Correlated Fragment Production in ^{18}O-Induced Reactions at $E/A = 84$ MeV

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Correlations between intermediate-mass fragments (IMF's) and heavy fragments were measured for ^{18}O-induced reactions on ^{nat}Ag and ^{197}Au at $E/A = 84$ MeV. Correlations of two coincident IMF's show a depletion at small relative velocities $v_{rel} \leq 1$ cm/ns, reflecting the proximity of the two IMF's at the point of creation. However, the time scales for IMF emission derived from this correlation are similar to those of binary-IMF–heavy-recoil coincidences which indicates a sequential nature of multifragment emission in these reactions.

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Nuclear fragmentation leading to multiple fragment production is predicted to be the major decay mode of heavy nuclei at high excitation energies.[1] In contrast to sequential evaporation processes, multifragmentation may be characterized by a nearly *simultaneous* breakup of a nucleus into several fragments. If two fragments are in close proximity at the point of creation and if the interaction between the fragments is dominated by their mutual Coulomb repulsion, one expects a depletion of events at relative velocities between the two fragments below $\simeq 2$ cm/ns. In line with conventional nuclear interferometry studies,[2] two-fragment correlations at small relative velocities may, therefore, be used to explore the space-time characteristics of fragmentation processes.

In this Letter we extract information on the time scale for intermediate-mass–fragment (IMF) emission from fragment-fragment correlations. We present experimental evidence that processes in which two (or more) IMF's are produced exhibit a time scale similar to binary decays where only one IMF is emitted.

The experiment was performed at the CERN synchrocyclotron. ^{nat}Ag and ^{197}Au targets of 1.1- and 0.6-mg/cm^2 areal density, respectively, were bombarded with ^{18}O ions of $E/A = 84$ MeV incident energy. Fragments emitted into an angular range $23° \leq \theta \leq 78°$ and $102° \leq \theta \leq 157°$ were detected in a heavy-ion hodoscope (HIH) consisting of twelve multiwire avalanche counters (PPAC).[3] This hodoscope subtends a large solid angle ($\Delta\Omega \approx 8.4$ sr) and yields the position, the energy loss, and a time-of-flight signal for each fragment. Coincident light particles emitted in this angular range were detected in a light-particle hodoscope consisting of an array of ten position-sensitive 10-mm-thick plastic scintillators positioned behind ten elements of the HIH. Fragments emitted at $2° \leq \theta \leq 20°$ were detected in a zero-degree hodoscope.[4] Isotopically resolved light and intermediate-mass fragments were measured with five Si telescopes[5] positioned at $\theta = 40°$, 51°, 63°, 73°, and 120° behind the two HIH elements that were not covered by the light-particle hodoscope.

The telescopes were used to trigger the data-acquisition system. As a result of the rather backward angles of these detectors, contributions from more violent collisions were enhanced already on the trigger level.[3] In the off-line analysis, for each event the interaction time in the target was reconstructed from the known energy and mass of the trigger particle. From the measured positions and the time difference between the PPAC's and the trigger particle we calculated the laboratory velocity vector of each fragment detected in the HIH. In the two-dimensional plots of energy loss versus the time of flight two distinct groups are clearly separated: one corresponding to IMF's ($Z \leq 20$) and the other corresponding to heavier fragments, i.e., fission products (F) or heavy targetlike recoils (HR). By use of the cases in which an IMF was simultaneously detected in one of the telescopes positioned behind the PPAC, the detection efficiency of the PPAC's, i.e., the probability that the time and all the position signals were recorded, was determined. The efficiency is close to 100% for $Z \geq 10$ but decreases for smaller Z. The efficiency in the range $Z < 10$ drastically increases if only the time signal is required which was done to determine the total fragment multiplicity M_f.

In the following we consider three different coincidence types:

F-F: Coincidences between two heavy fragments ($Z > 20$). In order to enhance binary events it was required that $M_f = 2$.

IMF-HR: Coincidences between an IMF and one heavy fragment are used to study the transition from binary fission (F-F) to multifragmentation processes.

