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Emission order of light particles and light fragments from hot nuclei followed by binary fission

Zhi Yong He, Gen Ming Jin, Zu Yu Li, Li Min Duan, Guang Xi Dai, Bao Guo Zhang, He Yu Wu, Wan Xin Wen, Yu Jin Qi, Qing Zheng Luo, Su Fang Wang

Institute of Modern Physics, Chinese Academy of Sciences, P. O. Box 31, Lanzhou 730000, Gansu Province, People's Republic of China

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Abstract. Emission orders of light charged particles and Li fragments from highly excited fissioning nuclei in the reaction of ^{40}Ar+^{197}Au at E_{beam}/A=25 MeV have been studied by measuring difference velocity distributions of two correlated particles at small relative angles in coincidence with two fission fragments. By comparing the data with three-body trajectory calculations, we found that high velocity deuterons are emitted prior to high velocity Li fragments but low velocity deuterons are emitted after low velocity Li fragments. On the other hand, no preferential emission was observed among light particles, such as protons and deuterons. Furthermore, the emission orders are found to depend only weakly on the mass asymmetry of fission fragments.

PACS. 25.70.z Low and intermediate energy heavy ion reactions – 25.70.Lm Strongly damped collisions – 25.70.Pq Multifragment emission and correlations

1 Introduction

It is well known that heavy-ion collisions at beam energies around the Fermi energy leads to the formation of hot nuclei (e.g. [1]). However, mechanisms for the formation and decay of these hot nuclei are still under active debate. For a recent review, we refer the reader to [2]. One of the presently most important questions about the decay of hot nuclei focuses on whether the emission of particles and fragments occurs sequentially as the system evolves (e.g., [3–5]) or simultaneously from a single freeze-out configuration (e.g., [6,7]). Emission orders and times of different particles and fragments from hot nuclei may shed some light on this question.

A powerful technique for extracting the emission orders is the analysis of the difference velocity distributions of two correlated particles or fragments with small relative angles [8–12]. Comparison of the difference velocity distributions to three-body trajectory calculations have indeed revealed some interesting information about the decay of hot nuclei. For example, it has been found that high-velocity light particles were emitted prior to Li fragments in the reaction of ^{40}Ar + ^{nat}Ag at E_{beam}/A=34 MeV [11]. In central ^{84}Kr + ^{197}Au collisions at E_{beam}/A=70 MeV, Cornell et al. found that carbon fragments were emitted prior to beryllium fragments when they have the same velocity. All these observations are actually consistent with the sequential decay picture of a thermal source [12].

In this paper we report on results of a study on the emission orders of light particles and fragments from hot nuclei followed by binary fission in the reaction of ^{40}Ar + ^{197}Au at E_{beam}/A=25 MeV. We found that high (low) velocity deuterons are emitted prior to (after) high velocity Li fragments. On the other hand, no preferential emission was observed among unlike light particles. Furthermore, the emission orders are found to depend only weakly on the mass asymmetry of fission fragments.

2 Experiment

The experiment was performed using the separated-sector cyclotron at the Heavy Ion Research Facility at Lanzhou (HIRFL). A 1.4-mg/cm^2 natural 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 germanite (BGO) scintillator for measuring the particle residual energies E [13]. Clear particle identifications, including all hydrogen isotopes, could then be made from the combination of the E and ΔE signals from each telescope, located 58 cm from the target. The center of the array was positioned at 20^o to the beam axis, an angle significantly larger than the calculated grazing angle of 6^o for our reaction partners, and to the right looking downstream in the horizontal plane. The angular separation between adjacent telescopes was 3.3^o; the maximum relative angle between distant telescopes located on the imaginary sphere of radius 58 cm 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 particular type of charged particles, the energy expected to be deposited in a BGO scintillator can be predicted using an energy-loss table from the energy corresponding to the measured energy loss in a ΔE detector. Only p, d, t, α, and lithium fragments with respective kinetic energies above 6, 8, 10, 24, and 49 MeV were included in off-line analyses.

