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PROJECTILE FISSION IN ^{58}Ni-INDUCED REACTIONS AT 15.3 MeV/u*

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The present study was intended as a search for sequential fission of projectilelike fragments for reactions induced by intermediate-mass heavy ions. The objective was to determine the fission probability as a function of excitation energy or energy loss in the first step of the reaction. The experimental configuration was optimized for the detection of three-body sequential fission events over the full range of possible energy losses. The detector arrangement included a large-area ionization chamber which had two independent upper and lower halves, each capable of measuring the energy, E, and the energy loss, ΔE, of reaction products as well as their (x,y) position. A second detector was operated in coincidence on the other side of the beam axis. It consisted of an ionization ΔE section backed by a position-sensitive silicon detector. This telescope covered a fixed in-plane angular range of −12° to −32°, while the large-area ionization chamber was operated at three angles covering the angular range of 4° to 39°.

The inclusive charge distributions measured with the large-area ionization chamber for reactions of ^{58}Ni + ^{58}Ni at 15.3 MeV/u were found to be dominated by products with $Z < 28$. Very little yield was observed for nuclei with charges greater than that of the projectile. It has been shown[1] that most of the shift toward lighter products is consistent with the effects of equilibrium evaporation. At the largest calculated energy losses, the inclusive charge distributions were found to be slightly asymmetric due to an increasing component of fragments with half or less of the projectile charge. These light fragments were observed to have much broader angular distributions than the corresponding heavier fragments of the same energy loss. These observations from the inclusive measurements already suggest the occurrence of sequential fission of the projectilelike fragment. More conclusive evidence is obtained from the coincidence measurements.

In Fig. 1(a) the distribution of coincident events is shown as a function of $Z_1 + Z_2$ and $E_1 + E_2$. A strong cluster of events appears centered at $Z_1 + Z_2 \approx 40$ and $E_1 + E_2 \simeq 440$ MeV. Events in this region originate from binary events. They involve large energy losses and, therefore, large amounts of charged-particle evaporation. The peak represents only a small portion of all binary events due to phase-space restrictions of our experimental geometry. In contrast, events with $10 \lesssim Z_1 + Z_2 \lesssim 30$ and $200 \lesssim E_1 + E_2 \lesssim 750$ MeV are not due to binary reactions between ^{58}Ni nuclei, but must originate either from three-body sequential fission events or from binary reactions between ^{58}Ni projectiles and light target contaminants.

Evidence that these coincident events are not due to reactions on a light target contaminant is obtained by a direct comparison of the results from the ^{58}Ni target with those obtained for the ^{58}Ni + ^{12}C reaction under identical experimental conditions. The coincident distributions for reactions on carbon are found to differ significantly from those on nickel.

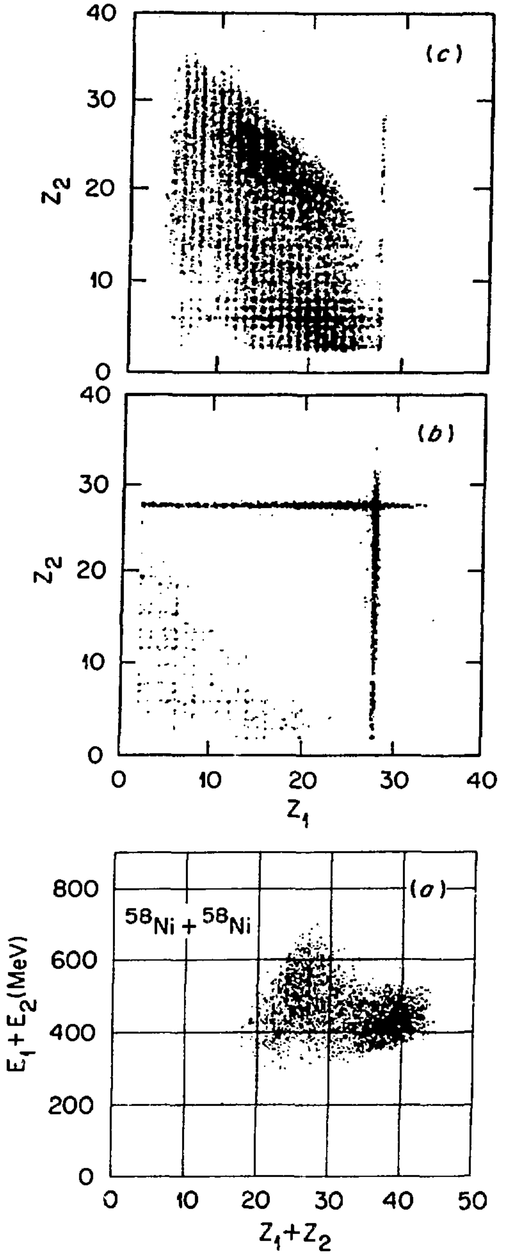

Fig. 1. Distributions of coincident products for reactions of $^{58}Ni + ^{58}Ni$ at 15.3 MeV/u. (a) Summed charge versus the summed laboratory energy. (b) Charge of fragment observed in lower half of ionization chamber versus charge observed in upper half. (c) Correlation between fragment charges observed on opposite sides of the beam by two different ionization chambers.

