interaction is stronger for the light particles with shorter emission times. The lowermost part of Fig. 2 shows the t-t correlation function. Comparing the experimental data with the calculated curves, a mean emission time of 200–300 fm/c was obtained for these tritons emitted at forward angles. The uppermost and middle parts of Fig. 2 show the p-d and d-d correlation functions, respectively. Similar emission times of 200–300 fm/c were obtained for these correlation functions. Thus, the emission times of these hydrogen isotopes change very little with the masses of the particles. Detailed comparisons of the emission order of nonidentical particles, such as p, d, and t, can be made using velocity difference methods [25,27].

B. Emission times of particles from in-plane and out-of-fission-plane emission

The azimuthal distributions of the emitted particles in nucleus-nucleus collisions can carry important information concerning the reaction dynamics and the nuclear equation of states (e.g., [29]). At incident energies below ≈50 MeV/nucleon the azimuthal distributions have been investigated by using large-relative-angle particle-particle correlations and the observed in-plane enhancement can be well explained by models incorporating the decay of a hot rotating source [30–33]. In this section, the emission times of particles emitted in and out of fission plane are discussed.

For each event the orientation of the reaction plane determined by the two fission fragments was defined as

$$\Phi_F=\frac{1}{2}(\phi_{f1}+\phi_{f2}+180°), \tag{2}$$

where ϕ_{f1} and ϕ_{f2} denote the azimuthal angles of the two fission fragments $f1$ and $f2$, respectively. Since the distribution of the relative azimuthal angle $\Delta\phi_{ff}=\phi_{f1}-\phi_{f2}$ between the two fragments was observed to be strongly peaked at $\Delta\phi_{ff}=180°$ with a full width at half maximum (FWHM) of 18°, the error in the fission plane determination was less than 10°. Then the difference in azimuthal angles between the correlated particle pair and the fission plane was computed as a measure of the in- or out-of-fission-plane emission of the particles. In fact, the out-of-plane emission of particles was measured via the telescope array PPAC 1 and PPAC 3 while the in-plane emission of particles was measured via the telescope array PPAC 2 and PPAC 4.

Figure 3 shows the in- and out-of-plane experimental and model-calculated d-d correlation functions. The mean emission time scale for in-plane emission was slightly shorter than that for out-of-plane emission, since there perhaps was a large preequilibrium component for in-plane emission of deuterons. For deuterons emitted in- and out-of-plane both had emission time scales of about 200–300 fm/c. Such a time scale is much shorter than the fission time scale [34–38], indicating that light particles emitted at forward angles mainly come from preequilibrium and prescission emission. The competition between the emission of light particles and fission will be discussed in detail in the next section.

IV. THE EMISSION TIME SCALES OF LIGHT PARTICLES FROM SYMMETRIC AND ASYMMETRIC FISSION

Recently fission time scales have been derived from the multiplicities of prescission light particles [35–38] and the

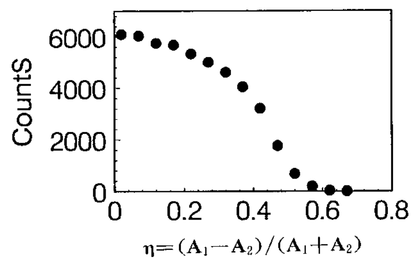

FIG. 4. The mass-asymmetry distribution for the fission fragments in the reaction 25 MeV/nucleon ^{40}Ar+^{197}Au. The variables A_1 and A_2 are the mass numbers for the binary fission fragments with $A_1 \geqslant A_2$.

in-plane angular distribution of fission fragments [34]. All of the results indicate that asymmetric fission of the highly excited nuclei was faster than symmetric fission. The fission time scale varies from about 3000–30 000 fm/c for symmetric fission to about 300 fm/c for asymmetric fission. To determine the emission time scales for light particles from symmetric and asymmetric fissions, the fourfold-coincident events were selected according to the mass asymmetry $\eta = (m_1 - m_2)/(m_1 + m_2)$ of the fission fragments, where m_1 and m_2 are the masses of the two fission fragments with $m_1 > m_2$. Figure 4 shows the distribution of the mass asymmetry η for the fission fragments in the reaction 25 MeV/nucleon ^{40}Ar+^{197}Au, where the uncertainty associated with η is about 0.1. To accumulate sufficient statistics for correlated light particles, all of the events with mass asymmetry $\eta \leqslant 0.2$ were considered as symmetric fissions, while the events with mass asymmetry $\eta > 0.2$ were considered as asymmetric fissions.

