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# REACTIONS BETWEEN $^{58}$Ni NUCLEI AT 15.1 MeV/u*

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This study was motivated by reports[1,2] of the observation of ternary events in Kr- and Xe-induced reactions corresponding to the fast fission, or "splitting," of projectilelike products. The first of these reports, by Olmi et al.,[1] emphasized indirect evidence obtained from inclusive data from the reaction $^{86}$Kr + $^{166}$Er at 12.1 MeV/u. It was argued that the observed drift to low-Z products as a function of increasing energy loss could not be accounted for by charged-particle evaporation since the observed yield of charged particles was too low. It was concluded that the distribution of projectile fragments reflected an admixture of ternary events. More direct evidence for this hypothesis was presented[1] by measurements of both projectile fragments, which indicated that relatively little energy loss is involved in the first step of the reaction and little charge transfer takes place prior to fission.

In a separate study[2] three-body fission events were observed in the case of $^{84}$Kr + $^{90}$Zr, $^{84}$Kr + $^{166}$Er, and $^{129}$Xe + $^{122}$Sn. In this work each event was kinematically completely determined (except for the effects of neutron emission), and it was deduced that the reaction involves two steps, with large energy losses in the first step leading to nonequilibrium fission in the second step. By interpreting the proximity effects which play a role in the three-body final state, it was concluded that the time interval between the two steps is of the order of $10^{-21}$ s.

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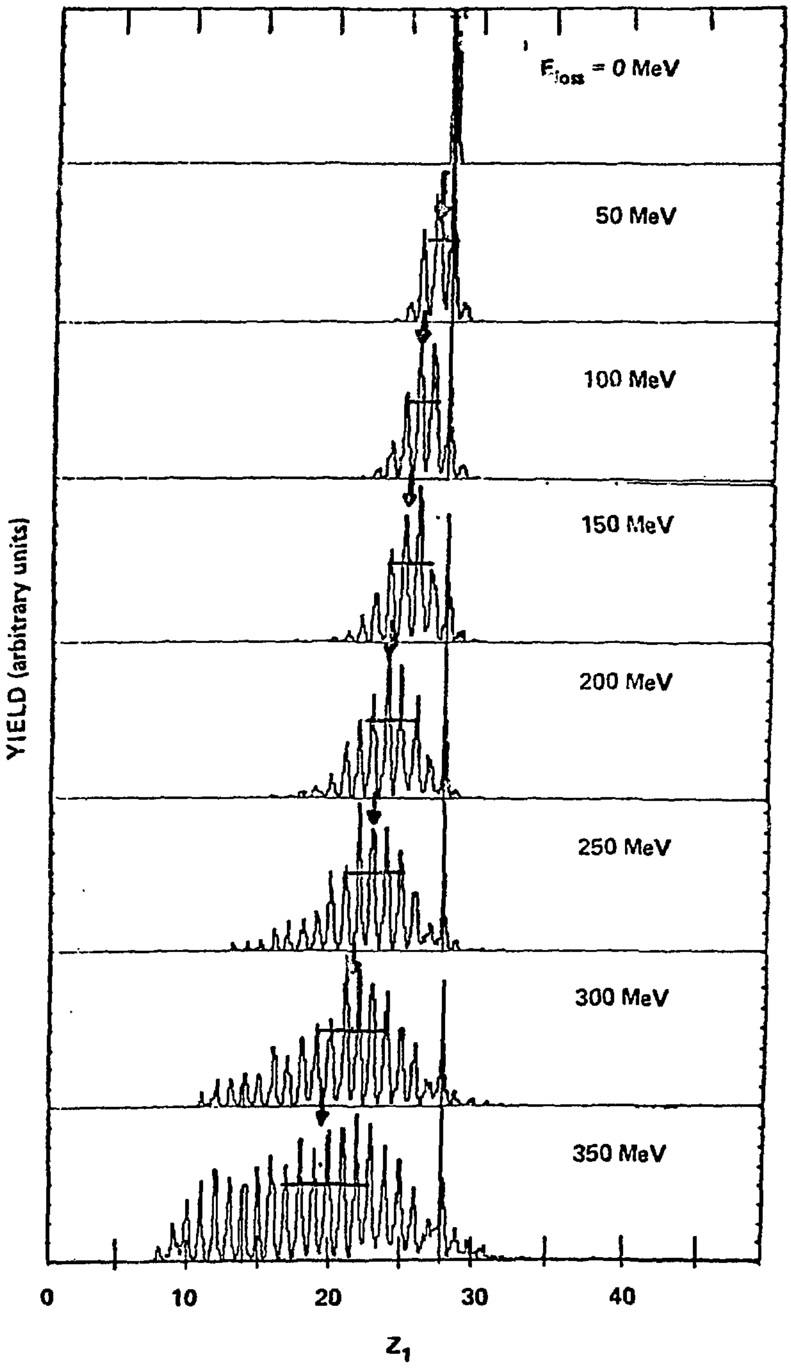

