Energy Division in Damped Reactions

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(Received 11 October 1983)

Nuclear charges and kinetic energies were measured for fragments resulting from reactions of ^{58}Ni + ^{58}Ni and ^{58}Ni + ^{197}Au at 15.3-MeV/u incident energy. These data suggest a nonequilibrium division of the available excitation energy between target and projectile for a large range of energy losses. This interpretation is supported by a consistent analysis of more complete data available for the ^{56}Fe + ^{165}Ho reaction at 8.5-MeV/u incident energy.

PACS numbers: 25.70.Lm, 24.60.-k

One of the primary goals in the investigation of inelastic reactions between heavy ions is to understand the mechanism of energy dissipation and nucleon exchange. At incident energies just above the interaction barrier there is evidence[1,2] that the neutron-excess degree of freedom is equilibrated quickly as the charge and neutron number of the primary reaction products move in the direction of the gradient of the two-dimensional dinuclear potential-energy surface.[3] However, recent results for asymmetric systems at energies well above the interaction barrier are not satisfactorily explained in terms of potential-energy–surface considerations alone.[4-6] At these energies particle evaporation may dominate the observed distributions which makes it essential to evaluate such effects carefully.

We have studied the ^{58}Ni + ^{197}Au reaction at 889-MeV incident energy and observe that the charge distributions of the projectilelike fragments are inconsistent with potential-energy–surface expectations unless the available excitation energy is shared equally between the target and projectile, rather than in proportion to their masses, as would have been expected if thermal equilibrium had been attained. Although this is in apparent contradiction to previous conclusions based on comparisons[7-10] of neutron emission from the projectilelike fragment (PLF) and targetlike fragment (TLF), it is shown that a careful analysis of such data supports the interpretation of a nonequilibrium energy division for reactions involving incomplete energy damping. These results constitute the first evidence that thermal equilibrium is not immediately attained in damped collisions between heavy ions.

The experiment was performed with use of an 889-MeV beam of ^{58}Ni produced by coupled operation of the tandem electrostatic and cyclotron accelerators of the Holifield Heavy Ion Research Facility in Oak Ridge. Projectilelike fragments resulting from interactions with targets of ^{58}Ni (1.9 mg/cm^2) and of ^{197}Au (1.2 mg/cm^2) were identified by their nuclear charge with a large-area, position-sensitive, gas ionization chamber located 1 m from the target. The ionization chamber was operated with CF_4 gas at a pressure of 500 Torr and subtended 21° in polar angle with a solid angle of 50 msr. It provided $\Delta E - \Delta E - E$ measurement with a total energy resolution of better than 1% for the elastically scattered ^{58}Ni. The observed fragment energies have been corrected for energy losses in the detector entrance window and in half of the target thickness. Center-of-mass energies were calculated with two-body kinematics and with product masses corresponding to the minimum of the valley of β stability. No corrections for particle evaporation have been applied to the data.

The angle-integrated charge distributions are presented in Fig. 1 for reactions on ^{58}Ni and ^{197}Au. The most striking feature of these distributions is the strong drift of the charge centroids, with increasing energy loss, towards charges smaller than that of the projectile. We have performed an evaporation calculation to determine whether the observed drift is consistent with equilibrium evaporation. For this calculation we have used a modified form of the evaporation code LILITA,[11] which allows a chosen primary distri-

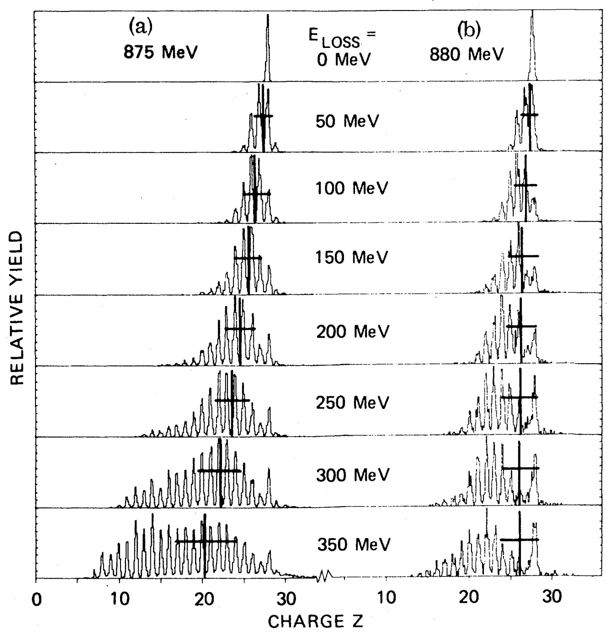

FIG. 1. Angle-integrated charge distributions summed over 25-MeV-wide energy-loss intervals for (a) ^{58}Ni + ^{58}Ni, integrated over the angular range $4 < \theta < 38.5$ ($\theta_{\mathrm{graz}} = 7.2$), and (b) ^{58}Ni + ^{197}Au, integrated over the angular range $6 < \theta < 38.5$ ($\theta_{\mathrm{graz}} = 18.6$). The crosses are described in the text.

