Fission Decay of Reaction Products with $A \lesssim 150$

T. C. Awes, R. L. Ferguson, R. Novotny,[a] F. E. Obenshain, F. Plasil, V. Rauch,[b] and G. R. Young
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

and

H. Sann
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, West Germany
(Received 5 February 1985; revised manuscript received 22 July 1985)

Fissionlike decay was observed for fragments resulting from reactions of $^{58}Ni + ^{58}Ni$ at 15.3-MeV/u incident energy. The measured probabilities for fission decay, as well as previous measurements are consistent with equilibrium fission calculations.

PACS numbers: 25.70.Lm, 25.85.−w

In damped reactions between heavy ions at high incident energy, the strong dissipation of relative kinetic energy and angular momentum into intrinsic degrees of freedom may result in the fission decay of one of the reaction partners. Recent measurements at incident energies above 10 MeV/u have suggested a nonequilibrium fission process[1–4] occurring with unexpectedly large probability.[1,3,4] The fission has been shown to occur on a short time scale, by the observation of proximity effects.[2–4]

In this Letter we report the observation of fissionlike decay of fragments resulting from interactions of ^{58}Ni on ^{58}Ni at 15.3-MeV/nucleon incident energy. We determine the probability for fissionlike decay of light nuclei with masses around ^{58}Ni for the first time. The measured decay probability is found to be consistent with equilibrium fission evaporation calculations. Furthermore, previous results[3,4] for the fission decay of heavier reaction products, which have been interpreted as indicating enhanced fission probability, are also shown to be consistent with calculated fission probabilities. This implies that primary products for these systems ($A \lesssim 150$) are not necessarily formed with deformations beyond the saddle-point configuration during the first step of the reaction.

The present experiment was performed with an 889-MeV beam of ^{58}Ni produced by coupled operation of the tandem electrostatic and cyclotron accelerators of the Holified Heavy Ion Research Facility in Oak Ridge. Inclusive and two-fragment exclusive measurements of products resulting from interactions with a ^{58}Ni target (1.96 mg/cm^2) were made with two large solid-angle gas ionization chambers. The first detector consisted of an ionization ΔE section backed by a position-sensitive silicon detector. It gave energy, charge, and in-plane information over a fixed in-plane angular range of $-12° < \theta < -32°$ with an out-of-plane acceptance of $\Delta\phi = 3.5°$. The second detector was a large-area ionization chamber with independent upper and lower halves, each capable of providing charge, energy, and (x,y) position information. It subtended an in-plane angular range of 21°. Each half subtended an out-of-plane angular range of $\Delta\phi = 3.3°$, with a dead region of $\Delta\phi = 1.2°$ separating the upper and lower halves. This detector was operated at three angle settings covering the angular range of $4° < \theta < 39°$. The observed fragment energies have been corrected for energy losses in the entrance window of the detectors and in half of the target thickness. For the analysis of the inclusive and coincidence measurements, two-body and three-body kinematics were employed, respectively. Product masses corresponding to the minimum of the valley of β stability were assumed. No corrections for particle evaporation have been applied to the data.

In Fig. 1 the total charge, $Z_1 + Z_2$, of the coincident fragments is plotted against the total kinetic energy in the center-of-mass system for the first step of the reaction on the assumption that the two observed fragments arise from sequential decay of a composite nu-

