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Relaxation of the mass-asymmetry degree of freedom in heavy-ion reactions

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The ^{58}Ni+^{165}Ho reaction has been studied at 5.9 and 6.5 MeV per nucleon (reverse kinematics). Coincident reaction fragments were detected with two position-sensitive parallel plate avalanche detectors. Correlations between energy, mass, and angle show that a small fraction of the events have fully relaxed kinetic energies, masses intermediate between those of the projectile (target) and symmetric fragmentation, and angular distributions with a marked forward-backward asymmetry.

During the last decade there has been considerable experimental and theoretical interest in heavy-ion-induced deep inelastic or damped reaction processes.[1] These reactions provide the opportunity to study phenomena occurring in nuclear matter under extreme conditions with respect to shape, intrinsic excitation, spin, mass-to-charge ratio, etc., and allow the control of these conditions by selecting appropriate initial and final reaction parameters. Damped reactions are characterized principally by (1) fragment mass (charge) distributions that are bimodal and peaked close to the masses (charges) of the projectile and target nuclei, (2) dissipation of large amounts of kinetic energy of radial and orbital motion (final total kinetic energies can be as low as those corresponding to the Coulomb repulsion of highly deformed fragments), and (3) angular distributions of the direct-reaction type indicating an interaction time scale corresponding to a fractional rotation of the dinuclear complex.

Another well-known heavy-ion reaction process leads to fusionlike products. If the reaction partners are heavy enough, this process is associated predominantly with fission fragments. From an operational point of view, the fragments from the latter reaction type are characterized by fully relaxed kinetic energies that follow fission fragment systematics, mass distributions that are peaked at symmetry, and angular distributions that are symmetric about 90° *for each mass.* For some heavy-ion systems at elevated bombarding energies the cross sections for fusionlike reactions may exceed those corresponding to the rotating-liquid-drop model (RLDM) limits on the angular momentum, i.e., $l_{\max} > l_{\text{RLDM}}(B_f=0)$, where $l_{\text{RLDM}}(B_f=0)$ is the angular momentum at which the theoretical fission barrier vanishes.

The experiments to be reported here were designed to investigate reactions with properties that are intermediate between those usually attributed to either damped or fusion-fission-like processes. A ^{58}Ni target of 200 μg/cm^2 thickness was bombarded with ^{165}Ho ions accelerated by the Lawrence Berkeley Laboratory SuperHILAC to energies of 970 and 1075 MeV. From previous studies of the ^{165}Ho+^{56}Fe reaction,[2] sizeable cross sections of damped and fusionlike processes were expected in the present study.

In the experiment, coincident reaction fragments were detected with two position-sensitive multiwire avalanche detectors (PSAD's). The active area of each detector subtended 300 mm in the reaction plane and 200 mm in the out-of-plane direction. The position resolution in each direction was 4 mm, corresponding to an angular resolution of approximately 0.4°. The position was determined *via* the delay-line readout of the wire planes. This position information from both PSAD's was used to determine the angles θ and ϕ of each of the correlated fragments, as well as their flight distances from the target to the detection site. The detectors produced timing signals as well, providing information on the time of flight difference of the correlated fragments. The absolute times were measured with respect to the rf signal from the SuperHILAC. The experimental time resolution [full width at half maximum (FWHM)] was 3 ns. The determination of the two angles (θ_1 and θ_2), of the two corresponding flight distances, and of the difference in times of flight, constitutes a kinematically complete measurement of two-body reaction events. The additional available information on the angles ϕ and on the absolute times allows one to correct for energy losses in the target and to reduce substantially background due to random coincidences. Assuming isotropic sequential particle evaporation, information on the average properties of the primary fragments is obtained.

In Fig. 1, the mass-angle correlations of the fragments observed for the ^{58}Ni+^{165}Ho reaction are shown as lines of constant $\sigma(A,\theta_{\text{c.m.}})$ in a two-dimensional contour diagram. At forward and backward angles, an increased intensity of fragments is observed with masses intermediate between those of the projectile (target) and of symmetric fragmentation.[3] The majority of the reaction fragments, however, can be attributed to either a damped reaction (such events are detected with low efficiency in the present experiment, due to the detection geometry) or a fusion-fission process. In the identification of the component of fragments from the latter type of process, the above operational definition of fusion-fission is utilized.

