EPJ Web of Conferences **88**, 00010 (2015)
DOI: 10.1051/epjconf/ 20158800010


# Inverse-kinematics study of $^{78}$Kr + $^{40}$Ca at 10 AMeV

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**Abstract**

The CHIMERA multi-detector array at LNS Catania has been used to study the inverse-kinematics reaction of $^{78}$Kr + $^{40}$Ca at a bombarding energy of 10 AMeV. Analysis of the experimental data focused on a class of selected events consistent with the complete fusion and subsequent binary split of the of the reacting system. This class of events features a broad A, Z distribution of fission fragments centered about symmetric fission while exhibiting relative velocities significantly higher than given by Viola systematics. The center-of-mass angular distribution ($d\sigma/d\Theta$) of the fission fragments exhibit an unexpected anisotropy inconsistent with a compound-nucleus reaction and indicates a dynamic fusion-fission like process. The observed angular distribution features an asymmetric forward-backward peaking most prevalent for mass-asymmetric events. Furthermore, the more massive fragment of mass-asymmetric events appears to emerge preferentially in the forward direction, along the beam axis, in analogy to dynamic fragmentation of projectile-like fragments. Analysis of the angular distribution of alpha particles emitted from these fission fragments suggests the events are associated mostly with central collisions.

The study of low-energy heavy-ion reaction dynamics in the energy domain moderately in excess of the Coulomb barrier offers a unique insight into the large-scale collective motion of the nucleons in the nucleus. Fusion-fission constitutes an important reaction channel for many such nuclear reactions and is an important probe into the nuclear structure of matter. As the bombarding energy increases, the role of dynamically-induced decay modes progressively increases. Processes such as pre-equilibrium emission of nucleons [1–3], "neck" emission of intermediate-mass fragments [4,5] and dynamic fragmentation of projectile-like fragments [6, 7] have developed recent interest.

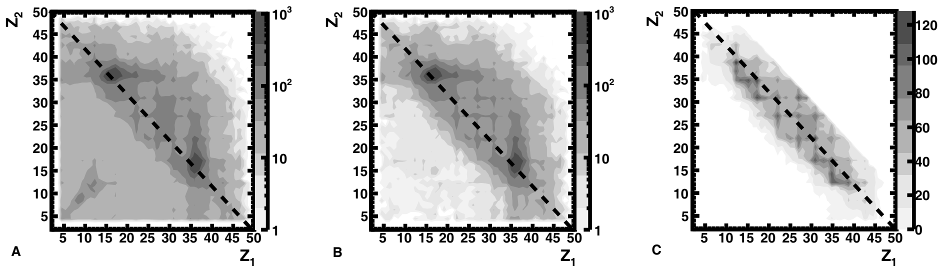


Figure 1: Progression of the double differential cross section presented as a function of $Z_1$ and $Z_2$. A) represents the inclusive data set. B) gate only on collinearity. C) gates on collinearity, relative velocity and $Z_1+Z_2<60$.

One method of simulating the dynamics of a many-body nuclear system is offered by the time-dependent Hartree-Fock theory (TDHF). Calculations performed in the late seventies applying the TDHF approximation predict a range of low angular momentum in which fusion does not occur [8,9]. The gap in partial waves is appropriately termed the "fusion window." For head-on collisions, i.e. low angular momentum, the system must absorb all the relative motion and convert it to vibrational energy or heat. As the energy increases the system may not be able to accommodate this conversion of energy without breaking apart. A plausible interpretation of the analysis of the present work suggests the existence of a phenomenon similar to a "fusion window" [10].

The experimental data used in the present study is a small subset of the data collected in the ISODEC experiment performed at the INFN-Laboratori Nazionali del Sud (LNS). The experiment utilized the CHIMERA multi-detector array [11] for the first time at low energies, with the main objective to study the competition between the various disintegration modes of $^{118,134}$Ba compound nuclei produced in the two reactions $^{78}$Kr+$^{40}$Ca and $^{86}$Kr+$^{48}$Ca at 10 AMeV. In contrast, the present work is an analysis of the data from only the neutron poor system, the focus of which was to look for dynamic splitting at forward angles. The energy calibration and particle identifications were performed earlier without regard to the present study. Details of the non-trivial time-of-flight particle identification technique are described in detail elsewhere [12].

