

## Reconstruction of Fission Events in Heavy-Ion Reactions Using CSHINE

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### Abstract

We investigated the method for reconstructing fast fission events in the  $^{86}\text{Kr} + ^{208}\text{Pb}$  reaction at CSHINE. The fission fragments were detected by three large-area parallel-plate avalanche counters, which can provide information on the fragment positions and arrival times. The start time information was provided by the RF signal of the cyclotron. We reconstructed the fission events using the velocities of the two fission fragments. The velocity distribution of the fission fragments and the broadening of the azimuthal difference both decrease with increasing folding angle, which is consistent with the picture of fast fission occurrence. Meanwhile, the anisotropic angular distribution of the fission axis also consistently reveals the dynamical characteristics of the fission events.

### Full Text

## Reconstruction of Fission Events in Heavy Ion Reactions with CSHINE

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We report the reconstruction method for fast fission events in 25 MeV/u  $^{86}\text{Kr} + ^{208}\text{Pb}$  reactions at the Compact Spectrometer for Heavy Ion Experiment (CSHINE). The fission fragments are measured by three large-area parallel plate avalanche counters, which deliver position and arrival timing information for the fragments. The start timing information is provided by the cyclotron radio frequency. Using the velocities of the two fission fragments, the fission events are reconstructed. The broadening of both the velocity distribution and the azimuthal difference of the fission fragments decreases with the folding angle, in accordance with the picture that fast fission occurs. The anisotropic angular distribution of the fission axis also consistently reveals the dynamic features of the fission events.

**Keywords:** Fast Fission, Heavy Ion Reactions, Parallel Plate Avalanche Counter, CSHINE

## INTRODUCTION

One of the primary motivations for studying heavy ion reactions (HIR) is to constrain the properties of the nuclear equation of state (EOS), which serves as a crucial input for modeling the evolution and properties of neutron stars and their mergers [1-3]. The isovector sector of the nuclear EOS, specifically the density dependence of the symmetry energy  $E_{\text{sym}}(\rho)$ , remains a long-standing open question in nuclear physics. At Fermi energies, several observables have been identified to constrain  $E_{\text{sym}}(\rho)$  near normal nuclear density, including isospin diffusion, dipole polarizability, and particle emissions [4-10]. Very recently, the PREX II experiment reported results on neutron skin thickness, yielding a stiff  $E_{\text{sym}}(\rho)$  that appears in tension with previous constraints [11, 12]. At supra-saturation densities, numerous experiments have made significant progress in measuring charged pion ratios or collective flow in heavy ion collisions to probe  $E_{\text{sym}}(\rho)$  [13, 14]. An External-target Experiment on HIRFL-CSR (CEE) is currently under construction for studies in this direction [15, 16].

Nuclear fission is a large-amplitude collective motion involving up to hundreds of nucleons. Recently, studies of nuclear fission have experienced a revival due to their significance in both nuclear physics and astrophysics. In stellar environments, the abundance of nuclides in the  $A \approx 160$  region is significantly influenced by the recycling of fission products [17-19]. Theoretically, statistical fission has been well described by microscopic theories and various phenomenological approaches [20-32]. When the excitation energy or angular momentum becomes sufficiently high, as achieved in HIRs well above the Coulomb barrier, the fission barrier tends to vanish. Consequently, the fission timescale becomes shorter by a factor of 10 to 100, and the variance of the mass asymmetry increases significantly (the mass asymmetry of the two fragments can be larger than 0.6),

compared to statistical fission [33–37].

In this regime, the dynamic features of the fission process become significant, and transport models have been successfully applied to describe the fast fission process [38–46]. Time-dependent Hartree-Fock theory can also provide an excellent description of fast fission starting from large deformation [47].

Experimentally, fast fission—often termed dynamic fission due to its vanishing fission barrier and short timescale—has been investigated in various systems over the past three decades [48–54].

The topic of fast fission with simultaneous particle emission deserves further investigation because the fissioning system provides an ideal laboratory for probing  $E_{\text{sym}}(\cdot)$ . The connection between fast fission studies and  $E_{\text{sym}}(\cdot)$  has recently been established through simulations with improved quantum molecular dynamics (ImQMD) [55, 56].

