Asymmetric Fission of ^{56}Ni

S. J. Sanders, D. G. Kovar, B. B. Back, C. Beck, B. K. Dichter, D. Henderson, R. V. F. Janssens, J. G. Keller, S. Kaufman, T.-F. Wang, B. Wilkins, and F. Videbaek

Argonne National Laboratory, Argonne, Illinois 60439

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Cross sections for the two-body channels populated in the $^{32}S + ^{24}Mg$ reaction at $E_{c.m.} = 60.8$ MeV have been measured by use of a coincidence technique which allows correction for secondary light-particle evaporation. The data show reaction yields with full equilibration of energy and mass-asymmetry coordinates. These results suggest an asymmetric fission mechanism and are contrary to what is expected from the previously proposed "orbiting" mechanism in light systems.

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In heavy-ion collisions involving light targets and projectiles ($12 \leq A \leq 40$), binary reaction products are observed which are characterized by full energy damping and angular distributions which are isotropic in the reaction plane. These reactions have generated considerable interest as being possible evidence for a deep-inelastic, "orbiting" mechanism,[1-6] a process in which the two nuclei form a long-lived rotating dinuclear complex without, however, forming a compound nucleus. In this Letter we present results of measurements of the fully damped binary reaction yields produced in the $^{32}S + ^{24}Mg$ reaction. Coincidence measurements were used to establish that the cross sections arise from the mass-asymmetric breakup of ^{56}Ni with no evident memory of the entrance channel. This behavior argues that these yields arise from an alternative mechanism of compound-nucleus formation followed by fission and not from an orbiting mechanism.

Several features of the observed fully energy-damped yields have been advanced to support an interpretation in terms of orbiting: (1) The total kinetic energy of the reaction products is consistent with their starting out with zero relative radial velocity from a nearly touching configuration; (2) the fragment masses in the dominant breakup channels have generally been found to be similar to the target and projectile masses, leading to the appearance of a strong entrance-channel dependence; and (3) the measured cross sections have been substantially greater than expected on the basis of evaporation calculations using the rotating-liquid-drop model to derive fission barriers. In the orbiting picture, the incident heavy ions are considered to be trapped in a pocket of their mutual interaction potential and are prevented from merging into a compound nucleus by the repulsive Coulomb and centrifugal barriers. Mass flow can occur from the entrance channel as long as suitable "pockets" exist in the new mass channels, but at each step there is competition between compound-nucleus formation, breakup, and further mass flow. Equilibration of the mass-asymmetry coordinate can only arise if the time scale for mass equilibration is short compared with the orbiting lifetime, a conclusion which is not supported by studies of the deep-inelastic process in heavier systems[7] and which has not been suggested for the lighter systems.

Several authors have suggested the possible importance of fission decay in these light systems,[8-12] although the measurements have generally been unable to determine the full mass dependence of the process. These studies have been motivated in part by recent theoretical work[13,14] indicating that fission barriers in light systems may be much lower than previously recognized, thus enhancing fission competition. The relative population of different mass channels through fission is determined by the curvature of the saddle-point energy along the mass-asymmetry coordinate,[15] and, for low-spin systems in this mass range, asymmetric fission is expected. The situation is, however, less clear for the high-spin systems populated through heavy-ion reactions. Both the fission and orbiting mechanisms would have similar experimental signatures, with the exception that a fission process should show full equilibration of the mass-asymmetry coordinate.

Our experimental arrangement consisted of five Si (surface-barrier) detectors and two Breskin-type,[16] position-sensitive avalanche counters. A 141.8-MeV, pulsed ^{32}S beam ($\Delta t \simeq 250$ ps) from the ATLAS facility was incident on a 160-μg/cm^2 self-supporting ^{24}Mg target. The five Si detectors were used to measure the energies and flight times of the reaction products, from which the masses of the reaction products could be derived. These detectors were all located on one side of the beam axis at laboratory angles and distances of 8° (86.7 cm), 16.3° (73.3 cm), 28.1° (40.0 cm), 38.2° (35 cm), and 48.2° (35 cm). The two gas counters were located on the opposite side of the beam axis and covered in-plane angular openings of 16° and 31°, respectively. In two settings, the gas counters covered completely the recoil range of $6° \leq \theta_{recoil} \leq 100°$. These detectors established the velocities of the recoil fragments by measurements of position and time of flight.