In order to estimate the cross section of the fusion-fission component, the double-differential cross section shown in Fig. 1 was sorted into six angular bins, each of 25° width. Projection of the data in each of these angular

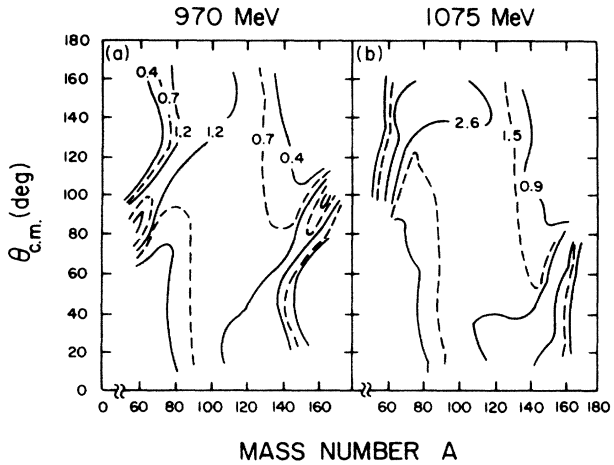

FIG. 1. Contour lines of the double-differential cross section $\sigma(A,\theta_{c.m.})$, in units of mb/individual mass number × rad, for the $^{58}Ni+^{165}Ho$ reaction plotted as a function of angle $\theta_{c.m.}$ and mass number A. The laboratory energies are (a) 5.9 and (b) 6.5 MeV per nucleon. The detector positions preclude a measurement of the entire damped reaction distribution. The rapid decrease in the intensity of the distribution for the 5.9 MeV per nucleon data for masses near the entrance channel results from the positioning of the detectors.

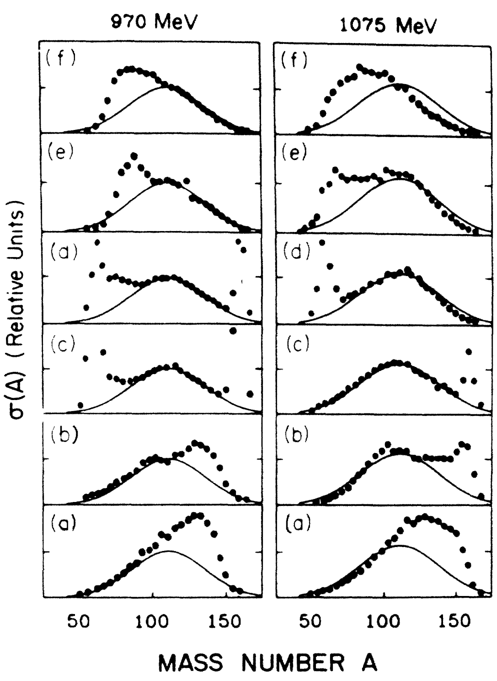

FIG. 2. Differential cross sections for the $^{58}Ni+^{165}Ho$ reaction in six different angular ranges: (a) 15°–40°, (b) 40°–65°, (c) 65°–90°, (d) 90°–115°, (e) 115°–140°, and (f) 140°–165°. Laboratory energies are 5.9 (left) and 6.5 (right) MeV per nucleon. The solid lines represent Gaussian mass distributions of equal intensity for each angular range at a given energy. This reaction component is assigned to a fusion-fission reaction mechanism. In some angular bins, peak cross sections for the damped reaction are off scale.

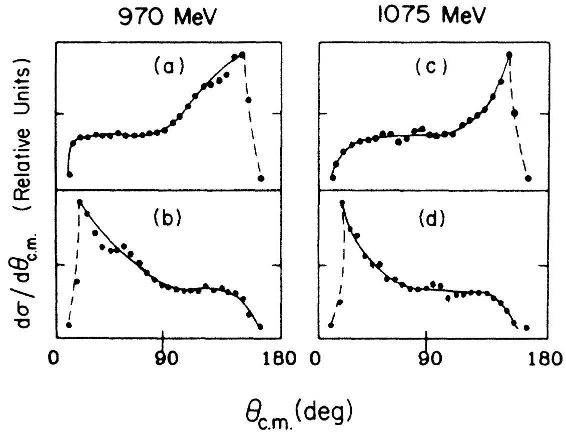

FIG. 3. Angular distributions (15°–165°) of reaction fragments in two different mass number ranges; (a) and (c) 80–90, and (b) and (d) 133–143. The measurements cover the angular range 20°–160°.

bins onto the mass axis results in the spectra [$\sigma(A)$ versus mass] plotted in Fig. 2. For each bombarding energy, a symmetric-mass fusion-fission component, with a centroid at $(A_T+A_P)/2$, a FWHM of 59 mass units, and a constant $d\sigma/d\theta_{c.m.}$ was fitted to the data for each angular bin. In order to deduce the total fusion-fission cross section, two limiting assumptions were made about the angular dependence of the cross section in the regions 0°–15° and 180°–165° not covered by the measurement. A distribution $d\sigma/d\Omega \propto 1/\sin\theta$ provides an upper limit to the cross section, since the exit channel orbital angular momentum becomes dealigned relative to the initial angular momentum due to thermal excitation of the tilting mode[4] of the composite system. A lower limit is obtained by assuming that $d\sigma/d\Omega$ is constant in the two above angular regions.

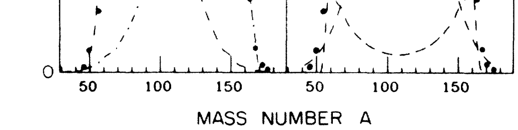

FIG. 4. Differential cross section as a function of mass for the $^{58}Ni+^{165}Ho$ reaction at 6.5 MeV per nucleon. These angle-integrated results include the measured angular range of 20°–160° in the center-of-mass system. (a) Resultant components, assuming that the mass drift increases continuously with decreasing impact parameter. (b) Resultant components, assuming that a symmetric mass component associated with fusion-fission is first subtracted.