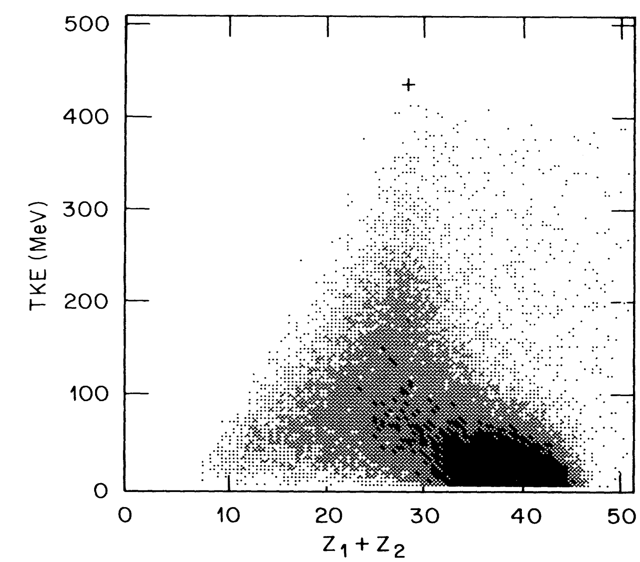

FIG. 1. Summed charge vs total center-of-mass kinetic energy during the first step of the reaction for all coincident products in reactions of $^{58}Ni + ^{58}Ni$ at 875 MeV.

cleus. Thus, $E_{K,\mathrm{tot}} = E_{12} + E_3$, where E_{12} is the kinetic energy of the 1-2 composite system and E_3 is the kinetic energy of the assumed third body which completes energy, momentum, and mass conservation. For a pure two-body reaction, $E_{K,\mathrm{tot}}$ as defined here is identically zero (for a purely binary reaction the assumed 1-2 composite system would correspond to the compound nucleus which has no kinetic energy in the center of mass); however, in the presence of particle evaporation this will be only approximately true.

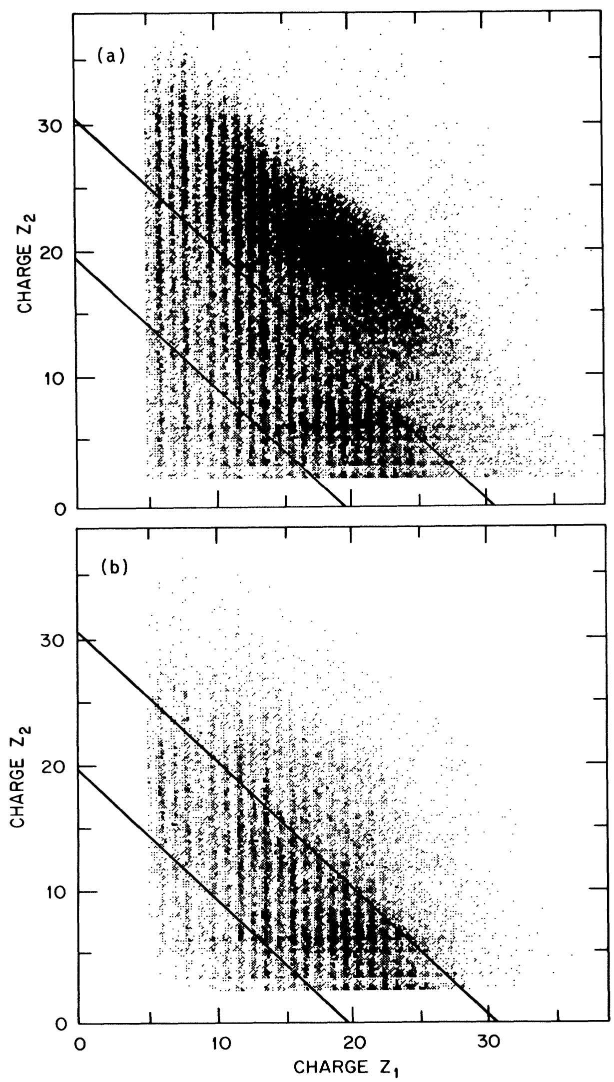

FIG. 2. Charge, Z_1, observed in the large-area ionization detector vs charge, Z_2, observed on the opposite side of the beam for (a) all coincident products and (b) coincident products with $E_{K,\mathrm{tot}} > 60$ MeV ($E_{K,\mathrm{tot,lab}} < 377.5$ MeV) resulting from reactions of $^{58}Ni + {}^{58}Ni$ at 875 MeV. Events in the region $19.5 < Z_1 + Z_2 < 30.5$ result mainly from decay of a nickel-like primary fragment (see Fig. 1).