Single-mass resolution was achieved in the two most forward, long-flight-path detectors for all observed

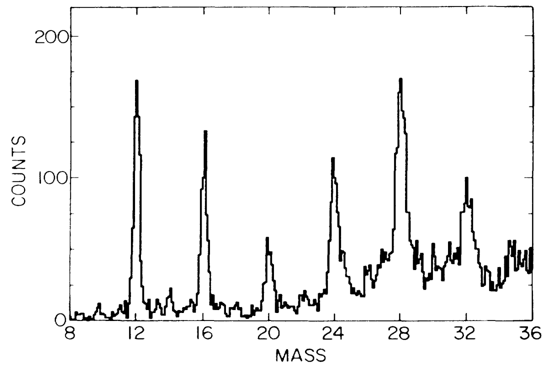

FIG. 1. Inclusive mass spectrum measured at $\theta_{lab}=28.1°$.

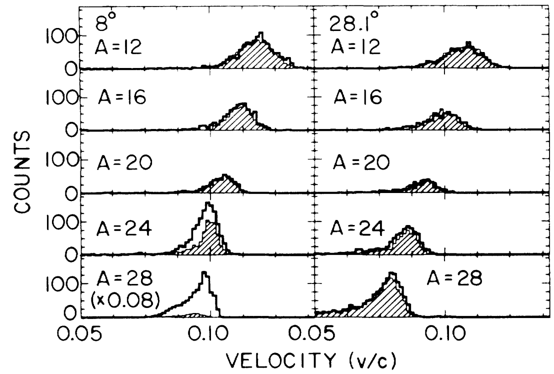

FIG. 2. Measured velocity spectra (bold histogram) and the corresponding LILITA simulations (shaded histograms).

masses, and only slightly worse mass resolution was found in the detectors at larger angles. Figure 1 shows the inclusive mass spectrum for the 28.1° detector. For all masses with $A \leq 28$ the energy-integrated yields at larger angles are found to correspond to a fully energy-damped process with angle-independent channel Q values. Very little yield was observed in the mass range $4 < A < 12$. For all but the 8° detector the recoil detection efficiency was found to be better than 80% for all masses through the mass $A=28$ channel. At 8° the efficiency was less because of (i) recoil angles which were smaller than covered by our gas counter and (ii) the low energies of some of the recoiling fragments.

To obtain the preevaporation mass distribution of the reaction fragments, it was necessary to correct for light-particle evaporation. This was done by simulation of the evaporation process with the Monte Carlo computer code LILITA.[17] In these calculations each mass channel with $12 \leq A \leq 28$ (corresponding to recoil masses with $44 \geq A_{recoil} \geq 28$) is specified by its relative probability P_A, the average Q value for the channel $\langle Q_A \rangle$, the Gaussian width of the Q-value distribution s_A, the total channel spin J_A (obtained with the sticking limit and with the assumption of a compound-system spin equal to the critical angular momentum for fusion), and a Gaussian width for the spread in the channel spin (taken as $0.085 J_A$). A $1/\sin\theta_{c.m.}$ angular dependence was assumed, corresponding to isotropic emission in the reaction plane. Of the three parameters which needed to be adjusted independently for each channel, $\langle Q_A \rangle$ and s_A were well determined by the measured velocity spectra, and P_A was found by iteration of the calculation until the observed (post-evaporation) mass distribution was reproduced.

The velocity spectra for the stronger mass channels measured at 8° and 28.1° are shown in Fig. 2 by the bold histograms. Also shown are the corresponding calculated velocity spectra (shaded histograms), appropriately normalized by the different detector solid angles. Excellent fits were obtained for the $A=12$, 16, and 20 distributions at all angles, supporting the angular-distribution and constant-mean-Q-value assumptions. For the $A=24$ distribution, there is some indication of a small forward-angle enhancement, and a strong forward peaking is observed in the $A=28$ channel—however, still at an energy consistent with substantial, but not full, energy damping. This forward-peaked component has the characteristics normally attributed to deep-inelastic scattering in heavier systems[7] and a similar mechanism may be contributing here. In the present analysis we focused on the larger-angle data for $A \geq 24$ where full energy damping and a $1/\sin\theta_{c.m.}$ angular dependence is observed.