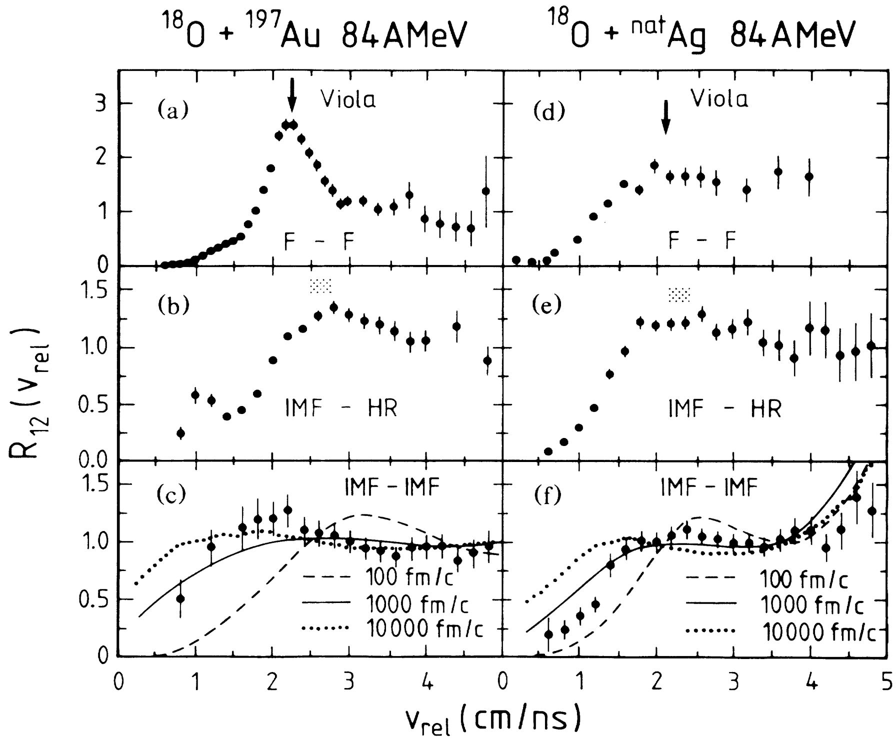

FIG. 1. Two-fragment correlation functions, Eq. (1), measured with reactions on Au (left) and Ag (right).

Again we required $M_f = 2$. In addition, a time of flight ≥ 25 ns was required for the heavy fragment in order to enhance coincidences with targetlike recoils.

IMF-IMF: As the most promising event type for the selection of multifragmentation processes we investigate coincidences between two IMF's.

We define the two-fragment correlation function $R_{12}(v_{rel})$ in terms of the coincidence yield $Y_{12}(v_{rel})$ and of the mixed coincidence yield $Y_{12,mix}(v_{rel})$:

$$R_{12}(v_{rel}) = C_{12} Y_{12}(v_{rel}) / Y_{12,mix}(v_{rel}). \tag{1}$$

Here v_{rel} denotes the relative velocity of the two fragments and C_{12} is a normalization constant which was determined by

$$C_{12} = \sum_{v_{rel}} Y_{12,mix}(v_{rel}) \left[\sum_{v_{rel}} Y_{12}(v_{rel}) \right]^{-1}. \tag{2}$$

$Y_{12,mix}$ was generated by mixing particles of different events.[6]

Correlation functions for the three coincidence types are shown in Fig. 1. The F-F correlation function for the Au target [Fig. 1(a)] shows a pronounced peak at $v_{rel} = 2.3$ cm/ns. The maximum is less pronounced in the case of the Ag target, Fig. 1(d). The positions of the maxima agree rather well with relative velocities expected for symmetric fission of Au and Ag nuclei according to the Viola systematic[7] [arrows in Figs. 1(a) and 1(d)].

IMF-HR correlation functions show a similar behavior. A strong anticorrelation at $v_{rel} \leq 1.5$ cm/ns and weak maxima at $v_{rel} \approx 2.8$ and 2.5 cm/ns for the Au and Ag targets, respectively, can be discerned. These velocities correspond to the Coulomb barrier of two mass-asymmetric spheres with a total mass and charge of a Au and Ag nucleus separated by $d = 1.224(A_1^{1/3} + A_2^{1/3}) + 2$ fm [shaded regions in Figs. 1(b) and 1(e)]. The binary character of the F-F and IMF-HR coincidences[8] is confirmed by the coplanarity of the two fragments: The azimuthal correlation functions $R_{12}(\Delta\phi)$—defined by analogy to Eq. (1) as a function of the relative azimuthal angle, $\Delta\phi$, and shown in Figs. 2(a) and 2(b) for reactions of Au—are strongly peaked at $\Delta\phi = 180°$.

