Two-body final-state coincidence measurements for fissionlike processes following $^{35}Cl + ^{27}Al$ fusion*

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A two-body final state with a mass distribution centered about half the mass of the compound system and with an average kinetic energy distribution equal to the Coulomb energy of the final system is observed following the fusion of ^{35}Cl with ^{27}Al at 170 MeV incident energy. Such a process is consistent with the onset of a fissionlike process resulting from the lowering of the rotating liquid drop fission barrier as a function of angular momentum.

[NUCLEAR REACTIONS, FISSION $^{35}Cl + ^{27}Al$ fusion, $E = 170$ MeV; measured fragment-fragment (E; A).]

It is well known that the s-wave fission barrier is well above the particle emission threshold for nuclei with $A \lesssim 210$. However, cross sections interpreted as fissionlike processes have been observed for medium[1] and light[2] mass systems formed in heavy-ion reactions. A lowering of the fission barrier B_f with increased angular momentum has been suggested as an explanation of such fission widths.[3,4]

The present communication reports data for the $^{35}Cl + ^{27}Al$ system at $E_{Cl}(\text{lab}) = 170$ MeV in which the energy and mass of one particle are measured in coincidence with the energy of the second particle. These coincidence measurements indicate a two-body final state with kinetic energies corresponding to the Coulomb separation energy of the two fragments. The mass distribution of the two correlated fragments is symmetric about half the mass of the composite system. Such data support the suggestion[1-4] that a fissionlike process competes in the deexcitation of the compound system when sufficient angular momentum is present.

The experiment was performed using the ^{35}Cl beam of the Brookhaven tandem facility and an 800 $\mu g/cm^2$ self-supported foil of natural Al. The time-of-flight (TOF) system[5] and the data acquisition and analysis techniques[6,7] are described elsewhere. Two-dimensional plots of laboratory energy E_{TOF} vs mass for the TOF singles data are shown in Fig. 1. At the forward angle 7.2°(lab) [Fig. 1(a)] the elastic peak, along with neighboring quasielastic mass lines and the fusion group ($A \approx 49-58$), dominates the spectrum. At 20° in the lab there is still a remnant of the elastic peak and the fusion products. In the 20° spectrum, however, a significant cross section is observed over a wide range of particle energies and masses ($19 \lesssim A \lesssim 44$) centered about $A \approx 31$, which is half the mass of the ^{62}Zn compound nucleus. There are also reaction products of mass 44–52 that probably correspond to a compound system which has evaporated more than two α particles. A coincidence measurement between the two final-state particles distinguishes the events which belong to fusion proceeding to multiple light particle evaporation from those corresponding to fusion fission.

The energies of particles in coincidence with the events in the TOF spectrometer were measured using a second silicon surface-barrier detector to cover all possible two-body kinematic coincidence angles for a given TOF angle defined to ±1°. The coincidence events are shown as a function of the recoil energy in the second detector (E_R vs E_{TOF}) in Fig. 2(a) ($\theta_{TOF} = 15°$ lab). Also shown in Fig. 2(b) is the corresponding E_{TOF} vs M plot. In the mass spectrum, the fusion group and the lower mass higher energy continuum of interest are clearly distinguishable. When the fusion group is removed from the TOF spectrum by setting an upper level discriminator on the mass signal (indicated by the vertical line and cross-hatched area), the portion of the E_R vs E_{TOF} coincidence spectrum indicated in Fig. 2(a) by the cross-hatched area disappears. Consequently, these cor-