One of the principal uncertainties in determining the preevaporation mass distribution P_A is related to the apportionment of the excitation energy between the reaction fragments. The coincidence data were used to establish this energy division. If no secondary light particles are emitted, momentum conservation gives for masses (labeled 1 and 2) $M_{1(2)}$ of the reaction products

$$M_{1(2)} = M_{\text{total}} \frac{V_{2(1)}^{\text{c.m.}}}{V_1^{\text{c.m.}} + V_2^{\text{c.m.}}},$$

where the velocities are the center-of-mass velocities of the fragments obtained by the assumption of two-body kinematics and $M_{\text{total}}=56$. The effect of light-particle evaporation is to broaden the mass distributions derived from the velocity measurements, but, under reasonable assumptions concerning the light-particle decay (see Ref. 7 for details), the average values of the deduced masses will not be changed. The preevaporation mass distributions derived in this manner and associated with various detected mass groups observed at $\theta=28.1°$ are shown in Fig. 3. Little evidence of secondary evaporation is found for the lighter-mass channels $A=12$, 16, and 20, where $\langle M_1^{\text{obs}} \rangle \simeq \langle M_1^{\text{preevap}} \rangle$. The situation is quite different for the $A=24$ and 28 channels where it is clear that a substantial fraction of the detected fragments arise from a heavier primary fragment. To reproduce these results, a

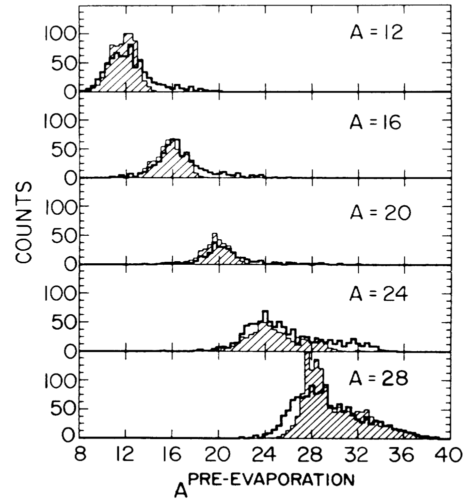

FIG. 3. Preevaporation mass distributions derived from the measured fragment velocities for different regions of the observed mass spectrum at $\theta_{lab} = 28.1°$ (bold histograms) and the corresponding mass spectra obtained from the LILITA calculation as described in the text (shaded histogram).

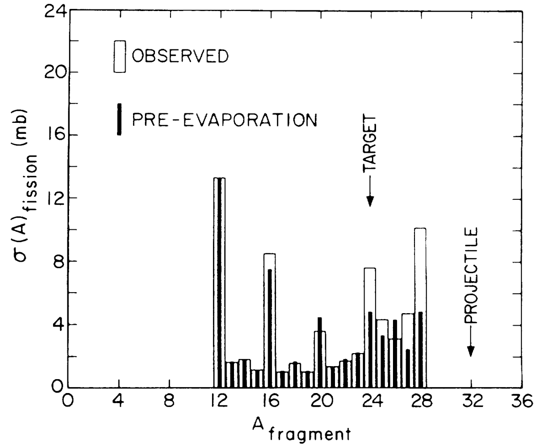

FIG. 4. Observed mass distribution (open histograms) and the corresponding deduced preevaporation mass distribution (solid histograms) for the fissionlike component of the $^{32}S + ^{24}Mg$ reaction at $E_{c.m.} = 60.8$ MeV.

functional form was taken for the excitation-energy division in the LILITA calculations which resulted in equal fragment excitation energy for the symmetric $A = 28$ channel (as required), and somewhat less excitation energy in the lighter fragment than would have been obtained if a division proportional to the fragment masses were assumed. The shaded histograms in Fig. 3 were obtained with use of LILITA to calculate the preevaporation masses at 28.1° based on the final (post-evaporation) velocities. The assumed excitation-energy division leads to a good reproduction of the experimental results.

The experimental mass distribution for that component of the reaction yield consistent with a $1/\sin\theta_{c.m.}$ angular dependence is shown in Fig. 4 by the open histograms. The preevaporation mass distribution needed by LILITA to reproduce this distribution is also shown in the figure. For these light nuclei, essentially all of the secondary evaporation is from p and α emission. Although the observed distribution appears to peak in both the symmetric $A = 28$ channel and the asymmetric $A = 12$ channel, it is clear that the enhancement at symmetry results from the downfeeding of heavier-mass channels. The deduced asymmetric, preevaporation mass distribution shows little, if any, memory of the entrance channel. Moreover, the relative mass yields are found to be independent of angle (except for the deep-inelastic component at forward angles with $A \geq 24$), indicating long reaction times compared with the times needed for mass equilibration.

