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Energy Dissipation and Nucleon Transfer in Heavy-Ion Reactions*

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We report a correlation between the kinetic energy loss and nucleon diffusion for Kr- and Xe-induced reactions on heavy targets. Although this correlation suggests that these two phenomena occur on the same general time scale, the rate of kinetic energy loss decreases with interaction time. Evidence is presented to show that the initial energy dissipation rate is consistent with a frictional force which is proportional to the relative velocity.

In this Letter we report on an observed correlation between two of the characteristic features of very-heavy-ion reactions. These two features are (1) the strong damping of the initial relative kinetic energy of the target and projectile nuclei into internal excitation energy and collective degrees of freedom, and (2) the occurrence of significant amounts of nucleon transfer or diffusion, although the reaction-product mass distributions are bimodal with centroids near the target and projectile masses. In furthering our understanding of these heavy-ion reactions it is crucial to know the relationship between energy dissipation and particle diffusion and, in particular, the relative time scales on which these two processes occur. It is often assumed that the time scale for the energy dissipation is very short compared to the time scale for particle diffusion. Recent experimental results[1-4] show that the energy dissipation and particle diffusion are strongly correlated and, hence, that the above assumption concerning time scales is not valid for all heavy-ion reactions.

Proton distributions of projectilelike fragments, studied at the Lawrence Berkeley Laboratory SuperHILAC with semiconductor counter telescopes, are discussed in this article for the reactions $^{209}Bi + ^{136}Xe$, $^{165}Ho + ^{136}Xe$, $^{209}Bi + ^{84}Kr$, and $^{165}Ho + ^{84}Kr$ at bombarding energies of 8.3 to 8.5 MeV/nucleon. A qualitative correlation between the kinetic energy dissipation and the width of the proton distribution was first observed for the $^{209}Bi + ^{136}Xe$ reaction.[1] Here we report a similar, more quantitative, correlation for the above four reactions where the inelastic events are integrated over angle. The width of the proton distribution, defined by the variance σ_Z^2, has been determined at each energy by fitting a Gaussian function to the experimental data. The Z distributions for the Xe-induced reactions are observed to remain Gaussian in shape with centroids near $Z = 54$ even for events with the largest energy loss.[1-4] For the Kr-induced reactions, the proton distributions are Gaussian in shape for small kinetic energy losses and then become progressively more skewed toward higher Z as the kinetic energy loss increases. The more asymmetric proton distributions for the Kr-induced reactions,

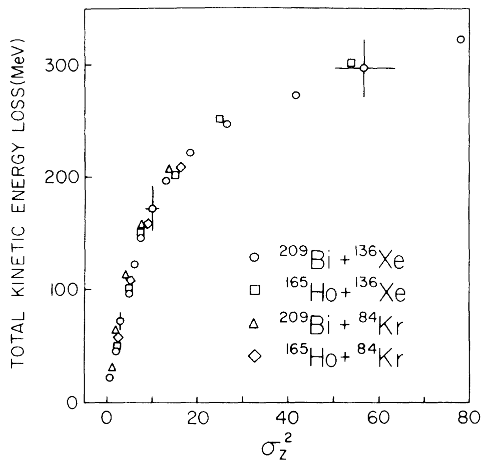

FIG. 1. Total kinetic energy loss in MeV as a function of the variance, σ_Z^2, of the proton distribution of the projectilelike fragment. All values of the variance are determined from angle-integrated data (see Fig. 3 for angular range). The abscissa is a time scale where 10 units in σ_Z^2 correspond to $(7\pm 3)\times 10^{-22}$ sec for the ^{165}Ho + ^{84}Kr reaction (see text). Estimated errors are included for selected points.

as compared to the Xe-induced reactions, are consistent with the underlying potential energy surfaces for these reactions.

The correlation between the measured variance of the proton distribution and the amount of kinetic energy loss for the above four reactions is shown in Fig. 1. The variance of the proton distribution, σ_Z^2, increases with increasing amounts of total kinetic energy loss. In addition, the slope of the energy dissipation as a function of the variance σ_Z^2 is largest for small values of the variance and decreases as the variance increases. The values of σ_Z^2 in Fig. 1 for the Kr-induced reactions are included only for total kinetic energy losses less than about 200 MeV. For the Xe-induced reactions, σ_Z^2 is, within experimental error, independent of angle for events of the same energy loss.[2,4] This is nearly true also for the Kr-induced reactions with the smaller energy losses mentioned above.

In order to investigate in more detail the correlation of σ_Z^2 and energy loss shown in Fig. 1, we introduce a simple diffusion theory which has recently been employed to explain the mass and proton distributions of reaction products from damped collisions.[5,6] We follow the formulation of Nörenberg[5] who obtained for the occupation probabilities,

$$P(Z,t) = (4\pi D_z t)^{-1/2} \times \exp[-(Z-Z_0-v_z t)^2/4D_z t]. \quad (1)$$

The quantity $Z-Z_0$ stands for the number of protons transferred during the interaction time t. The parameters v_z and D_z are constants and represent average proton drift and diffusion coefficients, respectively. The variance, σ_Z^2, of this distribution is given by $2D_z t$.