Fig. 1. Charge distributions of projectilelike products from reactions between $^{58}$Ni nuclei at 15.1 MeV/u at various values of energy loss, $E_{loss}$. For description of the arrows and of the horizontal bars, see the text.

The present study was intended to determine if such three-body events also occur in reactions with lighter projectiles and to establish the extent of charge transfer and energy loss in the first step of the reaction. The experimental configuration was optimized for the detection of three-body events over the full range of possible energy losses. The detector arrangement included a large-area ionization chamber capable of measuring the energy, E, and the energy loss, $\Delta E$, of reaction products as well as their (x,y) position. A second detector was operated in coincidence on the other side of the beam. It consisted of an ionization $\Delta E$ section backed by a position-sensitive silicon counter. This detector covered a fixed in-plane angular range of $-12^{\circ}$ to $-32^{\circ}$, while the large-area ionization chamber was operated at three angles, covering the angular range of $4^{\circ}$ to $39^{\circ}$. For every coincident event the quantities $Z_1$, $Z_2$, $E_1$, $E_2$, $\theta_1$, $\theta_2$, and $\phi_1$ were deduced from the recorded pulse heights. (Z refers to the nuclear charge; E to the kinetic energy; $\theta$ is the in-plane and $\phi$ the out-of-plane angle.) In the absence of light-particle emission, for a strictly three-body event, the above quantities are sufficient to fully determine the event. With increasing energy loss, the probability of significant light-particle emission increases, and conclusions based on measurements of the quantitites listed above become more ambiguous.

The inclusive charge distributions measured with the large-area ionization chamber were found to be dominated by products with $Z < 28$, and very little yield of nuclei with charges greater than that of the projectile was observed. The inclusive charge distributions are shown, for various values of energy loss, in Fig. 1. Since, in the case of a symmetric system, the driving force along the potential energy surface at the injection point does not act in the asymmetry degree of freedom, the pronounced shift toward lower Z values must either be due to charged-particle evaporation or to a strong component of three-body events, as argued in Ref. 1. In order to estimate the role of charged-particle emission in our case, we have performed the following simple calculation. First, the statistical moments of the charge distribution of projectilelike fragments were calculated in the context of the theory of Randrup.[3] This transport theory incorporates energy-damping nucleon exchanges using a one-body dissipation approach, as well as effects due to the blocking of transfers to occupied states around and below the Fermi surface because of the Pauli principle. This theory has been found to be in agreement with experimental results in the case of a system similar to ours, but at a lower energy.[4] Second, effects of deexcitation of the products by statistical particle emission were included in the calculations along the lines indicated in Ref. 4. The results are shown in Fig. 1. The arrows indicate the first moments of the calculated distributions, and the horizontal bars indicate their full widths at half maximum. Except for the highest energy losses, the agreement between the experimental and the calculated distributions is fairly good. We may conclude that most of the shift toward reaction products lighter than the projectile is consistent with the effects of evaporation from a primary distribution as given by Randrup's transport theory.