In the last section, the correlation functions of the two-particle relative momenta are used to extract emission times for the light particles. The results indicate that the emission times depended very weakly on the masses of the light particles, even if the correlation functions change greatly with the masses of particles. In this section the relative velocity $V_{\rm rel} = |P_1/m_1 - P_2/m_2|$ is used to restructure the correlation functions for $1 + R(V_{\rm rel})$, defined by replaced $R(q)$ in Eq. (1) with $R(V_{\rm rel})$ in order to accommodate and then sum the correlation functions for various particle pairs, such as p-d, d-d, and t-t. Such summing is possible because, as shown in Fig. 2 and discussed earlier, these correlation functions all had roughly the emission times of 200–300 fm/c for MENEKA fits and because the transformation of the correlation function from a function of q to a function of $V_{\rm rel}$ does not alter the value of emission time. The theoretical justification for the correlation functions of the two-particle relative velocity can be also found in the work of Kim *et al.* [18,19].

In Fig. 5 the correlation function $1 + R(q)$ and $1 + R(V_{\rm rel})$ are compared. The superimpossibility of the correlation functions of $V_{\rm rel}$ in Fig. 5(b) suggests that they may be summed over various particle pairs with little loss in correlation function resolution. This ''mixed-pair'' analysis permits the exploration of emission time scales with significantly improved statistical precision. Since obvious correlation peaks from unstable nuclei exist in the p-p, p-t, and d-t correlation functions [6], in the following mixed-pair correlation functions were constructed by summing over the p-d, d-d, and t-t pairs. Sufficient statistics was achieved via

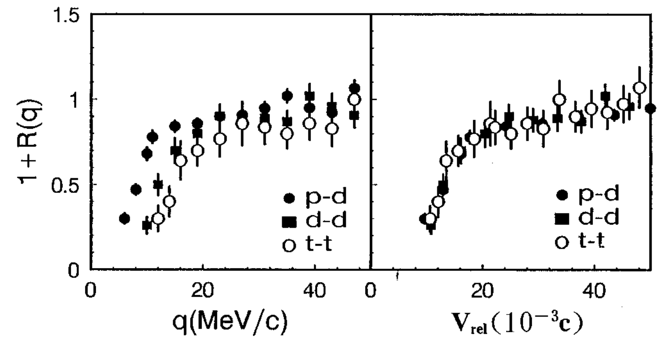

FIG. 5. The p-d, d-d, and t-t correlation functions of the relative momentum q (a) and the relative velocity $V_{\rm rel}$ (b), both in coincidence with fission.

this summation to allow the exploration of emission time scales as a function of the energy of the emitted particles.

A. Emission time scale for light particles from asymmetric fission

The two-particle correlation functions of $V_{\rm rel}$ measured in coincidence with two asymmetric fission having $\eta \geqslant 0.2$ are shown in Fig. 6. For these light charged particles emitted at $\theta_{\rm average} \approx 20°$, there is a prominent forward peak in the angular distributions, especially for the highest-energy particles. This high-energy, forward-peaked particle emission has often been attributed to ''projectilelike'' and ''intermediate-rapidity'' sources. But, of course, it may also include other direct or prethermalization emission. In addition, for these particles emitted at $\theta_{\rm average} \approx 20°$, it also includes low-energy particles from thermalization emission. So cuts are made on the total kinetic energy per nucleon $E = \frac{1}{2}(E_1/A_1 + E_1/A_1)$ to provide a systematic comparison between particle emission and fission versus E, where E_1/A_1 and E_2/A_2 are the kinetic energy per nucleon of particle 1 and particle 2, respectively.

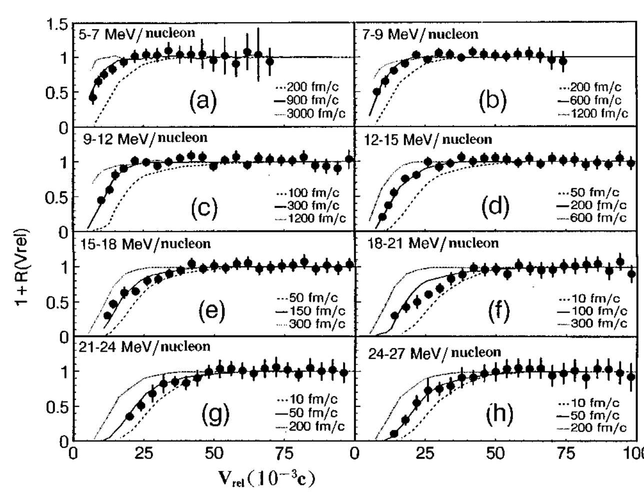

FIG. 6. The two-particle correlation functions of relative velocity $V_{\rm rel}$ in coincidence with asymmetric fission for various constraints on the kinetic energies of the particles for the pair of hydrogen nuclei. The curves show calculations using the trajectory code MENEKA for the indicated values of emission time.