TABLE I. Reaction parameters for the $^{58}Ni+^{165}Ho$ reaction. The parameters $Z^2/A=40.5$ and $(Z^2/A)_{eff}=37.8$.

E_{lab} (MeV)	$(E_{c.m.}-V_c)/\mu$ (MeV/nucleon)	σ_{react} (mb)	l_{max} ($\hbar$)	σ_{fus} (mb)	l_{fus} ($\hbar$)	σ_{inter}[a] (mb)	l_{inter}[a] ($\hbar$)	l_{RLDM} ($B_f=0$) ($\hbar$)
970	1.14	970 $\pm$100	127	139 $\pm$17	0–48	20	49–51	61
1075	1.78	1570 $\pm$150	169	317 $\pm$35	0–76	80	77–85	61

[a]Cross section and angular momentum window of fragments characterized by fully damped kinetic energy, partially relaxed mass asymmetry, and angular distributions with a forward-backward asymmetry. These data are for the angular range 20°–160°.

With these limits, the fusion-fission cross sections are (139 $\pm$ 17) and (317 $\pm$ 35) mb at bombarding energies of 5.9 and 6.5 MeV per nucleon, respectively. Although the symmetric-mass component, along with that for the damped process, exhausts most of the cross section for angular bins near 90°, an intermediate-mass component is evident in Fig. 2 at forward and backward angles.

The dependence of the angular distribution on fragment mass is illustrated in Fig. 3, where the mass-averaged cross section $d\sigma/d\theta$ is plotted versus angle for mass bins $A=80$–90 [Figs. 3(a) and 3(c)] and 133–143 [Figs. 3(b) and 3(d)]. Fragment angular distributions for these mass bins have a marked forward-backward asymmetry analogous to angular distributions measured for the $^{208}Pb+^{50}Ti$ and $^{208}Pb+^{56}Fe$ reactions by radiochemical methods.[5] More symmetric masses yield angle-independent values of $d\sigma/d\theta_{c.m.}$ over the angular range 15°–165°.

In Fig. 4 the differential cross section $\sigma(A)$ is plotted as a function of mass for the $^{58}Ni+^{165}Ho$ reaction at 6.5 MeV per nucleon. The cross section for each mass has been integrated over angles from 20° to 160°. The experimental data are decomposed in two ways. In Fig. 4(b), the symmetric-mass component resulting from angular integration of the fits shown in Fig. 2 is displayed along with the residual cross sections of events with partial relaxation of the mass-asymmetry mode. The magnitude of the cross section for these events with intermediate properties, in the angular range 20°–160°, is approximately 80(20) mb for a bombarding energy of 6.5(5.9) MeV per nucleon. An alternate interpretation[3] of the data is illustrated in Fig. 4(a). Here, a continuous evolution in the mass drift towards symmetry with decreasing angular momentum is assumed.

The present experimental data are consistent with a sizeable fraction of the fully damped events being associated with a fusion-fission process where the mass-asymmetry degree of freedom is fully relaxed, i.e., where the mass distribution is peaked at symmetry and the angular distribution for each mass is symmetric about 90°. In addition, however, events with fully damped kinetic energies are observed where the mass-asymmetry degree of freedom is partially relaxed and the angular distributions exhibit a forward-backward asymmetry. If one assumes that these latter events result from initial orbital angular momenta intermediate between those leading to fusion-fission and damped reactions, estimates of the corresponding l window can be deduced from cross section data with the assumption of the sharp cutoff model. These angular-momentum bins, along with other relevant parameters, are listed in Table I. It must be emphasized that the l values extracted from the cross section data are for illustrative purposes only, since the various reaction processes are expected to have diffuse boundaries in l space.

As shown in Fig. 3, the angular distributions of the events with partial relaxation of the mass-asymmetry degree of freedom are similar to those observed for the orbiting component of strongly damped reactions of similar systems,[1,2] i.e., the projectilelike (heavy) fragments peak forward at 0° and the targetlike (light) fragments peak at 180°. Employing the methods[6] previously used for estimating the lifetime of damped collisions as a function of kinetic energy dissipation, estimates of the relaxation time of the mass-asymmetry degree of freedom of a few times 10^{-21} s are obtained, in qualitative agreement with other estimates.[7] Based on the observed mass-angle correlations of these fragments, one surmises qualitatively that the intermediate composite system, from which the fragments originate, has never gone through a mononuclear stage. Since memory of the initial mass asymmetry and spatial orientation is retained, one concludes that the intermediate composite system maintains a dinuclear shape during its entire interaction lifetime. Quantitative understanding of the observed mass-angle correlations requires refinements of trajectory-type calculations[8] as well as the development of models dealing with the dynamical excitation of the tilting mode.[4]

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