It has been suggested that the fast fission process following HIR carries the effects of  $E_{\text{sym}}(\cdot)$  and provides sensitive probes, due to the formation of a low-density, neutron-rich neck and the larger surface area of the two fragments compared to non-fission processes [56, 57]. The isospin content of light particles emitted from fast fission events has been used experimentally to probe  $E_{\text{sym}}(\cdot)$  [10].

To conduct experimental studies of fast fission and the coincident emission of light charged particles (LCPs) and intermediate mass fragments (IMFs), a compact spectrometer for heavy ion experiment (CSHINE) has been constructed [58, 59]. While LCPs and IMFs are measured using silicon strip detector telescopes (SSDTs) [60, 61], fission fragments are detected by parallel plate avalanche counters (PPACs) [62].

In this paper, we present measurements of fast fission in  $^{86}\text{Kr} + ^{208}\text{Pb}$  reactions using CSHINE in its second phase. Following a brief introduction to the Phase-II CSHINE setup in Section II, the reconstruction of fission fragment velocities is described in Section III, and the dynamic features of fast fission are presented in Section IV. Section V provides a summary.

## CSHINE DETECTOR SYSTEM AND THE EXPERIMENTAL SETUP

The beam experiment was performed at the Radioactive Ion Beam Line I (RIBLL1) at the Heavy Ion Research Facility in Lanzhou (HIRFL), China. A  $^{208}\text{Pb}$  target with an areal density of  $1 \text{ mg/cm}^2$  was bombarded with a  $25 \text{ MeV/u } ^{86}\text{Kr}$  beam. Charged reaction products were measured using CSHINE, which is installed in a large scattering chamber located at the final focal plane of RIBLL1. In the current experiment, three PPACs were installed for fission fragment measurements to reconstruct the reaction geometry. Additionally, four SSDTs were installed covering the polar angle range  $10^\circ < \theta_{\text{lab}} < 60^\circ$ . The SSDT is a three-layer detector consisting of a single-sided SSD (SSSSD) for  $\Delta E_1$  as layer 1,

a double-sided SSD (DSSSD) for  $\Delta E_2$  as layer 2, and a  $3 \times 3$  CsI(Tl) array for residual energy measurements as layer 3. Both the SSSSD and DSSSD are BB7 type detectors (2 mm strip width, 32 strips per side) from MICRON Semiconductor Ltd. Each CsI(Tl) crystal is a square pyramid with dimensions of  $23 \times 23 \text{ mm}^2$  for the front face,  $27 \times 27 \text{ mm}^2$  for the rear face, and 50 mm in height. A photodiode (HAMAMATSU S3204) is used to read out signals from the CsI crystals. Figure 1 [Figure 1: see original paper] shows the detector setup of CSHINE in the experiment. Further details and performance characteristics of CSHINE can be found in references [58, 59]. Table 1 lists the distance  $d$  from the center of each detector to the target, the polar angle  $\theta$ , the azimuthal angle  $\phi$ , and the sensitive area  $S$  of the SSDTs and PPACs in the experiment. The thicknesses of  $\Delta E_1$  and  $\Delta E_2$  for each SSDT are also provided.

The fission fragment detector, PPAC, is a type of multi-wire chamber operating in the limited proportionality region. Signals induced by incident fragments on individual wires of the anode plane, either  $X$  or  $Y$ , are transmitted through a delay line to both ends. The time delay between the two signals  $X_1$  and  $X_2$  ( $Y_1$  and  $Y_2$ ) relative to the signal collected on the cathode plane, which provides timing information, yields the  $X$  ( $Y$ ) position of the hit in the sensitive area. Figure 2 [Figure 2: see original paper] shows a schematic view of the PPAC mechanics. The total thickness of the sensitive gas volume is approximately 2 cm. The PPACs were operated with 4.5 mbar isobutane at 465 V. Under these conditions, fission fragments can be recorded with efficiency above 95%, while LCPs and IMFs are suppressed.