The nearly constant value of $\langle Z\rangle$ for the Xe-induced reactions indicates that the drift coefficient v_z in Eq. (1) is small.[1] A similarly small drift coefficient has also been observed[5] for the ^{232}Th + ^{40}Ar reaction.[7] Hence, for analysis of these proton distribution data it is assumed that v_z is negligible. If the diffusion theory is valid for proton transfer at all stages of the process and D_z is a constant, then the abscissa of Fig. 1 converts to a time scale, with the interaction time given by $t=\sigma_Z^2/2D_z$. On the other hand, under the assumption of the sharp cutoff model and a monotonous decrease of l with energy loss, starting with the grazing angular momentum and zero energy loss, a deflection function $\theta(l)$ can be calculated from the experimental reaction data. From a comparison to the Coulomb deflection function, angular-momentum-dependent interaction times can be estimated, as will be discussed in a future publication. For example, for the ^{165}H$_0$ + ^{84}Kr reaction, 10 units in σ_Z^2 correspond to $(7\pm 3)\times 10^{-22}$ sec. This relationship changes slightly for the other reactions.

The projectilelike fragments emitted from the ^{209}Bi + ^{136}Xe, ^{165}Ho + ^{136}Xe, and ^{209}Bi + ^{84}Kr reactions exhibit a rather strong angular focusing (i.e., the maximum cross section is at an angle which is nearly independent of energy damping). This feature of very-heavy-ion reactions is characteristic of those systems for which the parameter $Z_T Z_P$ is large and $E_{\rm c.m.}$ exceeds $E_{\rm Coul}$ only slightly. Hence, for the latter three reactions the bombarding energy is too small to give a distinctive dependence of the Z distributions on scattering angle. However, one parameter on which the widths of the Z distributions of the fragments from these reactions clearly depend is the amount of kinetic energy loss in the collision. If one assumes an energy loss process in which the dissipative force is proportional to the relative velocity, $F_{\rm diss}=-kv$, one obtains the following rate of energy dissipation;

$$-dE/dt = 2(k/\mu)E, \quad (2)$$

where $E=E_{\rm c.m.}-T_{\rm loss}-E_{\rm Coul}$ with $T_{\rm loss}$ the total kinetic energy loss, μ is the reduced mass, and k is a frictional constant. If this functional form

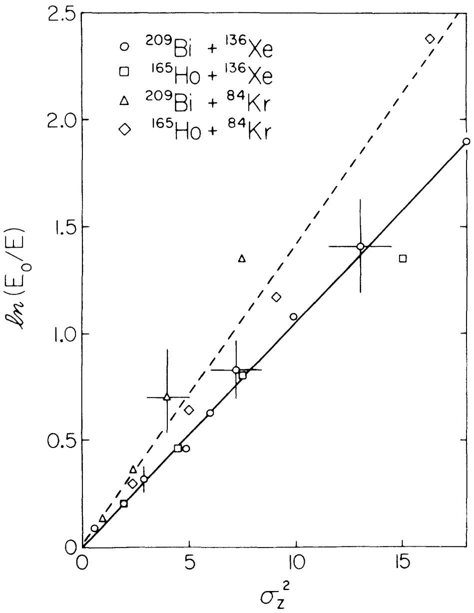

FIG. 2. Plot of $\ln(E_0/E)$ as a function of variance, σ_Z^2, of the proton distribution of the projectilelike fragment. See text for definitions of E and E_0. The solid line is drawn through the Xe data. The dashed line is calculated relative to the solid line for the Kr-induced reactions by Eq. (3). Estimated errors are included for selected points.

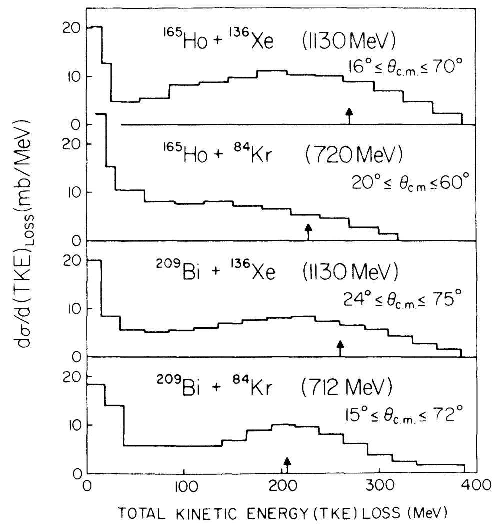

FIG. 3. Differential cross section, $d\sigma/dT_{\rm loss}$, for events of various degrees of kinetic energy damping $T_{\rm loss}$. As discussed in the text, some cross section is not accounted for in the ^{165}Ho + ^{84}Kr reaction. Each arrow corresponds to the kinetic energy loss for an event with final kinetic energy equal to that of the Coulomb energy at the separation distance of the strong absorption radius $R_{\rm SA}$.