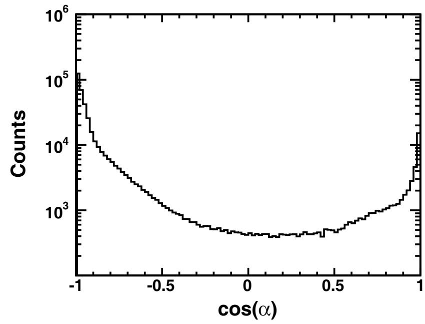


Figure 2: Fragment collinearity expressed as the cosine of the angle Θ between the C.M. velocities of the fragments.

The search for signatures of a dynamic fission-like process focused on a subset of events in which two or more correlated fragments are detected with atomic numbers Z>3. Observation of the double differential cross section ($\frac{d^2\sigma}{dZ_1 dZ_2}$) as a function of $Z_1$ vs. $Z_2$, as seen in $fig.$1.A for the inclusive set of data, revealed a high intensity of events along the anti-correlation ridge indicated by the dashed line. These events correspond to two massive fragments that account for the most (> 90%) of the system's total mass. Included in this distribution are dissipative reactions evident by the high intensity peaks for the PLF and TLF.

An important kinematical relationship between the reaction fragments for a fission-like process is the angle between the center of mass of the fissioning system, *i.e.* the collinearity. The collinearity of the two fragments measured as a cosine of the angle $\alpha$ between the center-of-mass velocities of the fragments is presented in $Fig.$2. The narrow, well-defined peak at $cos(\alpha) =$ -1 corresponds to fragments proceeding in opposite directions in the overall C.M. system as expected for a fission-like process following fusion with a full mass transfer. A "liberal" gate on the $\cos(\alpha)$ observable ranging from -1.0 to -0.7 was used to select fusion-fission-like events for further analysis. The consequences of this selection criterion on the differential cross section can be seen in $fig.$1.B. One observes a decrease in the intensity for events well below the anti-correlation ridge, while the intensity of events along the ridge remains approximately the same.

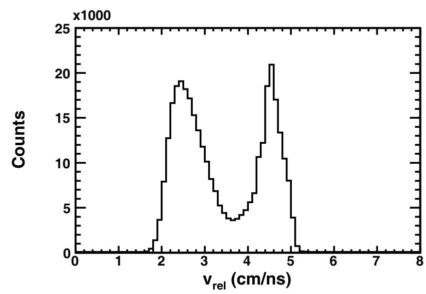


Figure 3: Distribution of the relative velocities of the fragments satisfying the collinearity condition.

The relative velocity of two fragments resulting from fission of a compound nucleus would depend exclusively on the Coulomb repulsion between the two fragments assuming the velocity at the fission barrier is approximately zero. The Viola velocity is a systematic parameterization of the relative velocity of fission fragments, which is approximately $v_{Viola} \approx 2.4$ cm/ns. The relative velocity distributions of the fragments that satisfy the collinearity condition previously discussed is presented in $fig.3$. One observes two distinct peaks, one centered at approximately the Viola velocity, indicative of compound nucleus fission, that is well separated from a peak at higher $v_{rel}$ corresponding to mostly dissipative collision events. Relative velocities between $v_{rel}$= 1.5 and 3.5 cm/ns correspond to the events of interest. A consideration that should be taken into account is that this condition might impose a small contamination of fully-damped dissipative collision events due to the overlapping tails of the $v_{rel}$ distributions. Of note, is the additional cut ( $Z_1+Z_2<60$) on incorrectly identified masses that sum to a total mass well above the physical limit. As one observes in $fig.1$.C, the conditions on collinearity, mass and relative velocity significantly reduce the intensity of events above and below the anti-correlation ridge. The events are almost exclusively distributed along the ridge consistent with a complete fusion-fission-like process assuming some mass loss due to evaporation.