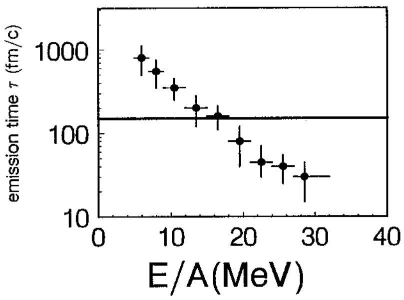

FIG. 7. Emission times extracted from the two-particle correlation functions in coincidence with asymmetric binary fissions as a function of the kinetic energy per nucleon of the particles. The horizontal solid line represents the time scale for asymmetric fission derived from the prescission neutron multiplicities for the $^{32}S+^{197}Au$ reaction at 26 MeV/nucleon [36].

Figure 6(a) shows the two-particle correlation function with the lowest kinetic-energy constraint $E\approx5$–7 MeV/nucleon. This constraint selected particles of low energy for which contributions from equilibrated compound nuclei and fission fragments were important. For these low-energy particles, an emission time of about 900 fm/c was determined from the best fit to the data. This emission time is close to the time to evaporate light particles from compound nuclei in heavy-ion reactions at incident energies below 10 MeV/nucleon [2]. The two-particle correlation functions of V_{rel} summed over the pairs of p-d, d-d, and t-t with the medium energy constraints $E=7$–21 MeV/nucleon are shown in Fig. 6(b)–6(f). In these transitional kinetic-energy ranges the yields include contributions from equilibrated compound nuclei and fission fragments, as well as preequilibrium emission. The mean emission time decreased with increasing particle energy, from about 600 fm/c for the data in Fig. 6(b) with the $E\approx7$–9 MeV/nucleon to about 150 fm/c for the data in Fig. 6(e) with $E\approx15$–18 MeV/nucleon. The shortest emission times were determined in Fig. 6(g) and 6(h) with $E\geqslant20$ MeV/nucleon. Comparing the experimental data with the calculated curves, a mean emission time of about 30–50 fm/c was obtained for these energetic particles. The traversal time defined by the radius of the target divided by the projectile velocity was about 30 fm/c for $^{40}Ar+^{197}Au$ reactions at 25 MeV/nucleon. This time is also the time interval required for the interpenetration of the projectile and target nuclei. Particle emission after fusion of the projectile and target nuclei and complete thermalization must come later. The mean emission time of about 30–50 fm/c for the energetic particles with $E\geqslant20$ MeV/nucleon is close to the traversal time and of the same order of magnitude as the time for direct emission predicted by dynamics models [39–41].

Figure 7 shows the mean emission time for the light particles determined from asymmetric fission events as a function of the average kinetic energy of particles. The horizontal solid line represents the time scale for asymmetric fission derived from the prescission neutron multiplicities for a neighboring system $^{32}S+^{197}Au$ reaction at 26 MeV/nucleon [36]. For the reaction systems undergoing the fission process, one can distinguish three subsequent time intervals: (1) the equilibration time τ_E for compound nucleus formation, (2) the transient time τ_t to reach a quasistationary probability flow across the saddle point for an irreversible development toward scission, and (3) the saddle-to-scission time τ_{ss} in a deformation toward the scission configuration. Neutron- or charged-particle-multiplicity experiments separating the prescission multiplicity M_{pre} from those of the fragments M_{post} by means of the different kinetic focusing of the respective moving sources yield only the sum $\tau_t+\tau_{ss}$. Absolute values for $\tau_t+\tau_{ss}$ deduced with the particle-multiplicity ''clock'' may be affected by systematic errors, e.g., uncertainties in the level densities applied or the initial equilibrium shape at maximum excitation, as well as uncertainties in the extraction of the prescission particle multiplicity. The most precise comparisons between fission time scales and emission time scales for light particles must perhaps be performed in the same experiments using similar methods. Emphasis in this section will be put on the competition between the emission of light particles and the fission process.