Figure 3 Figure 3: see original paper shows a two-dimensional histogram of  $Y_1 - Y_2$  versus  $X_1 - X_2$  for PPAC1 as an example. The projections onto the  $X$  and  $Y$  directions are plotted in Figures 3(a) and 3(c), respectively. Good timing performance, corresponding to good position resolution, is manifested by the sharp boundary of the two-dimensional distribution and the well-separated individual peaks in the projections. The distance between neighboring wires is 4 mm, and there are 61 peaks in Figure 3(a) and 71 peaks in Figure 3(c). From these data, a time resolution of  $\sigma_{\{T\}} = 300 \text{ ps}$  and a position resolution of  $\sigma_{\{r\}} = 1.35 \text{ mm}$  can be derived. The overall performance of the PPACs is detailed in reference [62].

SSDTs are used to measure LCPs and IMFs in coincidence with fission fragments. To reduce the total number of electronic channels, neighboring strips are merged into a single channel, correspondingly reducing the granularity. Multiple tracks may fire each SSDT. To reconstruct tracks in the SSDTs, a novel algorithm has been developed with special attention to the charge-sharing effect. More than 80% of hits in all layers of the SSDTs can be recognized and assigned to specific tracks. Further details can be found in reference [60].

The trigger system of CSHINE was designed for both beam experiments and calibration. PPAC timing signals were discriminated by CF8000 modules and logically combined by a CO4020 module to generate PPAC inclusive signals and PPAC two-body coincidence signals. SSDT logic hit signals were extracted

from the front side of the DSSSD ( $\Delta E_2$ ) using MSCF-16 discriminators, which generate an analog Multi-Trig signal proportional to the number of fired strips in the same module (16 channels). Both inclusive and exclusive logic signals can be generated by discriminating the Multi-Trig signal at different threshold settings.

In the beam experiment, the trigger signal includes SSD two-body events, PPAC two-body events, and coincidences between PPAC two-body and SSD one-body events. Additionally, inclusive triggers for each individual detector were also implemented, which could be optionally activated for detector calibration before or after beam data acquisition. Further details can be found in reference [60].

## RECONSTRUCTION OF THE VELOCITY

We focus on the reconstruction of fission events. The flight path of fission fragments (FFs) can be accurately determined from the position information provided by the PPACs. The velocity of each FF, however, is derived from timing information. In our experiment, the start time signal is provided by the radio frequency (RF) of the accelerator. The RF signal, typically a sinusoidal waveform, is discriminated by a CF8000 module and fed into a time-to-digital converter (TDC). Generally, for a particle hitting a given detector, the time-of-flight (TOF) is expressed as:

$$TOF = t_{det} - t_{RF} - C_{det}$$

where  $t_{\{det\}}$  and  $t_{\{RF\}}$  are the time signals from the detector and RF, respectively, recorded by the corresponding TDC channels. Both signals are calibrated in nanoseconds using a precise time calibrator.  $C_{\{det\}}$  is a constant representing a fixed electronic delay. The velocity is then computed by:

$$v = \frac{L}{TOF}$$

where  $L$  is the flight path length from the target to the hit position on the detector.

To verify the validity of this TOF measurement method, we used calibrated  $\alpha$  particles, for which the velocity can be independently determined from the energy measured in SSdT3. Figure 4: see original paper shows the correlation between  $\alpha$  energy and TOF derived from equation (1). The theoretical curve fitting the E-TOF profile yields a constant  $C_{\{det\}} = 431.8$  ns.

Panel (b) shows the difference between the TOF measured by TDC and the value  $L/v(E_{\{\alpha\}})$ , where  $v$  is derived from the energy  $E_{\{\alpha\}}$  and  $L$  is the distance from the target to the hit position in SSdT3. A width of 1.3 ns is obtained from Gaussian fitting. After subtracting the contribution from energy uncertainty, a TOF resolution of approximately 1.0 ns is obtained for SSdT.

For FFs measured in PPACs, the TOF resolution will be comparable, as the PPAC timing resolution of 300 ps is slightly better than that of SSDT.