Despite these similarities between F-F and IMF-Hr coincidences we also find distinct differences. Figures 2(d) and 2(e) show the measured distribution of the angle $\theta_{c.m.}$ between the relative velocity, $\mathbf{v}_{rel} = \mathbf{v}_{IMF} - \mathbf{v}_{HR}$ or $\mathbf{v}_{F,2} - \mathbf{v}_{F,1}$, and the beam velocity. The dotted lines are the results of Monte Carlo calculations assuming a binary decay isotropic in $\theta_{c.m.}$. For these calculations, the longitudinal momenta of the decaying systems were chosen such that the measured folding-angle distributions were reproduced. For the F-F distribution [Fig. 2(d)] no significant deviation from an isotropic emission can be found. The IMF-HR distribution, however, is clearly inconsistent with the assumption of an isotropic decay: The IMF's are primarily emitted into the forward hemisphere thus reflecting the remnants of dynami-

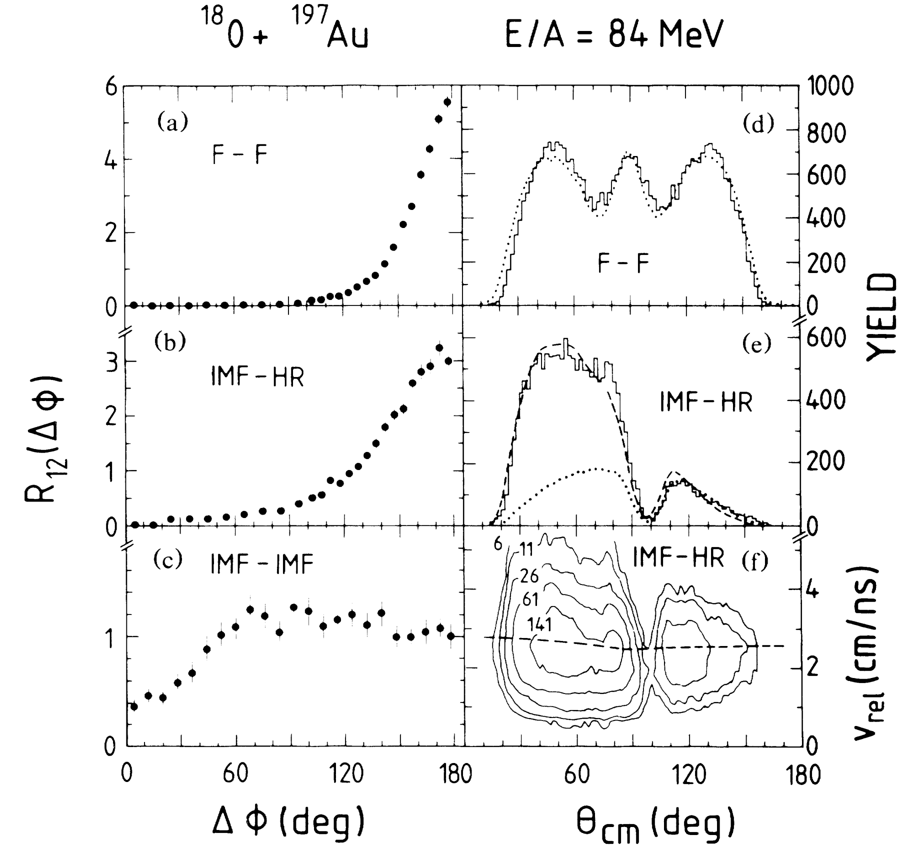

FIG. 2. (a)-(c) Two-fragment correlations as a function of the relative azimuthal angle, $\Delta\phi$, measured for ^{18}O-induced reactions on ^{197}Au. (d),(e) Coincidence yields as functions of the angle of the relative velocity with respect to the beam axis, $\theta_{c.m.}$. (f) Contour plot of constant yield as a function of $\theta_{c.m.}$ and the relative velocity, v_{rel}, for IMF-HR coincidences. The curves are explained in the text.

cal effects imposed by the entrance channel. An upper limit for contributions resulting from the decay of a pseudocompound nucleus of 37% can be estimated with the extreme assumption that the whole IMF-HR coincidence yield at $\theta_{c.m.} > 100°$ is due to isotropic compound-nucleus emission.[9] Although the most probable relative velocities do not significantly vary with $\theta_{c.m.}$ [dashed line in Fig. 2(f)], the dominant part of the IMF-HR coincidences does not result from the decay of a totally equilibrated compound system.

Motivated by the analysis of binary processes at low bombarding energies,[10] we have interpreted the anisotropy as a decay process of a rotating nuclear system. The rotation time τ_{rot} may be estimated from the imparted longitudinal momentum Δp, the impact parameter b, and the moment of inertia Θ, by use of the classical expression