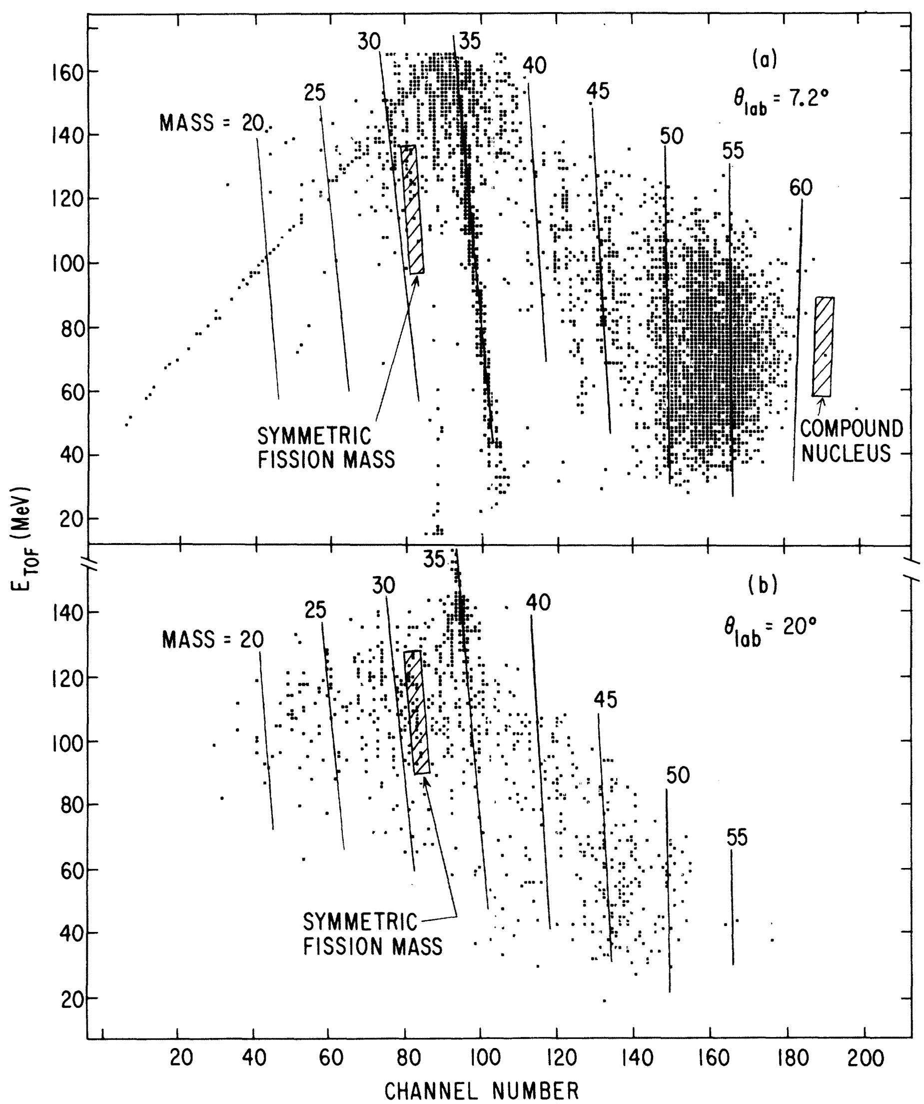

FIG. 1. Comparison of E_{TOF} (lab) vs M ($ET^2 \sim$ mass) spectra for 170 MeV ^{35}Cl incident on ^{27}Al at lab angles of (a) 7.2° and (b) 20°. Mass lines established as described in Ref. 6 are shown. The compound nucleus and symmetric fission masses are indicated.

related low energy events observed in the E_R vs E_{TOF} spectrum correspond to the light particles[8] emitted in the deexcitation of the fused compound system.

An E_R vs E_{TOF} coincidence spectrum obtained at $\theta_{TOF} = 25°$lab (where essentially no fusion products were detected) and its corresponding mass spectrum are shown in Fig. 3. The measured energies of the two coincident fragments as a function of mass, are in agreement with the kinetic energy centroid for two fragments separating with the Coulomb energy in the center-of-mass system. The calculated centroid-energy curve is shown as solid line in Figs. 3(a) and 3(b). The E_{TOF} vs M spectrum is centered about $A = 31$, which is the symmetric fission mass of the ^{62}Zn compound system [see Fig. 3(b)].