Thus, the cluster of events seen with $Z_1 + Z_2 \simeq 40$ and $E_{K,\mathrm{tot}} \approx 0$ clearly arise from binary reactions accompanied by a large amount of particle evaporation. Those events with $E_{K,\mathrm{tot}} \gtrsim 60$ MeV arise mainly from the sequential decay of projectilelike fragments. This is indicated by the fact that the reconstructed charge and scattering-angle distributions of the 1-2 composite system closely follow those obtained in inclusive measurements of projectilelike fragments for this reaction.[5] A sequential process is indicated by the fact that, independent of total kinetic energy, the average relative energy of the two fragments is approximately given by $[4Z_1Z_2/(Z_1+Z_2)^2]\langle E_K \rangle$, where $\langle E_K \rangle$ is the mean kinetic energy released in fission as given by the systematics due to Viola.[6]

Because the decaying fragments produced in this reaction have fissilities $[X({}^{58}\mathrm{Ni}) = 0.27]$ well below the Businaro-Gallone[7] point, they are expected to be unstable against asymmetric distortions. Thus, on the basis of liquid-drop considerations, one expects a maximum in the potential and, therefore, a minimum in the yield for symmetric decay.[8] This behavior has recently been observed[9] for the decay of the system $^{9}Be + {}^{74}Ge$. Coincident charge distributions are shown in Fig. 2(a) for all events and in Fig. 2(b) for those events with $E_{K,\mathrm{tot}} > 60$ MeV which eliminates most binary reactions. From Fig. 2(b) it can be seen that asymmetric decay is the predominant mode of heavy-fragment emission for the primary fragments ($Z_1 + Z_2 \approx 28$), with a strong contribution from $Z_2 = 6$ events. (The kinematics and asymmetry of our experimental geometry favor the observation of the heavy fragment at forward angles in the large-area ionization chamber.) A slightly enhanced symmetric component ($Z_1 \approx Z_2 \approx 14$) can also be observed in Fig. 2(b). This enhancement may be understood qualitatively in terms of shell effects which might be important for such a light system.

The observation of a strong contribution of coincidences with carbon immediately raises the question of possible light contaminants on the target which would undergo deep-inelastic or fusion-fission reactions yielding coincident distributions similar to those from projectile decay. To rule out this possibility, measurements were also made on a ^{12}C target under identical experimental conditions. As a result of the inverse kinematics, light contaminants give apparent energy losses which are much smaller, and overlap very little, with those observed with the ^{58}Ni target. From this difference we can conclude that possible contributions from light target contaminants are less than 5% and are confined to the region of small $E_{K,\mathrm{tot,lab}}$. Although the experimental geometries and systems studied were different, there is a similarity between our results on carbon[10] and the $^{86}Kr + {}^{89}Y$ coincidence measurements of Ref. 1 in the region of small apparent energy loss. A possible light contaminant would explain the apparently large projectile fission probability at small energy loss observed in Ref. 1 but not seen in our case or in that of Ref. 4.

The experimental fission probabilities are shown in Fig. 3 for all fissionlike events with Z_1 and $Z_2 > 3.5$ and also for symmetric fission events only (Z_1 and $Z_2 > 8.5$). To extract the fission probabilities, a Monte Carlo simulation was made to determine the coincidence detection efficiency. The primary distribution of decaying fragments was taken from the measured inclusive distributions.[5] In the intrinsic frame, we have assumed the fission decay to be isotropic in the reaction plane with a Gaussian distribution out of the reaction plane. The calculated coincidence efficiencies are typically a few times 10^{-3} with an estimated uncertainty of 50%. The excitation energy of the decaying nickel-like fragment was assumed to be half of the calculated energy loss. This neglects the effects of particle evaporation and Q values for mass transfer which, however, may be compensated by the width in the sharing of the excitation energy.