With equation (1) validated, we can now discuss the TOF of FFs. Since PPACs cannot identify the charge or mass of FFs, nor measure the total kinetic energy, one must rely on velocity determination, which requires TOF information and flight path lengths  $L$ . In equation (1), the relative difference in delay constants,  $C_{\text{ppac1}} - C_{\text{ppac2}}$ , between two PPACs can be adjusted to zero using a pulser prior to the experiment, and the systematic uncertainty can be well controlled within  $\pm 2$  ns. However, the absolute value of  $C_{\text{ppac}}$  for each individual PPAC cannot be determined as in SSDT because the particle type and total energy are unknown. To overcome this difficulty, we employ the Viola systematics, which indicates that the average relative velocity of FFs is 2.4 cm/ns [63]. Therefore, by tuning the  $C_{\text{ppac}}$  constants, one can optimize the value to achieve  $v_{\text{FF}} = 2.4$  cm/ns. Figure 5 [Figure 5: see original paper] shows the distribution of  $v_{\text{FF}}$  at different delay constants. It is evident that varying the delay constant by 1 ns causes a significant shift in the peak position of  $v_{\text{FF}}$ . In our experiment,  $C_{\text{ppac}} = 115.5$  ns was optimized, and the corresponding  $v_{\text{FF}}$  distribution is plotted in panel (b). Based on transport model calculations, the variation of  $v_{\text{FF}}$  is better than 0.1 cm/ns, and a systematic uncertainty of 2 ns in the TOF of FFs is estimated, which does not affect the conclusions of the following analysis. We note that coincident events recorded by PPAC1 with PPAC2 (denoted as PPAC1  $\times$  2) or with PPAC3 (denoted as PPAC1  $\times$  3) correspond to fission fragments, as the high-voltage conditions are set such that the PPAC response to energetic LCPs and IMFs is completely suppressed, given that the energy loss of these particles is more than an order of magnitude lower than that of FFs. Additionally, correlations between a heavy projectile-like fragment (PLF) and a target-like fragment (TLF) are outside the current geometrical coverage.

## RESULTS AND DISCUSSIONS

Before discussing the reconstruction of fission events, we first define the fission kinematics. In the incomplete fusion picture, a heavy TLF is formed through the fusion of part of the projectile with the target. The fraction of projectile momentum transferred to the TLF is called linear momentum transfer (LMT). With a certain probability depending on the total angular momentum of the reaction system, the TLF may undergo fission or fast fission in competition with the evaporation residue channel. For fission events, Figure 6 [Figure 6: see original paper] illustrates the kinetic geometry of a TLF fission event. As shown, the origin point  $O$  represents the target nucleus in the laboratory frame, and the vector  $OO$  represents the beam direction. The velocity vectors  $\mathbf{v}_{\text{f1}}$  and  $\mathbf{v}_{\text{f2}}$  of the two fission fragments in the laboratory system are represented by  $OA$  and  $OB$ .  $\mathbf{v}_{\text{tl}}$  is the velocity of the TLF, and the velocities of the two fragments in the center-of-mass system of the fissioning TLF are represented by  $\mathbf{v}$  (back-to-back collinear). Here, we define plane  $OAB$  as the fission plane,

plane  $OOA$  as the projection plane, and the reaction plane is defined as plane  $DOO$ . Once the TOF is determined, the velocity of the FFs can be computed event-by-event using the hit positions of the FFs in the PPACs, allowing the complete fission event to be reconstructed.

Figure 7 [Figure 7: see original paper] shows the velocity distribution of the two fission fragments in  $PPAC1 \times 2$  and  $PPAC1 \times 3$  events. Here,  $\mathbf{v}_{\{f1\}}$  corresponds to the FF recorded in PPAC1, and  $\mathbf{v}_{\{f2\}}$  corresponds to the FF in PPAC2 (PPAC3) for  $PPAC1 \times 2$  ( $PPAC1 \times 3$ ) events. It is shown that for  $PPAC1 \times 2$  events, since the two PPACs are nearly symmetric with respect to the beam, the distributions of  $\mathbf{v}_{\{f1\}}$  and  $\mathbf{v}_{\{f2\}}$  are very similar. Meanwhile, a high-velocity tail is clearly evident in the  $PPAC1 \times 2$  events, and the velocity spectra are broader than those in  $PPAC1 \times 3$  events. This component is mainly due to events with smaller folding angles corresponding to larger LMT, as will be discussed below.