To select central and mid-central events in which hot nuclei with an average excitation energy of about 3-4 MeV/ nucleon are formed [14], 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^o or $\pm 90^o$ relative to those of the telescopes to measure the in- and out-of-fission-plane emission of particles in coincidence with the fission fragments. The four PPAC's were centered at azimuthally symmetric angles around the beam axis, i.e., to the right of, above, to the left of, and below the beam axis, and subtended the polar angles 32^o-73^o, 36^o-84^o, 32^o-73^o, and 43^o-90^o, respectively. The position resolution of 4 mm for each PPAC led to an angular resolution of 0.7^o. The thresholds of the PPAC's were adjusted to suppress fragments with mass numbers below A=20. In the off-line analysis, 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 to probe the emission order of light particles and fragments from hot nuclei.

3 Results and discussion

The yield distributions of coincident pairs of light and heavy particles measured by the telescope array has been constructed as a function of their difference velocities, $V_{diff}=V_{light}$-V_{heavy}. This function has been found to be useful for extracting the relative emission order of the correlated pairs [8–12]. Since these particles measured by the telescope array are emitted with small relative angles, the difference between the positive and negative branch of the V_{diff} spectrum can be used to extract emission order. If the light particle is emitted first and with a higher velocity than the heavy particle, i.e., $V_{diff} > 0$, the Coulomb interaction between them is weak. The telescope array can thus detect them. On the other hand, if the light particle is emitted first but with a lower velocity than the heavy particle, i,e., $V_{diff} < 0$, the heavy particle catches up to the light particle and will be scattered by the strong Coulomb interaction. The relative angle between them is increased so that the telescope array probably can not detect them. Thus, a suppression will be observed for $V_{diff} < 0$ if the light particle is emitted first and vice versa.

We first concentrate on the analysis of V_{diff} spectrum for correlated p-d pairs in coincidence with binary fission fragments. Our data are shown with filled circles in Fig. 1a. It is seen that the spectrum is about symmetric about $V_{diff} = 0$, indicating that there is no preferential emission order for protons or deuterons in the reaction. The dip at $V_{diff} = 0$ is due to the well-known Coulomb interaction between the pair of particles. To be more quantitative about the emission order we have performed three-body trajectory simulations using the code MENEKA [8] which has been widely used in studying the emission time and order of light particles and fragments(e.g., [11,15, 16]). The emission order of particles is given at the beginning of simulations. The time delay (t) between successive emission of two particles is characterized by an exponential probability distribution p(t) $\sim e^{-t/\tau}$, where τ is the emission time and is taken as an adjustable parameter. More detailed discussion about the model can be found in [8]. It is, however, worth mentioning that the acceptance of our detector array has been taken into account in the simulation.

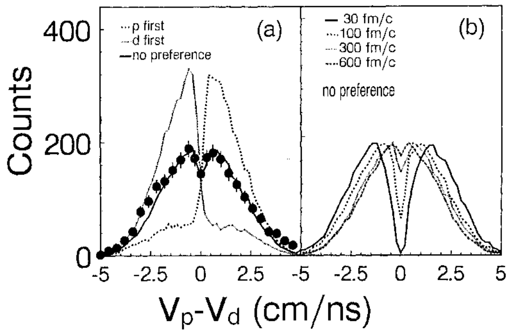

Fig. 1. **a** Difference velocity distributions $V_{diff}=V_p$-V_d for p-d particle pairs in coincidence with fission in the reaction ^{40}Ar + ^{197}Au at E_{beam}/A=25 MeV. The *curves* show calculations using the three-body trajectory code MENEKA. **b** calculated V_{diff} for p-d particle pairs using the three-body trajectory code MENEKA with various values of emission time

The dependence of V_{diff} on the emission time is studied in Fig. 1b, assuming no preference in emission order. It is seen that although the minimum at $V_{diff} = 0$ decreases as the emission time increases as one expects, the spectra are all symmetric about $V_{diff} = 0$ and are rather insensitive to the emission time for $100 < \tau < 600$ fm/c. Results of simulations with $\tau = 300$ fm/c and assuming proton or deuteron emission first, respectively, are shown in Fig. 1a. They are strongly asymmetric about $V_{diff} = 0$ and their quantitative variations are consistent with our early discussions. It is clearly seen that the calculation (solid line) assuming no preference of emission can well reproduce the experimental data.