Two-body final states having a mass distribution centered about the symmetric breakup mass of the composite system and with an average kinetic energy distribution of the Coulomb energy of the final system are characteristic of fission. The present data[9] do not distinguish between the fission of a fully equilibrated compound system and pre-equilibrium fission.[1] The observed fission, however, can be understood in terms of the fission

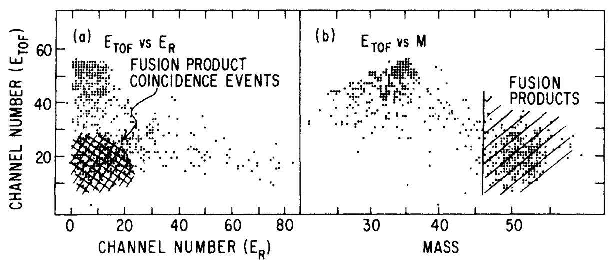

FIG. 2. (a) E_R(lab) vs E_{TOF}(lab) coincidence spectra for 170 MeV ^{35}Cl incident on ^{27}Al at $\theta_{TOF} = 15°$ lab. (b) Corresponding E_{TOF} (lab) vs M spectra for events which are in coincidence with the recoil detector $\theta_R = 28-72°$ lab. When an upper level mass discriminator is set as shown by the cross-hatched area to eliminate the fusion products from the E_{TOF} vs M coincidence spectrum, the low energy TOF recoil events [cross-hatched area in Fig. 2(a)] are eliminated.

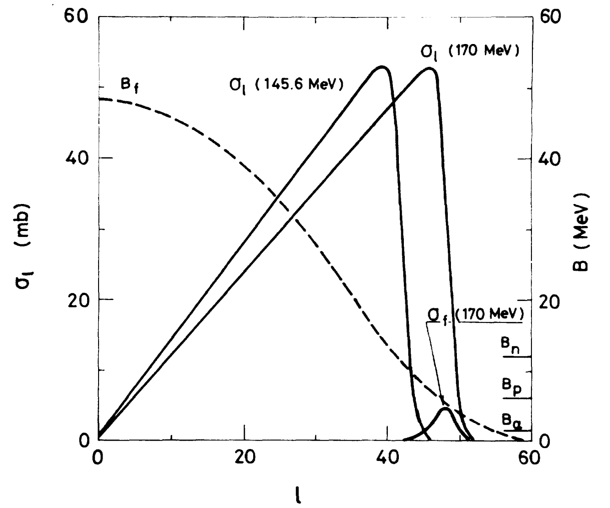

FIG. 4. Predicted partial cross section population σ_l as a function of l for 145.6 and 170 MeV ^{35}Cl incident on ^{27}Al. The partial fission cross section σ_f predicted from the competition between particle evaporation and fission through the rotating liquid drop barrier (shown as a function of l by the dashed curve labeled B_f) also is shown for 170 MeV. The values of σ_f are the product of the ratios of fission to total decay widths Γ_f / Γ_{tot} and σ_l. (Γ_f / Γ_{tot} was calculated using the code ALICE—see Refs. 4 and 10.) Therefore, second chance fission (which would be negligible in the present case near the fission threshold) is not included in σ_f. The excitation energies of the n, p, and α particle emission thresholds in ^{62}Ni are indicated by B_n, B_p, and B_α. The cross section scale on the left hand side of the figure applies to σ_l and σ_f, whereas, the energy scale for B_f, B_n, B_p, and B_α is shown on the right hand side of the figure.

barrier of a rotating liquid drop.[3,4] The liquid drop fission barrier calculated for the present case using the code ALICE[4,10] is shown as a function of angular momentum l in Fig. 4. Also shown are partial cross sections σ_l vs l for 145.6 and 170 MeV ^{35}Cl on ^{27}Al ($E_{c.m.} = 63.4$ and 74.0 MeV, respectively). Fission should compete with particle emission for those partial waves where the fission barrier is comparable with the lowest particle emission threshold plus the Coulomb barrier for particle decay. Indeed a fission cross section ~1.5% of the total reaction cross section is predicted