The emission times in Fig. 6 and the emission times in Fig. 7 decrease from nearly 1000 fm/c for the lowest-energy constraint to about 30 fm/c for the highest-energy constraint with increasing particle kinetic energy. In the analysis of the fission time scales using the particle multiplicity clock in Ref. [36], the particle energy spectra were decomposed into preequilibrium, prescission, and postscission contributions with a constrained, moving-source analysis, where preequilibrium emission contributed to the high-energy tail of the energy spectrum, while postscission emission contributed to the low-energy part of the energy spectrum. Figure 7 clearly shows that the particles from the preequilibrium contribution were emitted in a short emission time of less than 100 fm/c in asymmetric fission, while the particles from postscission contribution were emitted after a long time of nearly 1000 fm/c. Since asymmetric fission of highly excited nuclei was shown to be faster than symmetric fission, the particles emitted in asymmetric fission with kinetic energy $E\leqslant10$ MeV/nucleon probably came from postscission emission.

B. Emission time scales for light particles from symmetric fission

The two-particle correlation functions of V_{rel} in coincidence with the symmetric fission events defined by $\eta\leqslant0.2$ are shown in Fig. 8 for three ranges of E/u. Similar to asymmetric fission the emission times for the light particles from symmetric fission decreased with increasing kinetic energy of the particles. A complete set of the mean emission time values for light particles in coincidence with symmetric fission versus E/u is plotted in Fig. 9, this time with the horizontal solid line representing the time for a symmetric fission to occur [36]. The evolution of emission time of particles with their kinetic energies in symmetric fission is very similar to that observed in asymmetric fission, i.e., the logarithm of the particle emission time is roughly proportional to the particle kinetic energy, even though the fission time scales derived both from the prescission particle multiplicities [35–38] and from the in-plane anisotropic distribution of fission fragments [34] indicate that asymmetric fission of the highly excited nuclei was faster than symmetric fission. The particles with kinetic energy $E/A=18$–32 MeV are emitted in a short time of less than 100 fm/c, while the particles with $E/A\leqslant9$ MeV are emitted in an emission time of about 600–1000 fm/c. Such a long emission time for low energy par-

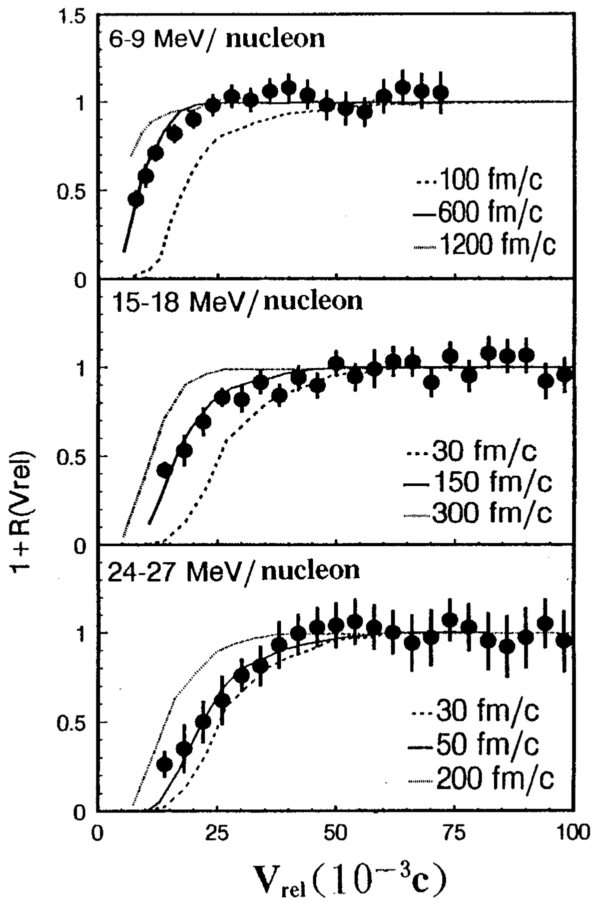

FIG. 8. The two-particle correlation functions of the relative velocity V_{rel} in coincidence with the symmetric fission for three constraints on the kinetic energies of the particles. The curves show calculations using the trajectory code MENEKA for the indicated values of emission time.

ticles is of the same order of magnitude as the time scale for symmetric fission [36]. Two-particle correlation functions of V_{rel} were also measured as functions of the mass asymmetry of the fission fragments using the five windows η=0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4, and greater than 0.4. As shown in

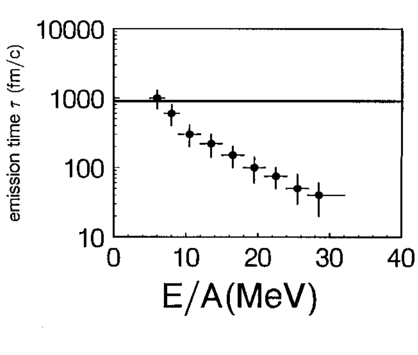

FIG. 9. Emission times extracted from the two-particle correlation functions for the emission of two hydrogen nuclei in coincidence with symmetric binary fission as a function of the kinetic energy per nucleon of the particles. The horizontal solid line represents the time scale for symmetric fission derived from the prescission neutron multiplicities for the $^{32}S+^{197}Au$ reaction at 26 MeV/nucleon [36].