Protons and deuterons measured in our experiment can come from both pre-equilibrium or direct emission and equilibrium emission of hot nuclei or secondary emission of fission fragments. From the reaction dynamics, one expects that protons and deuterons from the former to have relatively higher kinetic energies than those from the latter processes. To study whether the emission order of protons and deuterons are different in the above processes, we have studied the kinetic energy dependence of the emission order by subdividing protons and deuterons into two

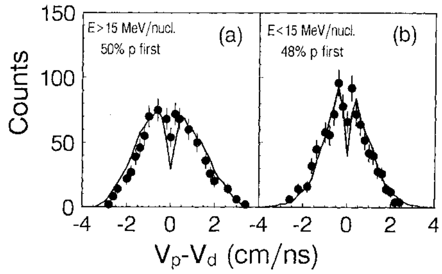

Fig. 2. Difference velocity distributions V_{diff} for p-d particle pairs with high (left) and low (right) energy constraint in coincidence with fission in the reaction ^{40}Ar + ^{197}Au at E_{beam}/A=25 MeV. The *curves* show calculations using the three-body trajectory code MENEKA

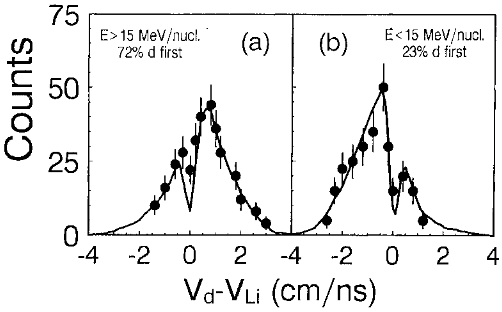

Fig. 3. Difference velocity distributions V_{diff} for d-Li pairs with different energy constraint in coincidence with fission in the reaction ^{40}Ar + ^{197}Au at E_{beam}/A=25 MeV. The *curves* show calculations using the three-body trajectory code MENEKA

groups with kinetic energies higher and lower than 15 MeV/nucleon. As shown in Fig. 2 the V_{diff} spectra for p-d pairs with E≥15 MeV/nucleon and E≤15 MeV/nucleon, can be well fitted assuming that protons are emitted first $(50 \pm 10)\%$ and $(48 \pm 10)\%$ of the time, respectively. The uncertainty of about 10% is primarily due to the uncertainties associated with the fitting procedure, as well as the relative uncertainty in kinetic energies of protons and deuterons. These results together with those shown in Fig. 1 clearly demonstrate that no preference of emission exists among protons and deuterons from hot nuclei followed by binary fission.

We now turn to the V_{diff} spectra for correlated pairs of light particles and Li fragments. Since the various hydrogen isotopes were identified with the telescope array, the velocity of these particles can be readily deduced from their kinetic energy with good precision. However, only element identification was made for Li fragments and the mass number was chosen to be 7 for all Li isotopes. This mass uncertainty results in an uncertainty associated with the velocity of about 10%, i.e., less than 0.7 cm/ns. Figure 3a shows the V_{diff} spectra for d-Li pairs with kinetic energies higher than 15 MeV/nucleon. These energetic particles and fragments may come from the preequilibrium process and projectile-like remnant. In fact, we obtained a very short emission time of about 50 fm/c which is close to the direct emission time predicted by dynamical models [17–20] for these energetic particles. In Fig. 3a, an obvious suppression is observed for the energetic deuterons and Li fragments in the region of $V_{diff} \leq 0$, indicating that the energetic deuterons are emitted prior to the Li fragments. Comparing the experimental data with trajectory simulations, we found that the deuterons were emitted first $(72 \pm 15)\%$ of the time, where the uncertainty of about 15% includes the uncertainty of velocity of Li fragments. Figure 3b shows the V_{diff} spectrum for d-Li pairs with lower kinetic energies. Deuterons and Li fragments in this kinetic energy range mainly come from the decay of equilibrated hot nuclei and primary fragments. A clear suppression is seen in the $V_{diff} \geq 0$ branch of the spectrum, indicating that the fragments from hot nuclei are emitted prior to light particles. More quantitatively, we found that the Li fragments are emitted prior to deuterons $(77 \pm 15)\%$ of the time.