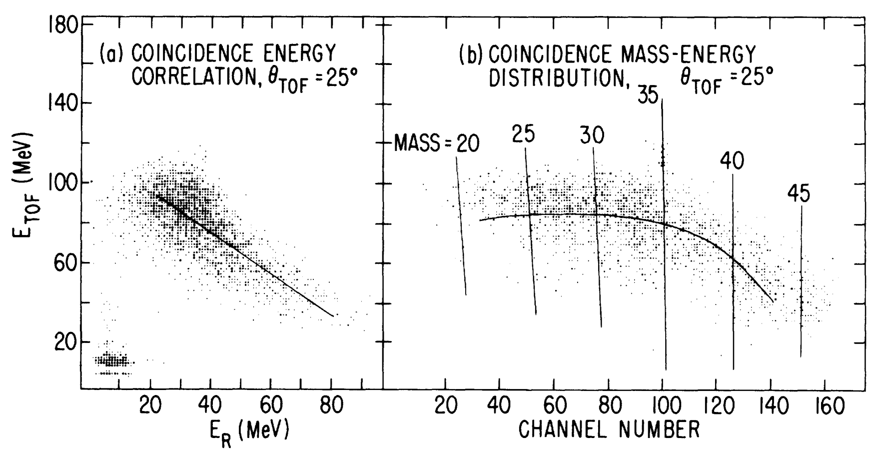

FIG. 3. (a) E_R(lab) vs E_{TOF}(lab) coincidence spectrum and (b) corresponding E_{TOF}(lab) vs mass spectrum for 170 MeV ^{35}Cl on ^{27}Al ($\theta_{TOF} = 25°$, $\theta_R = 28-72°$). The predicted coincident laboratory kinetic energy centroid and E_{TOF} (lab) vs mass centroid for two fragments separating with the Coulomb energy of two touching spheres is indicated by the full-drawn lines in (a) and (b), respectively. A radius $1.3(A_1^{1/3} + A_2^{1/3})$ was assumed in the Coulomb energy calculation. The predicted kinetic energy centroids shown have been corrected for kinematics and energy losses in the target and in the TOF system.

for the present system at an incident ^{35}Cl energy of 170 MeV (see Fig. 4). For $E_{Cl} = 145.6$ MeV, a much smaller fission cross section is predicted, since those partial waves for which fission competes are not populated. Such fissionlike cross sections were not observed in similar TOF data measured for this system at incident energies up to 145.6 MeV.

Note added in proof: We should like to thank M. Blann for pointing out an error in the normalization of Γ_f in the code ALICE which changes the present values for the calculated fission cross section from those previously reported.[11] Data in which the mass of one fragment is measured in coincidence with the charge of a second fragment have recently been reported[12] establishing a fissionlike binary mass division for the composite system formed by 140 MeV ^{32}S incident on ^{50}Ti.

We would like to thank the authors of Ref. 2 for discussing the results of their work with us prior to publication.

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[1]See F. Plasil, in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, 1974,* edited by R. L. Robinson *et al.* (North-Holland, Amsterdam, 1974), Vol. II, p. 107; and references therein.

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[8]These events probably correspond to α particles since protons would lose only a very small amount of energy in the 60 μm recoil detector. In fact, the higher energy α particles may not be completely stopped either; thus these energies should not be taken literally.

[9]It is assumed, however, that the present process is similar to that recently observed (Ref. 2) for 130 and 144 MeV ^{32}S incident in ^{48,50}Ti. In these data the measured angular distributions follow an approximate $(\sin\theta^{-1})$ dependence and therefore are consistent with fission from an equilibrium compound system.

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