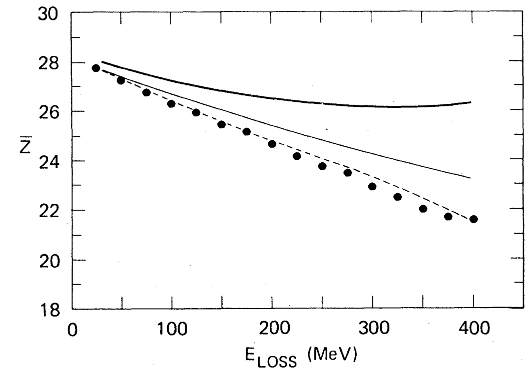

FIG. 2. Centroids of the angle-integrated charge distributions (see Fig. 1) for ^{58}Ni + ^{197}Au at 880 MeV. The centroids have been extracted by a moment analysis with a smooth interpolation through $Z = 28$ at large energy losses to avoid the influence of possible beam tail. The calculations are described in the text.

bution to be sampled in all variables. The primary distribution is specified by an excitation energy distribution and, at each excitation energy, by a bivariate distribution in proton and neutron number, a Gaussian distribution in dissipated angular momentum, and a Gaussian distribution in the relative sharing of the excitation energy. The energy loss for the evaporation results was calculated in the same manner as the experimental data. This evaporation code has been compared with the code PACE [12] for representative cases, and it was determined that the same qualitative conclusions would result from PACE.

The theoretically calculated centroids and full width at half maximum are indicated in Fig. 1 by the vertical and horizontal lines, respectively. For these calculations the primary distributions predicted by Randrup's transport model[13] were used as input. In this model the relative kinetic energy of the two nuclei is dissipated by the stochastic transfer of nucleons. The nucleon transfer is driven by the available phase space as determined by the dinuclear potential-energy surface and finite-temperature Fermi-Dirac statistics. For the calculations of Fig. 1, it was assumed that the excitation energy is shared according to mass and that the dissipated angular momentum increases linearly from zero at zero energy loss to the sticking limit at the interaction barrier. For the ^{58}Ni + ^{58}Ni reaction the calculation is shown to reproduce the observed widths and centroids quite well, up to the largest energy losses where the charge distributions become asymmetric because of fissionlike decay of the PLF. These three-body events will be discussed in a forthcoming publication. This agreement suggests that equilibrium evaporation is the dominant source of the drift toward smaller charges.

For the ^{58}Ni + ^{197}Au reaction the values of the predicted charge centroids are larger than those observed, which indicates a deficiency in the assumed primary distribution. This discrepancy might be the result of a thermal gradient between the two fragments which acts during the initial stages of the reaction to give an anomalous drift towards charge asymmetry and equal temperatures for the separating fragments, as recently suggested by Moretto.[14] An alternative explanation is that, at high bombarding energy, the interaction time is too short to permit an equilibrium division of the excitation energy between the PLF and TLF. In Fig. 2 it is shown that if the excitation energy is assumed to be shared equally between the two fragments (light solid curve), rather than according to mass (heavy solid curve, also the calculation shown in Fig. 1), then a reasonable description of the observed charge distributions is obtained. It is interesting that if the primary N and Z centroids are fixed at the entrance-channel values with the excitation energy shared equally, then the agreement is improved further (dashed curve).

The assumption of equally shared excitation energy is in contradiction to conclusions reached in experiments[7-10] in which the energy spectra of neutrons emitted from the PLF and TLF are observed to have the same slopes. These results suggest that the fragments are at the same temperature and, therefore, that the excitation energy divides according to mass. With this assumption it has been further shown[9] for the ^{56}Fe + ^{165}Ho reaction at 476 MeV that the multiplicity of neutrons emitted from each fragment could be understood only if the system had also equilibrated to the N/Z ratio of the composite system already for the smallest energy losses. However, recent mass and charge measurements[6] for the same system at 465 MeV show that the N/Z ratio is not fully equilibrated, even for the largest energy losses, which indicates an internal inconsistency in the interpretation of the neutron data.

In Fig. 3 we show the measured N and Z centroids and the neutron multiplicities from Refs. 6 and 9, respectively. Three calculations are shown in Fig. 3 for the assumptions that (1) the excitation energy is shared according to mass (long-dashed curve), (2) the excitation energy is shared equally (short-dashed curve), and (3) the excitation energy division makes a smooth transition from equal sharing at small energy loss to equal temperatures at large energy loss (solid curve). For each calculation the dissipated angular momentum was assumed to increase linearly to the sticking limit, as described above, and the primary distributions were allowed to vary freely within the constraint given below. The calculated centroids were found to be quite insensitive to extreme variations of all widths of the primary distribution. Since there is no constraint on the primary Z distribution, all three calculations are able to reproduce the observed charge centroids [Fig. 3(a)]. The primary N distribution is weakly constrained by the fact that at a given energy loss, the primary N centroid must be greater than the observed centroid plus the average multiplicity of emitted neutrons [see line at $N \approx 30.5$, Fig. 3(b)]. With this constraint and the assumption of thermal equilibrium, it is not possible to reproduce the observed N centroids. In Fig. 3(c) it is shown that, for energy losses less than about 50 MeV, the assumption of thermal equilibrium yields too little neutron emission from the PLF and too much emission from the TLF. The multiplicities are predicted correctly here if the excitation energy is shared equally between the fragments. On the other