After determining the velocities of the two FFs, the folding angle method can be applied to calculate the LMT of the reaction. Recalling the definitions from Figure 6, the folding angle  $\Theta_{\{FF\}}$  is defined as the angle  $AOC$ , spanned by the projections of the FF velocity vectors onto the projection plane. Clearly, given the velocities  $\mathbf{v}_{\{f1\}}$  and  $\mathbf{v}_{\{f2\}}$ , the folding angle depends on the TLF velocity  $v_{\{t1\}}$ ; that is, the larger  $v_{\{t1\}}$ , the smaller  $\Theta_{\{FF\}}$ . Figure 8 [Figure 8: see original paper] presents the distribution of the folding angle  $\Theta_{\{FF\}}$ . The  $PPAC1 \times 2$  coincident events are distributed in the range of  $70^\circ$ - $120^\circ$  with a peak at approximately  $95^\circ$ , corresponding to larger LMT (red), while the  $PPAC1 \times 3$  events lie in the range of  $120^\circ$ - $170^\circ$ , corresponding to smaller LMT (blue). The valley between the two components is simply due to the efficiency loss caused by the gap between PPAC2 and PPAC3, and the efficiency correction for incomplete azimuthal coverage has not been applied in this plot.

As the fission geometry is determined by the two velocity vectors, it is of interest to examine the planarity of fission events. Figure 9 Figure 9: see original paper presents the azimuthal correlation of the two FFs through a scatter plot of the azimuthal angle difference  $\Delta\phi$  versus the folding angle  $\Theta_{\{FF\}}$ . It is clearly shown that for FFs from both central and peripheral reactions, the most probable value occurs at  $\Delta\phi = 180^\circ$ , consistent with the picture of binary decay. We note that  $\Delta\phi$  is a directly measurable quantity that requires no assumptions. The inset shows the projection distribution of  $\Delta\phi$ , from which a standard deviation of approximately  $\sigma(\Delta\phi) = 10^\circ$  is derived.

Such broadening suggests that emission of LCPs or IMFs may alter the flight direction of the FF and smear the back-to-back characteristic of the fission event. To examine how this evolves with reaction violence, panel (b) plots the standard deviation of the azimuthal angle  $\sigma(\Delta\phi)$  as a function of the folding angle  $\Theta_{\{FF\}}$ . It is shown that  $\sigma(\Delta\phi)$  decreases with  $\Theta_{\{FF\}}$  across the entire range, with the exception of a discontinuity near  $\Theta_{\{FF\}} = 130^\circ$  caused by the gap between PPAC2 and PPAC3. To exclude the possibility that this trend originates from asymmetry in the geometrical placement of the PPACs, we

further restrict the analysis to events where the two FFs fly symmetrically with respect to the beam direction, i.e., under the condition  $\theta_1 = \theta_2$ , where  $\theta_i$  is the polar angle of the  $i$ th fragment. The result is shown by the black squares, where the bin width for each  $\Theta_{\text{FF}}$  is  $\pm 2.5^\circ$ . This condition is applicable only for PPAC1  $\times$  2 fission events because these two PPACs are placed in approximate left-right symmetry with respect to the beam line. Clearly, the data points with the symmetry condition lie on top of those without the condition, indicating that the decreasing trend of  $\sigma(\Delta\phi)$  as a function of  $\Theta_{\text{FF}}$  is truly due to reaction violence. Since post-scission particle emission changes the velocity of the FF through recoil effects, this trend suggests that in fission following intermediate-energy heavy ion reactions, sufficient excitation energy remains at the scission point depending on LMT. In reactions with larger LMT, more excitation energy remains and is released through particle emission in the post-scission stage. This is consistent with the picture of fast fission, rather than statistical fission where the excitation energy is nearly depleted at the scission point.