Coincidence results are shown in Figs. 2 and 3. In the top part of Fig. 2 the distribution of coincident events is shown as a function of $Z_1 + Z_2$ and of $E_1 + E_2$. A strong cluster of events appears centered at $Z_1 + Z_2 \gtrsim 40$ and $E_1 + E_2 \gtrsim 440$ MeV. Events in this region can be shown to originate from binary events. They involve large energy losses and, therefore, large amounts of charged-particle emission. The peak represents only a small portion of all binary events due to phase-space restrictions resulting from our experimental configuration. The above interpretation is supported by the observation that these events have rest frame velocities similar to the velocity of the center of mass. In contrast, events with $10 \lesssim Z_1 + Z_2 \lesssim 30$ and $200 \lesssim E_1 + E_2 \lesssim 750$ MeV (see Figs. 2 and 3A) are not due to binary reactions between $^{58}$Ni nuclei, but must originate either from ternary sequential fission events or from binary reactions between $^{58}$Ni projectiles and light target contaminants.

Several arguments can be presented for the three-body interpretation of the events with $Z_1 + Z_2 \lesssim 30$. First, the rest frame velocity of these events is centered near 3.8 cm/ns, which is consistent with a fully damped two-body reaction on $^{58}$Ni followed by a sequential fission process. For comparison, the velocity of the center of mass of the $^{58}$Ni + $^{58}$Ni system is 2.7 cm/ns, and the c.m. velocity of the $^{58}$Ni + $^{12}$C system ($^{12}$C contaminant) is 4.5 cm/ns. Second, a comparison of the $E_1 + E_2$ vs. $Z_1 + Z_2$ distribution from $^{58}$Ni + $^{58}$Ni reactions can be made with that obtained from reactions between $^{58}$Ni and mylar (i.e., between $^{58}$Ni and carbon and oxygen). Such a comparison is shown

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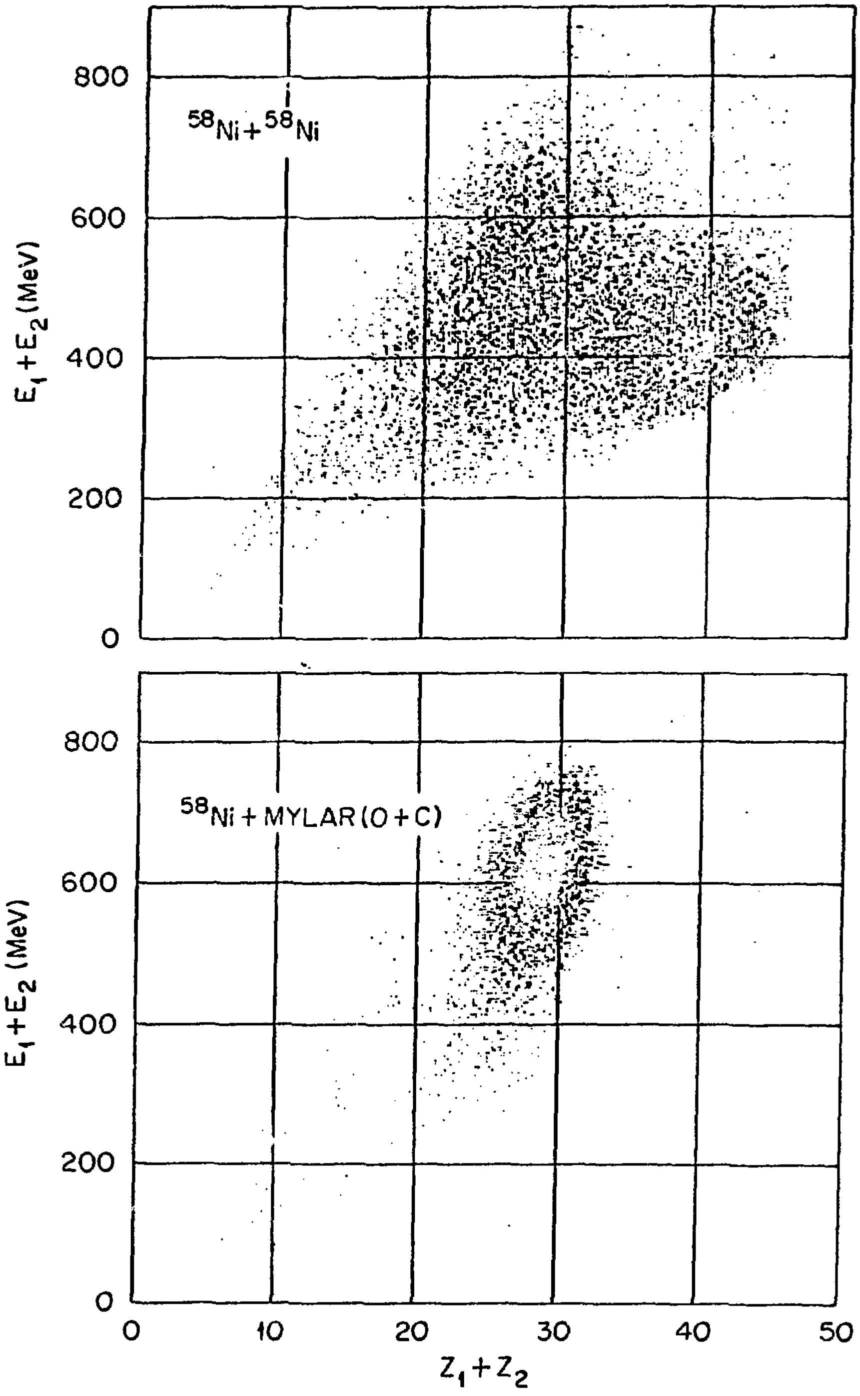