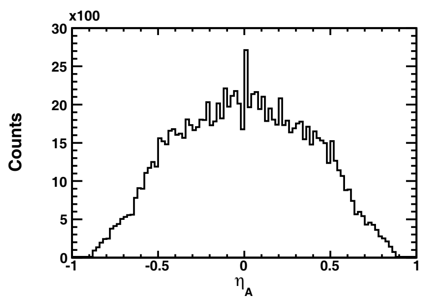


Figure 4: Mass asymmetry distribution of the fission-like fragments.

The mass asymmetry spectrum is presented in $fig.4$, which is here defined as $\eta_A = \frac{A_1-A_2}{A_1+A_2}$. The distribution is randomized about symmetry ($\eta_A$=0), and features a peak at zero asymmetry. The fission of the system is predominately symmetric, with little or no memory of the initial "entrance" channel, except for a slight bump in the distribution at $\eta_A$=±0.3 (the initial asymmetry). This can be attributed to a small contamination by dissipative collisions, because the tail end of the relative velocity distribution for such events extends below relative velocities of 3.5 cm/ns and could not be completely eliminated by the gating condition. The large mass transfer is inconsistent with fully damped collisions. The driving forces do not favor a symmetric split of the dinuclear complex and the system would not survive long enough to facilitate a complete equilibration of mass, contrary to what one observes. It is, however, consistent with a fusion-fission like process. This longer lived process accommodates the time needed for the system to equilibrate such a large mass transfer.

The center-of-mass angular distribution ($d\sigma/d\Theta$) of fission fragments emitted from an equilibrated compound nucleus is symmetric, with a maximum at $90^o$. The angular distribution, defined with respect to the heav-

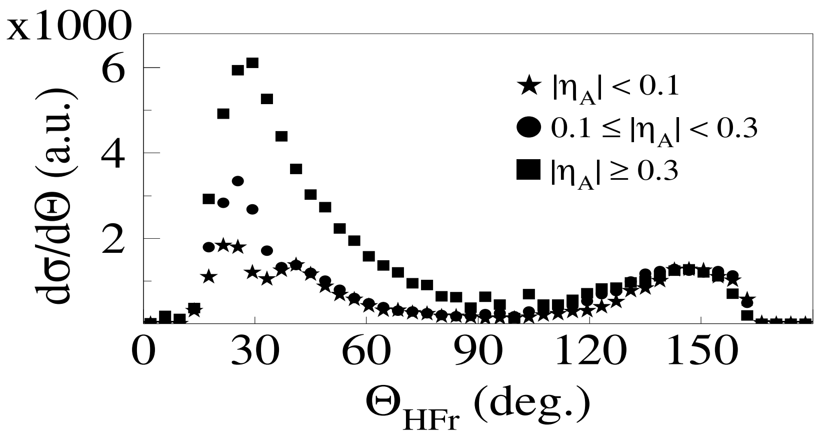


Figure 5: Angular distribution of the larger (of two) fragments in the center-of-mass system for various asymmetries.

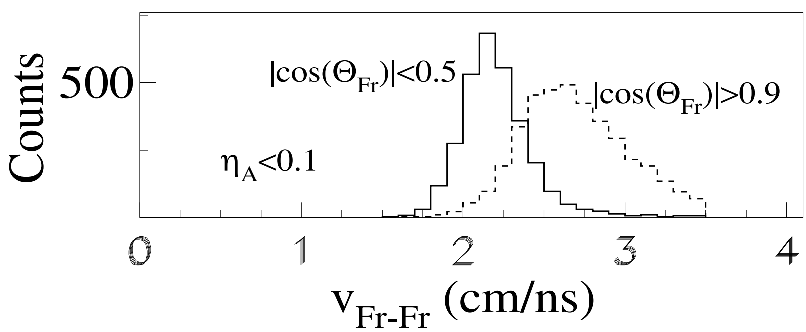


Figure 6: Relative velocity spectra of fragments emerging in the beam direction (dashed line) and away from the beam direction (solid line).