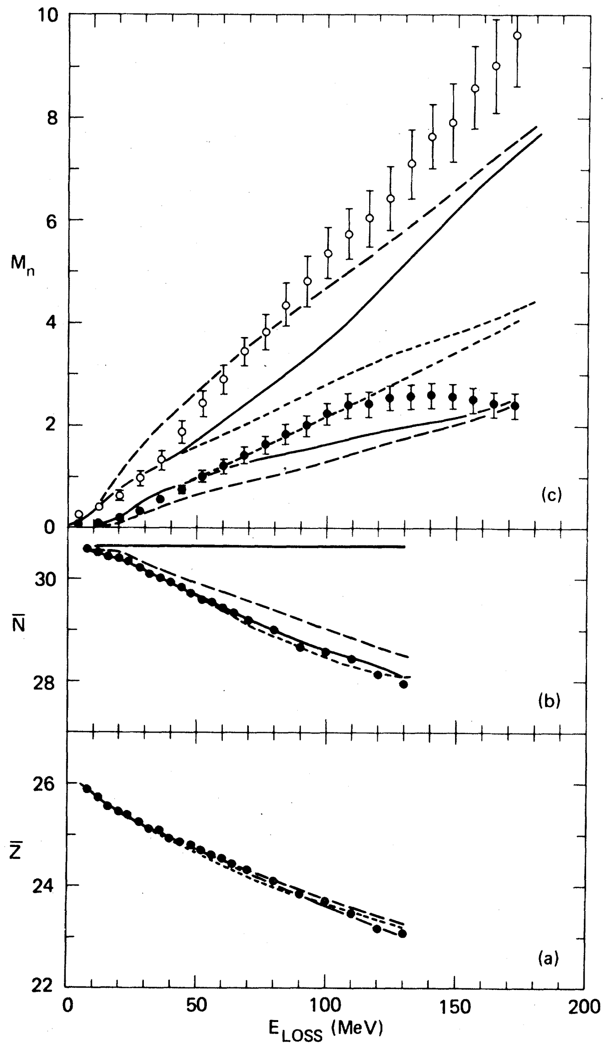

FIG. 3. Centroids of the (a) charge and (b) neutron number distributions of PLF's for the ^{56}Fe + ^{165}Ho reaction at 8.5-MeV/u incident energy (Ref. 6). Note: In Ref. 6 a small correction for neutron evaporation was made to the energy loss. (c) Average multiplicity of neutrons emitted from the TLF (open circles) and PLF (filled circles) (Ref. 9). The calculations are described in the text.

hand, at the largest energy losses the assumption of thermal equilibrium gives results which best reproduce the observed multiplicities. It follows that a smooth transition from the limit of equal sharing of the dissipated energy at small energy loss to the limit of equal temperatures at large energy loss gives the best overall description of the data. For the calculation of Fig. 3 (solid curve), a linear transition was assumed to occur from the limit of equal sharing at excitation energies of 30 MeV or less to the equal-temperature limit for excitation energies of greater than 130 MeV. Although qualitatively correct, this transition cannot be accurately determined since the calculation underpredicts the neutron multiplicity from both fragments for large energy losses. This overall deficiency of emitted neutrons cannot be removed by reasonable variations of the primary distribution. The form of the transition is in qualitative agreement with recent calculations for this system, which include the dissipation of relative energy into deformation of the fragments.[15] It is also in agreement with earlier suggestions[16] and recent results which suggest a nonequilibrium energy division in the quasielastic region.[17]

It is not certain to what extent the present results are inconsistent with results obtained by comparisons of the energy slopes of PLF and TLF neutron spectra. Since the slopes of the neutron spectra are proportional only to the square root of the excitation energy, they are less sensitive to the energy division than the integrated multiplicities. Also the extracted spectral shapes may be influenced by small contributions from nonequilibrium emission and by the procedure of decomposition into the two components.

In conclusion we have demonstrated that, at incident energies well above the Coulomb barrier, the excitation energy is divided about equally between target and projectile for small energy losses and may approach an equilibrium division only for the largest energy losses. At the higher incident energy of the ^{58}Ni + ^{197}Au reaction, the primary distributions are consistent with expectations based upon the dinuclear potential-energy surface only if the nonequilibrium division of excitation energy extends over a much larger range of energy losses. This interpretation of the ^{58}Ni + ^{197}Au reaction does not preclude the possibility of purely stochastic nucleon transfer with negligible driving force, as might arise from two-body nucleon-nucleon collisions.

We thank J. Randrup for providing the transport-model calculations. This research was sponsored by the Division of High Energy and Nuclear Physics, U. S. Department of Energy, under Contract No. W-7405-eng-26 with the Union Carbide Corporation.

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