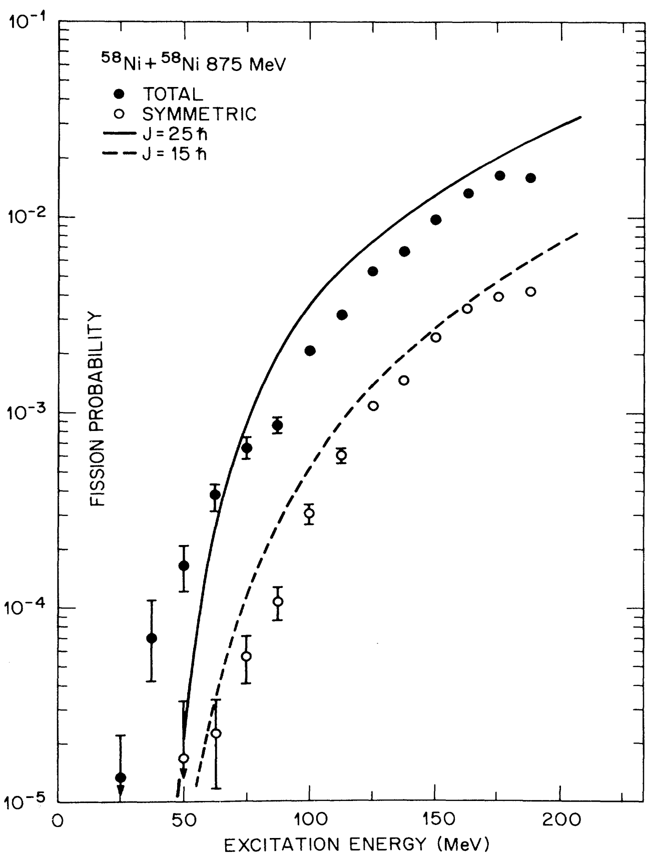

FIG. 3. Fission probability for all heavy fragment decays with $19.5 < Z_1 + Z_2 < 30.5$ for (Z_1 and Z_2) > 3.5 (solid points) and symmetric decay only (Z_1 and Z_2) > 8.5 (open points). Fission evaporation calculations for ^{58}Ni are shown for $a_f/a_n = 1.0$, $a = A/7.5$, and $J = 25\hbar$ (solid curve) or $J = 15\hbar$ (dashed curve).

In order to determine whether the observed probabilities for fissionlike decay are consistent with an equilibrium process or instead indicate nonequilibrium effects, we have made statistical model calculations using the evaporation code PACE.[11] This code has recently been modified to include the fission barriers and moments of inertia calculated in the rotating-finite-range model of Sierk. These include the effects of the finite range of the nuclear force as well as the diffuseness of the nuclear surface. It has been shown[12,13] to reproduce measured fission excitation functions over a wide range of masses and angular momenta. Strictly speaking, it is not proper to apply such a calculation to light systems ($A \lesssim 100$) that do not have a true symmetric saddle point. However, such a procedure may be used to determine whether the observed decay probabilities are consistent with a statistical process or to what extent a dynamic process is required. There are two parameters of importance for the calculation, the ratio of saddle point to ground-state level densities, a_f/a_n, which we take to be 1.0, and the spin of the decaying nucleus. A distribution of contributing spins is expected, ranging from sticking at the critical angular momentum to sticking at the grazing angular momentum. This gives a range of spins from $J \simeq 10\hbar$ to $J \approx 35\hbar$. The calculated result is shown in Fig. 3 for the decay of ^{58}Ni with $J = 25\hbar$ (solid curve), which corresponds to two-thirds of the grazing value and is probably a realistic estimate of the average. An additional result is shown for $J = 15\hbar$ (dashed curve) to demonstrate the spin dependence.

From Fig. 3 it can be seen that the statistical model is able to account for the measured fissionlike decay probability quite well. The calculation is expected to underpredict the probability for the sum of symmetric and asymmetric events, since it uses a single barrier corresponding to symmetric decay which is larger than the barriers for asymmetric decay. On the other hand, it is expected to overpredict the probability for symmetric events taken alone since the competition with asymmetric decay will reduce the observed probability for symmetric decay. From this calculation we conclude that the observed decay is consistent with a statistical process.