ier fragment, is presented in $fig.$5. One observes a very strong forward-backward peaking with a distinct preference for the larger fragment to be emitted in the forward direction. This asymmetry in the angular distribution is observed to increase for increasing values of mass asymmetry. It is important to note that the angular distribution of fragments emitted away from the beam direction (emissions between $60^0$ and $120\ ^0$ in the center-of-mass) appears to be constant, which suggests a superposition of reaction processes, *i.e.*, compound nuclear fission and dynamic fission. If one compares the relative velocities of fragments emitted away from the beam axis

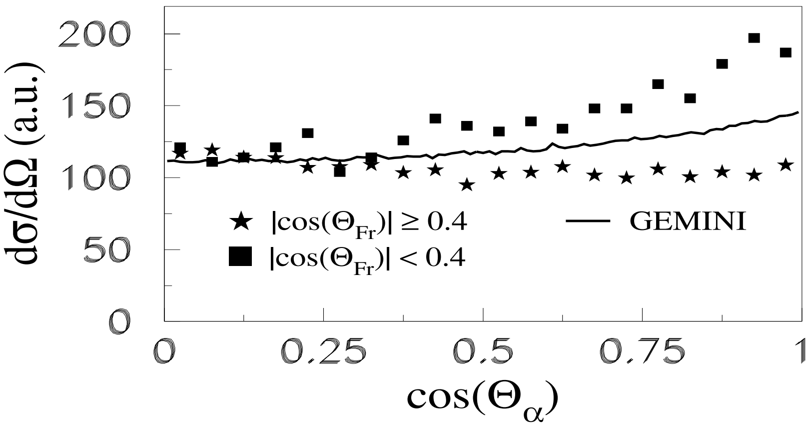


Figure 7: Angular distribution of alpha particles emitted from heavier fragments in the forward hemisphere (away from the lighter fragment) relative to the fragmentation axis aligned with the beam axis (stars) and perpendicular to the beam axis (squares). The solid line illustrates predictions by the code GEMINI.

($|\cos(\Theta)| < 0.5$ ) to those of fragments emitted in the forward-backward direction ($|\cos(\Theta)| > 0.9$ ) one observes the influence of an "extra push" leading to greater relative velocities on average for fragments emitted in the forward-backward direction. This feature can be seen in $fig.$6 and is indicative of a dynamical process that preserves some memory of the initial direction of flight of the projectile.

The angular distribution of alpha particles emitted from fully accelerated fission fragments offers insight into the centrality of the fusion-fission-like process in question. A rotating composite nucleus that subsequently fissions will impart rotation on the emerging fragments. The rotation of a composite nucleus is related to the centrality of the collision, *i.e.*, the initial angular momentum of the relative motion. Central collisions are associated with little or no collective rotation, therefore, the angular distribution of emitted alpha particles is isotropic with respect to the fission axis. For composite systems originating from mid-peripheral collisions, the rotation of the system would be observed as an anisotropy in the angular distribution of the emitted alpha particles. $fig.$7 shows that the angular distribution of alpha particles likely emitted from the heavier fragments moving along the beam direction ($|\cos(\Theta)| \geq 0.4$) is isotropic, as expected for the case of emission from spinless fission fragments. In contrast, the angular distribution of alpha particles emitted from fragments moving away from the beam direction ($|\cos(\Theta)| < 0.4$) shows noticeable anisotropy, consistent with a non-zero fragment spin. Included are predictions by the code GEMINI for the emission of alpha particles from fragments with spins in the range of I = 0 - 12. This observation further suggests that fragments emerging along the beam direction are virtually spinless and arise from a dynamical process, while those emitted in the transversal direction are consistent with well-known processes for fusion-fission and quasi-fission.

In summary, the anisotropy of the angular distribution observed for a certain class of correlated fragments from a fission-like process is inconsistent with formation and decay of an equilibrated compound nucleus. The strong forward-backward peaking of the differential cross section is indicative of a dynamical irrotational process that preserves a "memory" of the initial relative motion. The energy appears to be temporarily stored, possibly in a collective vibrational mode, and subsequently reused in the system's fragmentation. The observations made in this work are reminiscent of the predicted fusion window. Validation of this conclusion requires further dedicated experiments optimized to study this phenomenon.

## Acknowledgments

This work was supported by the U.S. Department of Energy grant No. DE-FG02-88ER40414.

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