The dynamic features of fast fission can be further explored through the velocity distribution of the FFs. Figure 10 [Figure 10: see original paper] presents the average (a) and standard deviation (b) of the velocities of FFs recorded in the PPACs as a function of folding angle. Panel (a) shows that the average velocity  $v_{\text{f}}$  decreases with folding angle. Panel (b) shows the standard deviation of the velocity  $\sigma(v_{\text{f}})$ , and it is also evident that the velocity broadening of the FFs decreases with folding angle. This result is consistent with the trend observed for  $\sigma(\Delta\phi)$  in Figure 9.

The scission point is reached early when the excitation energy of the fissioning TLF is still high; thus, statistical fluctuations (corresponding to the remaining excitation energy) enhance the variance of the FF velocity. This is consistent with earlier experimental observations in Ar +  $^{209}\text{Bi}$  reactions at 25 MeV/u [64, 65].

Finally, the dynamic features of fast fission may also cause anisotropy in the angular distribution of the fission axis. Here, the fission axis is defined as the vector of relative velocity  $\mathbf{v}_{\text{FF}}$  from f2 to f1, where f1 and f2 are the two fragments. The angle of the fission axis  $\Lambda_{\text{FF}}$  is the angle of the fission axis with respect to the beam axis, as defined in reference [55].

Typically, experimental measurement of the  $\Lambda_{\text{FF}}$  distribution requires careful correction for geometric efficiency and is therefore better suited for a  $4\pi$  detection system.

In our experiment, the PPACs cover only a portion of the full solid angle. To minimize ambiguity in the geometric efficiency correction, we fix the direction of the first FF in PPAC1. In this case, we need only correct for the efficiency of the second FF on PPAC2 and PPAC3, and the trend of the fission axis angular distribution can be inferred. Figure 11 [Figure 11: see original paper] presents the correlation plot of parallel and transverse velocities of the FFs.

Here, the transverse velocity of FFs recorded in PPAC1 is defined as positive,

while that in the other two PPACs is defined as negative. It is clearly shown that there is a dead area of less than  $20^\circ$  between PPAC2 and PPAC3. The dashed lines define a narrow range of  $40^\circ < \Lambda_{\text{FF}} < 45^\circ$ , which is fixed for investigating the distribution properties of the fission axis as follows.

The distribution of  $d\sigma/d \cos(\Lambda_{\text{FF}})$  is plotted in Figure 12 [Figure 12: see original paper]. The geometric efficiency arising from the incomplete azimuthal coverage of PPAC2 and PPAC3 is corrected in each  $\Lambda_{\text{FF}}$  bin. Events from PPAC1  $\times$  2 and PPAC1  $\times$  3 are represented by symbols, while the curve represents their sum.

It is clearly shown that the efficiency loss due to the gap between PPAC2 and PPAC3 causes a kink over a wide range of  $63^\circ < \Lambda_{\text{FF}} < 80^\circ$ . Excluding the kink region and the uncovered region where  $\Lambda_{\text{FF}} < 50^\circ$ , the distribution of  $dN/d \cos(\Lambda_{\text{FF}})$  increases steadily with  $\cos(\Lambda_{\text{FF}})$  and tends to peak at forward angles, which differs from the expectation of an isotropic distribution for statistical fission. This trend is in qualitative agreement with previously reported experimental results in heavy ion reactions at Fermi energies [48, 49].

## SUMMARY

In summary, fission fragments from 25 MeV/u  $^{86}\text{Kr} + ^{208}\text{Pb}$  reactions have been measured with the CSHINE detection system. In the current phase, three PPACs and four SSDTs are installed to measure fission fragments and coincident LCPs and IMFs, respectively. Using the timing and position signals from the PPACs and the start timing from the accelerator RF, one can measure the velocities of the fission fragments and reconstruct the fission events, from which the linear momentum transfer can be derived via the folding angle.

It is shown that the width of the azimuthal angle difference, as well as the mean value and width of the velocity distribution of the fission fragments, decrease with the folding angle. An anisotropic angular distribution of the fission axis has been observed. These results are consistent with the picture of fast fission. Prospectively, with the capability to reconstruct fission events, CSHINE provides opportunities for studying isospin dynamics and nuclear symmetry energy through further analysis of coincident, isotope-resolved LCPs and IMFs.

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