Fig. 2. Distributions of coincident products as a function of the sum of their observed kinetic energies and of the sum of their charges. The upper part is from reactions between $^{58}$Ni nuclei at 15.1 MeV/u, and the lower part is from reactions between $^{58}$Ni and mylar (i.e., O and C).

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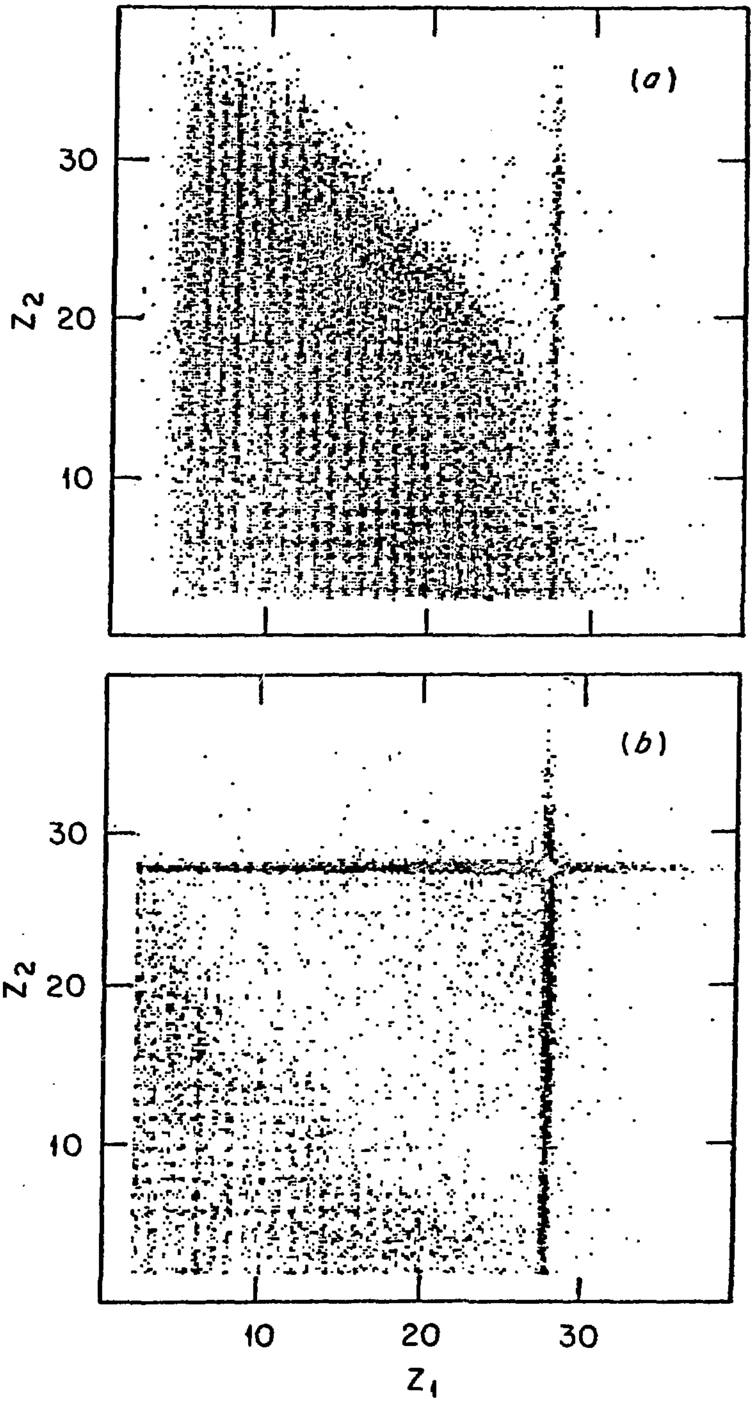