Finally, we study the dependence of the emission order of light particles and fragments on the mass asymmetry ($\eta \equiv (A_1 - A_2)/(A_1 + A_2)$) of fission fragments in the fourfold coincident events. To achieve sufficient statistics, events are divided into two groups with mass asymmetry of $\eta \leq 0.2$ and $\eta > 0.2$, respectively. The V_{diff} spectra for p-d pairs and d-Li pairs in events with $\eta > 0.2$ and $\eta \leq 0.2$ are shown in the four windows of Fig. 4. As shown in Fig. 4a and Fig. 4b, the V_{diff} spectra for p-d pairs are nearly symmetric about V_p-V_d=0 for both groups of events. Comparison to the trajectory calculations indicates that there is no preferential emission between light p-d pairs in the events with $\eta > 0.2$, while deuteron is emitted first $(53 \pm 10)\%$ of the time in the events with $\eta \leq 0.2$. On the other hand, the V_{diff} spectra for d-Li pairs in Fig. 4c and Fig. 4d show that the d-Li pairs with $V_{diff} = V_d - V_{Li} \geq 0$ are slightly suppressed for both groups of events. A careful fitting to the spectra using the trajectory calculations suggests that lithium is emitted first $(62 \pm 15)\%$ of the time in the events with $\eta > 0.2$ and $(58 \pm 15)\%$ of the time in the events with

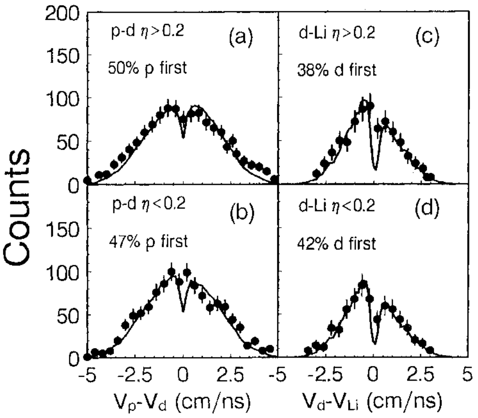

Fig. 4. Difference velocity distributions V_{diff} for p-d d-Li pairs in coincidence with asymmetric fission fragments (η >0.2) and symmetric fission ($\eta \leq 0.2$) in the reaction ^{40}Ar + ^{197}Au at E_{beam}/A=25 MeV. The *curves* show calculations using the three-body trajectory code MENEKA

$\eta \leq 0.2$. Our analysis thus indicates that the emission orders of particles and fragments are only weakly sensitive to the mass asymmetry of fission fragments.

4 Conclusions

In summary, the relative emission order of light particles and fragments from hot fissioning nuclei formed in the reaction of ^{40}Ar+^{197}Au at E_{beam}/A=25 MeV has been investigated by comparing the measured difference velocity distributions with trajectory simulations. Our analysis indicates that high velocity deuterons are emitted prior to high velocity Li fragments but low velocity deuterons are emitted after low velocity Li fragments. On the other hand, no preferential emission was observed among unlike light particles, such as protons and deuterons. Furthermore, the emission orders are found to depend only weakly on the mass asymmetry of fission fragments.

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