$$\tau_{rot} = 2\pi\Theta/b\,\Delta p. \quad (3)$$

The high associated light-particle multiplicity measured in the light-particle hodoscope[3] and the fact that with the present trigger conditions no significant contributions of (charged) projectile remnants have been observed in the zero-degree hodoscope suggest a strong overlap between the target and projectile nuclei and thus impact parameters $b \le 4$ fm. On the other hand, the IMF-HR coincidence cross section—corrected *only* for the geometrical efficiency—of 300 ± 100 mb constraints b to values larger than 2 fm. Using, therefore, $b = 3$ fm, $\Delta p = 2800$ MeV/c, and, for simplicity, a rigid moment of inertia of a spherical nucleus with $A = 197$, we obtain a rotation time $\tau_{rot} \approx 3 \times 10^3$ fm/c. With the assumption that the initial asymmetry in the entrance channel causes a preferential direction for the splitting in the rotating system and neglecting energy and angular momentum dissipation, an exponential time distribution for the fragment emission, $\exp(-0.693t/\tau_{IMF\text{-}HR})$, may be transformed in an angular distribution $\sim\exp(-\theta_{c.m.}/\theta_0)$. Here θ_0 and the half-life $\tau_{IMF\text{-}HR}$ are related according to $\tau_{IMF\text{-}HR} = 0.693\tau_{rot}\theta_0/2\pi$. With use of this simple *Ansatz*, the experimental $\theta_{c.m.}$ distribution can be described by $\theta_0 = 50°$ [dashed line in Fig. 2(e)], corresponding to $\tau_{IMF\text{-}HR} \approx 300$ fm/c. An analysis of the Ag case yields a somewhat lower half-life of about 200 fm/c.

The IMF-IMF correlation functions [Figs. 1(c) and 1(f)] show, similar to the other binary processes, a significant depletion of coincidences at small relative velocities and, furthermore, a weak enhancement at $v_{\rm rel} \approx 2$ cm/ns. However, the azimuthal correlation $R_{12}(\Delta\phi)$, Fig. 2(c), is comparatively flat, consistent with the production of more than two fragments. The depletion at small $\Delta\phi$ has the same origin as the minimum at small $v_{\rm rel}$ in Fig. 1(c).

In the case of multiple fragment production, momentum conservation will, in addition to the mutual Coulomb repulsion, influence the correlation functions at small relative velocities. In order to quantify both effects, we performed Monte Carlo calculations, simulating the sequential emission of two IMF's from primary ^{197}Au and $^{\rm nat}$Ag nuclei. In these simulations classical two- and three-body Coulomb trajectories were calculated following the emission of the first and second IMF, respectively, conserving the total mass and momentum of the system. The distribution of the time interval Δt between the emission of the two IMF's was parametrized as

$$p(\Delta t) = p_0 \exp(-0.693\Delta t/\tau_{\rm IMF\text{-}IMF}).$$

At the point of emission the IMF and the residual nucleus were separated by a distance of $d = 1.224(A_{\rm IMF}^{1/3} + A_R^{1/3}) + 2$ fm, where $A_{\rm IMF}$ and A_R denote the mass of the IMF and of the residue, respectively. The mass and the primary velocity distributions of the IMF's were constrained to reproduce approximately the inclusive distributions measured in the telescopes. Events for which the center-to-center distance between two of the three fragments became less than $1.224(A_1^{1/3} + A_2^{1/3}) + 2$ fm were rejected. Finally, the measured efficiency of the detector system was taken into account.

The results of these calculations for different values of $\tau_{\rm IMF\text{-}IMF}$ are shown by the lines in Figs. 1(c) and 1(f). Clearly, sequential emission processes which take only momentum conservation into account and neglect interactions between the two IMF's, i.e., long half-lives $\tau_{\rm IMF\text{-}IMF} \gtrsim 10^4$ fm/c, cannot describe the data measured with the Ag target. Obviously, an additional (Coulomb) repulsion between the two IMF's, i.e., a shorter lifetime, is necessary in order to explain the strong suppression at small $v_{\rm rel}$. From the calculations shown in Figs. 1(c) and 1(f), we estimate a half-life for multifragment emission of $\tau_{\rm IMF\text{-}IMF} = 500 \pm 300$ fm/c corresponding to an average initial separation of the two fragments $d_{\rm IMF\text{-}IMF} \approx 50$ fm. The IMF-IMF correlation measured with the Au target is consistent with a half-life of the order of 10^3 fm/c ($d_{\rm IMF\text{-}IMF} \sim 130$ fm).

In summary, the observed azimuthal angular and relative velocity correlations between IMF's ($8 \leq Z \leq 20$) and heavy targetlike recoils indicate a partially equilibrated decay process. However, the emission of the IMF's are strongly forward peaked with respect to the heavy recoil. This suggests that the breakup occurs on a fast time scale compared to the rotation time of the composite system. In the simple picture of a rotating nuclear system we estimate a half-life for the IMF-HR complex of 200–300 fm/c. A comparison of IMF-IMF correlations to results of Coulomb trajectory calculations indicates a half-life for multifragment emission between 200 and about 1000 fm/c. Therefore, proceeding from IMF-HR decay to multifragment emission, no significant change in the time scale involved is observed which indicates a sequential nature of multifragment emission in these reactions.

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