Fig. 3. Correlated charge distributions of coincident products from 875-MeV $^{58}$Ni reactions with $^{58}$Ni. Figure 3A shows products detected on opposite sides of the beam by two different ionization chambers. Figure 3B shows products detected on the same side of the beam by two halves (top and bottom) of the same ionization chamber.

in Fig. 2. It is clear that reactions on light contaminants result in a sum charge distribution which would suggest little charge transfer and a sum energy distribution which would suggest little energy loss, similar to the conclusions of Ref. 1. In contrast, we observe that energy losses of at least 200 MeV are required in the first step of the reaction before symmetric fission products are observed, and that the sum charge, for three-body events, shows a shift toward products lighter than the projectile, just as observed in the inclusive distribution (see Fig. 1). Finally, very little contribution from light target contaminants would have been expected since a thick $^{58}$Ni foil of 1.9 mg/cm$^2$ was used.

The above considerations are confirmed by direct evidence shown in Fig. 3B. This figure depicts coincident events obtained with the lower and upper halves of the large-area ionization chamber. Thus, both of the observed partners of each event detected in this manner were observed on the same side of the beam. The concentration of events along the lines $Z = 28$ is obviously due to random events associated with elastically scattered products. However, those events in the region $Z_1 + Z_2 \lesssim 28$ are primarily valid coincidences. Simple considerations of momentum conservation immediately rule out any kind of binary events, and a third large reaction product must be present on the other side of the beam.

In Fig. 3A 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. In this case the line of random coincidences at $Z_2 = 28$ is absent since this detector was located beyond the grazing angle and, thus, was not exposed to a large flux of elastically scattered particles. The concentration of yield at $Z_1 + Z_2 \gtrsim 40$ due to binary events is again clearly observed. A striking feature of Figs. 3A and 3B is the very broad distribution of the three-body events over nearly all possible $Z_1$, $Z_2$ combinations having sum charge less than or about equal to $^{58}$Ni. In fact, it is most likely that there are more than three bodies in the final state. There also appear to be indications of an enhanced probability for an asymmetric split of the nickel-like fragment (see Fig. 3B).

Our preliminary conclusion is that ternary fission events occur in reactions between $^{58}$Ni nuclei at 875 MeV after substantial energy loss.

Further work is in progress in an effort to determine the relative probability of these events and to obtain information on the role, if any, of proximity effects.

We are indebted to J. Randrup for providing us with his theoretical calculations[3] for our case. We also wish to acknowledge the dedication and perseverance of the staff of the Holifield Heavy Ion Research Facility, which resulted in the production, by means of coupled accelerator operation, of excellent $^{58}$Ni beams.

## REFERENCES

1. A. Olmi et al., Phys. Rev. Lett. 44, 383 (1980).
2. P. Glässel et al., Phys. Rev. Lett. 48, 1089 (1982); D. v. Harrach et al., Phys. Rev. Lett. 48, 1093 (1982).
3. J. Randrup, Nucl. Phys. A327, 490 (1979).
4. H. C. Britt et al., Phys. Rev. C 26, 1999 (1982).