In particular, the rest frame velocity of those events on ^{58}Ni with $Z_1 + Z_2 \lesssim 30$ is peaked near 3.8 cm/ns, which is consistent with a fully damped two-body reaction followed by sequential fission. On the other hand, due to the inverse kinematics, the center-of-mass velocity of the $^{58}Ni + ^{12}C$ system is 4.5 cm/ns. From these differences we can conclude that possible contributions from light target contaminants are less than 5%.

Due to the inverse kinematics, it is clear that reactions on a light target contaminant would result in a coincidence distribution which might be interpreted as resulting from three-body sequential fission occurring after little energy loss. Although the experimental geometry and systems studied were different, there is a similarity between our results on ^{12}C and the $^{86}Kr + ^{89}Y$ coincidence measurements presented in Ref. 2 in the region of small, apparent energy losses.

Further direct evidence for the three-body interpretation of our results is shown in Fig. 1(b) by the correlation between coincident charges, Z_1 and Z_2, obtained with the lower and upper halves of the ionization chamber. Thus, both of the detected fragments were observed on the same side of the beam, which, by momentum conservation, immediately implies that a third reaction product must be present on the other side of the beam. The concentration of events with $Z = 28$ is obviously due to random coincidences with elastically scattered ions.

In Fig. 1(c) the correlation between the nuclear charge, Z_1, observed in the large ionization chamber is shown versus the nuclear charge, Z_2, observed in the small detector. This presents a less biased selection of coincident events than those of Fig. 1(b), which were constrained to small opening angles due to the angular acceptance of the ionization chamber. The concentration of yield at $Z_1 + Z_2 \simeq 40$ due to binary events is again clearly observed. A striking feature of Figs. 1(b) and 1(c) is the broad distribution of three-body events over nearly all possible Z_1, Z_2 combinations with sum charge less than or about equal to ^{58}Ni. Since the sum charge is sometimes much less than 28, it is likely that there are occasionally more than three large fragments in the final state. In Fig. 1(c) two different components are observed to contribute to the coincident events with $Z_1 + Z_2 \approx 28$. One component corresponds to symmetric fission with both fragments observed to have about equal charges. The second component corresponds to an asymmetric decay with the emission of a carbonlike fragment $Z_1 \simeq 20$, $Z_2 \simeq 6$. (The corresponding asymmetric decay $Z_1 \simeq 6$, $Z_2 \simeq 20$ is biased against by our experimental configuration.)

In Fig. 2 the experimental fission probabilities are shown for all fissionlike events with Z_1 and $Z_2 > 3$ (asterisks) and also for symmetric fission events only [crosses, $|Z_1 - Z_2| \lesssim 0.3\ (Z_1 + Z_2)$]. To extract the fission probabilities shown in Fig. 2, we have made a Monte Carlo simulation in order to determine the coincident detection efficiency. To obtain the fission probability, we have divided the efficiency-corrected fission cross section by the total cross section at each energy loss. The excitation energy of the nickellike fragment is assumed to be half of the calculated energy loss. This neglects the effects of particle evaporation and the width in the sharing of the excitation energy, which will have compensating effects on the actual excitation energy of the fragment.

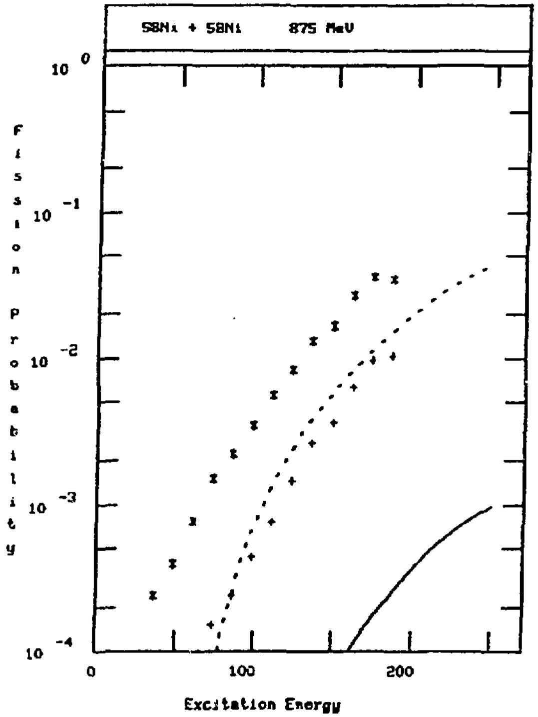

Fig. 2. Excitation function of fission probability. Experimental results are preliminary with an estimated uncertainty of 50% due to uncertainties associated with the simulation process. Experimental points: all fissionlike events (asterisks); symmetric fission events (crosses); calculations: $J = 25$, $B_f = 0.8\ B_f^{RLDM}$, $a_f/a_n = 1.05$ (dashed curve); $J = 25$, $B_f = B_f^{RLDM}$, $a_f/a_n = 1.00$ (solid curve).

Also shown in Fig. 2 are the results of statistical model calculations of the fission probability of ^{58}Ni using the evaporation code PACE.[3] For this calculation an angular momentum of $J = 25$, corresponding to the sticking condition, was assumed, together with a fission barrier corresponding to 0.8 of the rotating liquid drop barrier and a level density parameter $a_f/a_n = 1.05$. This calculation is found to reproduce the probability for symmetric fission surprisingly well. The large probability for asymmetric fission of the projectilelike fragment might be explained by liquid drop calculations which predict a decreasing barrier with increasing mass asymmetry for systems with low fissility. The enhanced yield at carbon might be due to modifications of the liquid drop barrier due to cluster effects for systems this light.

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