This is in contrast to conclusions reached for the reaction ^{129}Xe + ^{122}Sn,[3,4] which suggested a nonequilibrium fission process, based in part on measured fission probabilities which were found to be one to two orders of magnitude larger than those estimated with use of the statistical model[14] with reasonable parameter values.[3,4] However, we have used PACE with the same parameters of Refs. 3 and 4 ($a_f/a_n = 1.08$ and $J = 40\hbar$), and with rotating-finite-range barriers, and obtained adequate agreement with experiment. For example, at 250-MeV excitation energy a fission probability of $P_f = 6.2\%$ was obtained for fission of ^{129}Xe, which compares with a measured probability of $P_f = 9\%$ for fission of nuclei with mass 110 to 150 amu. (Complete agreement could be obtained by a slight increase of the average spin.) Also consistent with observation,[4] the calculated fission probability was found to vary by about a factor of only 2 over the mass range of 110 to 150 amu, for fixed values of excitation energy and spin. These calculations imply that, in this case, the measured fission probability is also consistent with a statistical process and not necessarily the result of a dynamical mechanism.[15]

However, for the reaction $^{129}\mathrm{Xe} + {}^{122}\mathrm{Sn}$ it has been shown[2,4] that the sequential fission decay is not a fully equilibrated process by the observation of a preference for asymmetric fission with the heavy fragment emitted opposite to the direction of the third body. These results indicated that the reaction products decay from any asymmetric deformation induced by the first step of the reaction. The fact that the observed decay probability is consistent with the statistical model, albeit with the assumption of a symmetric saddle point, suggests that the dynamics of the first reaction step are not necessarily carrying the system over the conditional saddle point. It is interesting that the short scission-to-scission time observed[2-4] for the reaction $^{129}\mathrm{Xe} + {}^{122}\mathrm{Sn}$ is not inconsistent with Fokker-Planck calculations[16] of the saddle-to-scission time for this system. In the future, such measurements of the fission time scale may allow a determination of the nuclear dissipation strength by comparison to calculation.

This research was sponsored by the U. S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

[(a)]Present address: University of Giessen, D-6300 Giessen, West Germany.

[(b)]Present address: Centre de Recherches Nucléaires, F-67037 Strasbourg, France.

[1]A. Olmi *et al.*, Phys. Rev Lett. **44**, 383 (1980).

[2]P. Glässel *et al.*, Phys. Rev. Lett. **48**, 1089 (1982).

[3]D. v. Harrach *et al.*, Phys. Rev. Lett. **48**, 1093 (1982).

[4]P. Glässel *et al.*, Z. Phys. A **310**, 189 (1983).

[5]T. C. Awes *et al.*, Phys. Rev. Lett. **52**, 251 (1984).

[6]V. E. Viola *et al.*, Nucl. Data, Sect. A **1**, 391 (1966).

[7]U. L. Businaro and S. Gallone, Nuovo Cimento **1**, 629, 1277 (1955).

[8]Luciano G. Moretto, Nucl. Phys. **A247**, 211 (1975).

[9]L. G. Sobotka *et al.*, Phys. Rev. Lett. **53**, 2004 (1984).

[10]T. C. Awes *et al.*, in *Proceedings of the Eleventh International Winter Meeting on Nuclear Physics, Bormio, Italy, 24–29 January 1983* (Univ. of Milano Press, Milano, Italy, 1983), p. 425.

[11]A. Gavron, Phys. Rev. C **21**, 230 (1980).

[12]J. van der Plicht *et al.*, Phys. Rev. C **28**, 2022 (1983).

[13]F. Plasil *et al.*, Phys. Rev. C **29**, 1145 (1984).

[14]R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1983).

[15]Preliminary results for the reaction $^{129}\mathrm{Xe} + {}^{122}\mathrm{Sn}$ at 18 MeV/nucleon indicate that the fission probability is not determined by the incident energy, but rather by the absolute energy loss in the collision, as would be expected for a statistical process. (H. J. Specht, private communication.)

[16]Helmut Hofmann and J. Rayford Nix, Phys. Lett. **122B**, 117 (1983); J. R. Nix and A. J. Sierk, private communication.