of the energy-loss rate is correct, one obtains

$$\ln(E_0/E) = (k/\mu D_z)\sigma_Z^2, \qquad (3)$$

where $E_0 = E_{\rm c.m.} - E_{\rm Coul}$. Hence a linear relation is predicted between $\ln(E_0/E)$ and σ_Z^2. Such a plot is shown in Fig. 2 where $E_{\rm Coul}$ is calculated at the strong absorption radius.[8] Good agreement between experiment and theory is obtained for energy losses up to 200 MeV. However, such a simple theory neglects several factors including energy tied up in collective degrees of freedom.

If k/D_z is the same for Kr- and Xe-induced reactions, the slope given by Eq. (3) is slightly larger for Kr-induced reactions (compare the dashed and solid lines in Fig. 2). The data plotted in Fig. 2 support a rate of energy loss which depends on the square of the relative velocity or on the available energy E. From the two slopes shown in Fig. 2, an average value of $k/D_z = (0.9 \pm 0.3)\times 10^{-43}$ MeV sec^2 fm^{-2} is obtained. From the earlier relationship between σ_Z^2 and the interaction time t for the ^{165}Ho + ^{84}Kr reaction, a value of the proton diffusion coefficient $D_z = (0.7 \pm 0.3)\times 10^{22}$ sec^{-1} is deduced. The corresponding value of the frictional constant, k, is $(0.6 \pm 0.3) \times 10^{-21}$ MeV sec fm^{-2}.

It is important to emphasize the continual range of total kinetic energy damping for these very-heavy-ion reactions. This is illustrated in Fig. 3 where the differential cross section in millibarns per MeV of total kinetic energy loss is plotted versus the total kinetic energy loss. For the Xe-induced reactions, the integral of the plotted differential cross section gives the total reaction cross section. However, in the case of the ^{165}Ho + ^{84}Kr reaction some 700 mb of the cross section is in the range $\theta_{\rm c.m.} < 20°$ and missing in this figure. In addition, these events are relatively strongly damped.[3] The kinetic energy loss indicated by each arrow in Fig. 3 is based on a final kinetic energy equivalent to the Coulomb energy at the strong absorption radius $R_{\rm SA}$.[8] One observes that the peak in the cross section of each Xe-induced reaction is at an energy loss considerably less than that for events with final kinetic energy equal to $E_{\rm Coul}(R_{\rm SA})$. However, with a large number of l waves and a range of separation distances it is not possible to disentangle the contributions to the observed kinetic energy due to the Coulomb energy and the translational energy at separation.

In summary, it is shown that the kinetic energy loss and variance σ_Z^2 in the proton distribution of the projectilelike fragment are related in the same way for four heavy-ion reactions. The slope of the energy dissipation as a function of σ_Z^2 is largest for small values of the variance and decreases as the variance increases. Under the assumption of the time scale discussed earlier, the initial energy loss rate is approximately 4×10^{23} MeV/sec, whereas this rate is decreased by a factor of 25 at a much later time when the total kinetic energy loss is 300 MeV (see Fig. 1). These results are consistent with the view that there is some type of rapid energy dissipation mechanism during the early stages of the collision (e.g., as proposed by Broglia, Dasso, and Winther[9]). However, the results may be consistent also with a statistical model where most of the energy loss goes into the production of particles and holes and transfer of nucleons. A more detailed presentation of the data in terms of the angle dependence of the variables will be submitted for publication.

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Measurements of Fusion Cross Sections for Heavy-Ion Systems at Very Low Energies*

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Measurements of the fusion cross sections for $^{10,11}B+^{12}C$, $^{12}C+^{13}C$, $^{12}C+^{14}N$, $^{14}N+^{14}N$, and $^{14}N+^{16}O$ at sub-Coulomb-barrier energies, together with earlier results for $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$, show that the average energy dependence of the fusion cross section can change dramatically with only small variations in the mass and charge of the interacting nuclei.

The measurement of heavy-ion reaction cross sections for systems such as $^{12}C+^{12}C$ [1-3] at energies well below the Coulomb barrier has been a rich source of information on nuclear structure in the continuum. Perhaps because of their astrophysical significance,[4] the reactions which have been studied at the lowest possible bombarding energies until recently have involved only the α-conjugate nuclei ^{12}C and ^{16}O.[5-7] The discovery of "quasi-molecular" resonances in the fusion cross sections, σ_{fus}, for the reactions $^{12}C+^{12}C$ (Refs. 1 and 2) and $^{12}C+^{16}O$ (Ref. 5) has prompted measurements in many other systems near the Coulomb barrier.[8] However, in the search for narrow resonances in these other systems, the significance of the gross energy dependence of