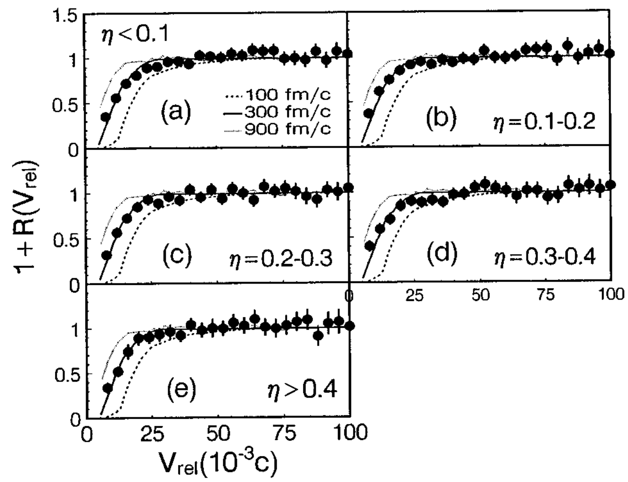

FIG. 10. The two-particle correlation functions of the relative velocity V_{rel} for five windows η=0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4, and greater than 0.4.

Fig. 10, the emission times extracted from them changed very little with increasing mass asymmetry η. This is because these light charged particles emitted at $\theta_{average}\approx 20°$ come from a mixed emission of several sources, such as a projectilelike source, intermediate-rapidity source, thermalized compound nuclei, or fission fragments. Thus, the emission time values of the particles were nearly independent of the fission mass asymmetry, but very sensitive to the degree of equilibration in the emitting nucleus.

V. SUMMARY

Two-particle correlations of both the relative momenta q and the relative velocity V_{rel} were measured in coincidence with two fission fragments in the reaction 25 MeV/nucleon $^{40}Ar+^{197}Au$ in fourfold coincidences in which the two correlated light particles were detected using a close-packed array of 13 ΔE-E telescopes and the two fission fragments were detected using four large-area, parallel-plate avalanche counters. The sensitivity of these correlation functions to final-state interactions between the emitted particles offers a tool for the determination of the emission time scales of the particles in coincidence with fission via correlation fits using the MENEKA code [27]. Anticorrelations were observed at low q in the p-d, d-d, and t-t correlation functions. The emission times for the emitted hydrogen nuclei were found to vary little with their individual masses. A slightly shorter emission time scale was determined for the particles emitted in the fission plane compared to out of fission plane due to preferential in-plane preequilibrium emission with shorter emission time.

The emission times were also deduced as a function of particle kinetic energy for the hydrogen nuclei in coincidence with symmetric and asymmetric fission events. There was a strong variation of the emission times with the particle kinetic energy, but a very weak dependence on the mass asymmetry of the fission fragments. The emission time of the particles was found to depend mainly on the degree of equilibration in the emitting nuclei. A very short emission time of 30–50 fm/c was deduced for energetic particles with $E\geqslant 21$ MeV/nucleon, for which rapid preequilibrium emission contributions dominated. Such a short time indicated that these energetic particles were promptly ejected in direct emission processes while the projectile and target nuclei interpenetrated. A long emission time of 600–1000 fm/c was determined for low-energy particles with $E \leqslant 9$ MeV/nucleon. Such a long time suggests evaporative emission of these low-energy particles from either equilibrated compound nuclei or fission fragments. This evaporation time range of 550–1000 fm/c is of the same order of magnitude as the time scales for symmetric fission determined in [36] for the reaction 26 MeV/nucleon $^{32}S + ^{197}Au$, a reaction very similar to our own.

ACKNOWLEDGMENTS

The authors would like to acknowledge the group of A. Elmaani *et al.* for providing the trajectory code MENEKA [27] which made determinations of the emission times possible. We would like to thank L. Patrick Somerville for help with the English. We would also like to thank the staff of HIRFL for providing the high-quality ^{40}Ar beams. The members of the data acquisition group and the NIM pool are also acknowledged for their warm cooperation. This work was supported by the National Natural Science Foundation of China under Project No. 19675053 and Project No. 19575055 and the Science Foundation of the Chinese Academy of Sciences.

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