The possibility that the observed mass distribution results from an "orbiting" process was explored within two different models. A semiclassical, one-body dissipation model[18] was used to explore the dynamics of the scattering process—no suggestion of a deep-inelastic, orbiting component was found in these calculations. A second, equilibrium model for fusion and orbiting[4,19] has also been studied. Here orbiting is viewed as a consequence of reaction flux being trapped in pockets of the exit-channel, nucleus-nucleus potentials. As found in lighter systems,[4,19] the potential-energy surface of the orbiting dinuclear complex seems to favor a mass split near the entrance channel. The large, positive Q value for the symmetric $^{28}Si + ^{28}Si$ exit channel results in the prediction that almost all of the orbiting cross section is in this channel—in direct contradiction to our measured results which show that the asymmetric channels are favored.

The total cross section contained in these fully damped yields is 59 ± 12 mb (including systematic uncertainties). On the assumption of an asymmetric fission mechanism, the total fusion cross section for this system should be taken as the sum of the evaporation-residue cross sections and this fission cross section. At this energy we find that fission contributes approximately 6% to the total fusion cross section.

The ratio of fission to evaporation-residue cross sections σ_f/σ_{er} can be understood in terms of recent fission-barrier calculations.[14] The competition between these processes can be modeled with the statistical evaporation code CASCADE[20] (e.g., Ref. 11). Assuming a partial cross section given by $\sigma_l \propto (2_l+1)/\{1+\exp[(l-l_{cr})/\Delta]\}$, with $\Delta = 1.4\hbar$ and l_{cr} set by σ_{er}, the calculation predicts $\sigma_f/\sigma_{er} = (106 \text{ mb})/(992 \text{ mb})$, in reasonable agreement with the experimental values of $\sigma_f = 59 \pm 12$ mb and $\sigma_{er} = 1050 \pm 50$ mb (see Hinnefeld *et al.*[21]). Similar calculations, using the same diffuseness parameter, can be done for the other light systems where fully damped cross sections have been attributed to an orbiting process (denoted σ_{orb}). For the ^{28}Si + ^{12}C reaction at $E_{c.m.} = 30$ MeV, we calculate $\sigma_f/\sigma_{er} = (9\ \text{mb})/(970\ \text{mb})$, which is to be compared with the measured cross sections[2,22] $\sigma_{orb}/\sigma_{er} = (7\ \text{mb})/(967\ \text{mb})$; at $E_{c.m.} = 54$ MeV, $\sigma_f/\sigma_{er}(\text{calc}) = (40\ \text{mb})/(765\ \text{mb})$ is to be compared with[19,23] $\sigma_{orb}/\sigma_{er}(\text{meas}) = (95\ \text{mb})/(728\ \text{mb})$. Similarly for the ^{16}O + ^{48}Ti reaction at $E_{c.m.} = 75$ MeV, σ_f/σ_{er} (calc) is found to be (76 mb)/(1214 mb), which is to be compared with $\sigma_{orb} = 66$ mb and an estimate of $\sigma_{er} = 1300$ mb (see Ref. 6). Considering the uncertainties in the calculations, the above predictions are in excellent agreement with the data. Essentially perfect agreement can be achieved by a fine tuning of the CASCADE parameters on a case-by-case basis, although the value of such fine tuning, without additional experimental input, is doubtful. It is clear for all of these systems that the magnitudes of the observed fully damped yields are what is expected for compound-nucleus fission on the basis of recent fission-barrier estimates.

In summary, we have measured the mass dependence of the fully energy-damped, binary reaction products from the ^{32}S + ^{24}Mg reaction at $E_{c.m.} = 60.8$ MeV. That component of the yield which is consistent with the decay of a long-lived, intermediate system shows full mass equilibration with no evident memory of the entrance channel. This result suggests that these binary yields result from the fission decay of the ^{56}Ni compound nucleus, and not through an orbiting mechanism. The magnitude of the fission cross section can be reproduced in model calculations based on recent estimates of fission-barrier energies in light nuclei. In view of the observation that these calculations also predict a fission component in reactions involving even lighter systems, it may be useful to reevaluate the fully damped yields observed in these light systems which have previously been attributed to orbiting, but may actually result from compound-nucleus decay.

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