Evidence for Large Rotational-Energy Contributions to the Kinetic Energies of Products of Deep Inelastic Reactions*

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Products of the completely damped deep inelastic collisions of 120-MeV ^{20}Ne with ^{27}Al have kinetic energies significantly larger than expected to occur from Coulomb repulsion at the time of scission. The contribution to the fragment kinetic energy from rapid rotation of the fissioning system is comparable to the kinetic energy resulting from Coulomb repulsion.

There is currently a great deal of interest in the macroscopic aspects of heavy-ion–induced reactions. Particular emphasis has been placed on studies of the onset of deep inelastic reactions and corresponding decrease of the fusion probability as the projectile energy, the orbital angular momentum, the charge product (Z_1Z_2), or the mass symmetry of the collision increase.[1-4] The fusion probability has been parametrized in terms of l_{crit}, the limiting angular momentum for fusion.[5] Projectiles corresponding to partial waves of orbital angular momentum slightly greater than the limiting angular momentum for fusion may undergo strong damping of their kinetic energies producing moleculelike systems which break apart without forming a totally equilibrated compound nucleus. Significant mass transfers may occur during the life of such systems.

The kinetic energies of the products of completely damped deep inelastic collisions reflect the configuration of the composite nucleus at the time of scission. We have measured the kinetic energies of the products from such collisions, 120-MeV ^{20}Ne projectiles with ^{27}Al target nuclei. The resultant energies are found to be much larger than would be expected on the basis of Coulomb repulsion alone. Calculations suggest that approximately one-half of the observed kinetic energy results from the rapid rotation of the scissioning system.

For the experiment a counter telescope employing a gridded ionization chamber[6] as a ΔE detector was used to detect and identify products of the reactions of 120-MeV ^{20}Ne projectiles with a 372-μg/cm^2 Al target. Energy distributions and angular distributions of each element were obtained. On the basis of these distributions, products with atomic number ≥ 12 were taken to be the evaporation residues of the ^{47}V compound nucleus. The measured cross section for these residues is 935 ± 90 mb which corresponds to a limiting angular momentum of $(33.6 \pm 1.7)\hbar$. With use of a potential of the form proposed by Bass,[7] a critical distance for fusion of $(0.96 \pm 0.05)(A_1^{1/3} + A_2^{1/3})$ F is indicated. This value is slightly dependent upon the nuclear potential choice. However, from the variation of l_{crit} with energy, Ngo[8] has determined a critical radius parameter of 0.96 F for the fusion of ^{12}C with ^{27}Al. Thus values less than 1.00 F seem appropriate in this mass region.

The products with $Z < 12$ are characterized by a distinctive low-energy peak in the spectrum which becomes a more prominent part of the spectrum as the laboratory angle increases. At the larger angles, the laboratory energy spectra consist of single, relatively narrow, near-Gaussian peaks.

Only the atomic numbers of the products were identified in this experiment. However, in other experiments in progress,[9] mass measurements using a $\Delta E,E$ time-of-flight system have shown that for $Z < 12$, the isotope of highest yield is that for which $N = Z$ and that the yields of isotopes for which $|N - Z|$ is greater than 1 are very small. These narrow isotopic yield distributions reflect the steepness of the valley of stability in the light-mass region.

Using this mass information we have transformed the energy spectra of the elements from C to Na into the center of mass. Figure 1 presents the transformed data as contour plots of $(d^2\sigma/dE\,d\theta)_{c.m.}$ as a function of the energy $E_{c.m.}$ and angle $\theta_{c.m.}$. Before the transformation the energies were corrected for energy losses in the target and detector windows as well as for small pulse-height defects. The figure clearly depicts the increased damping of the initial kinetic energy with increasing transfer of charge or increasing angle of emission. At large angles the most probable kinetic energies, indicated by the dashed lines, and the widths of the distributions become constant, indicating that the kinetic energy damp-

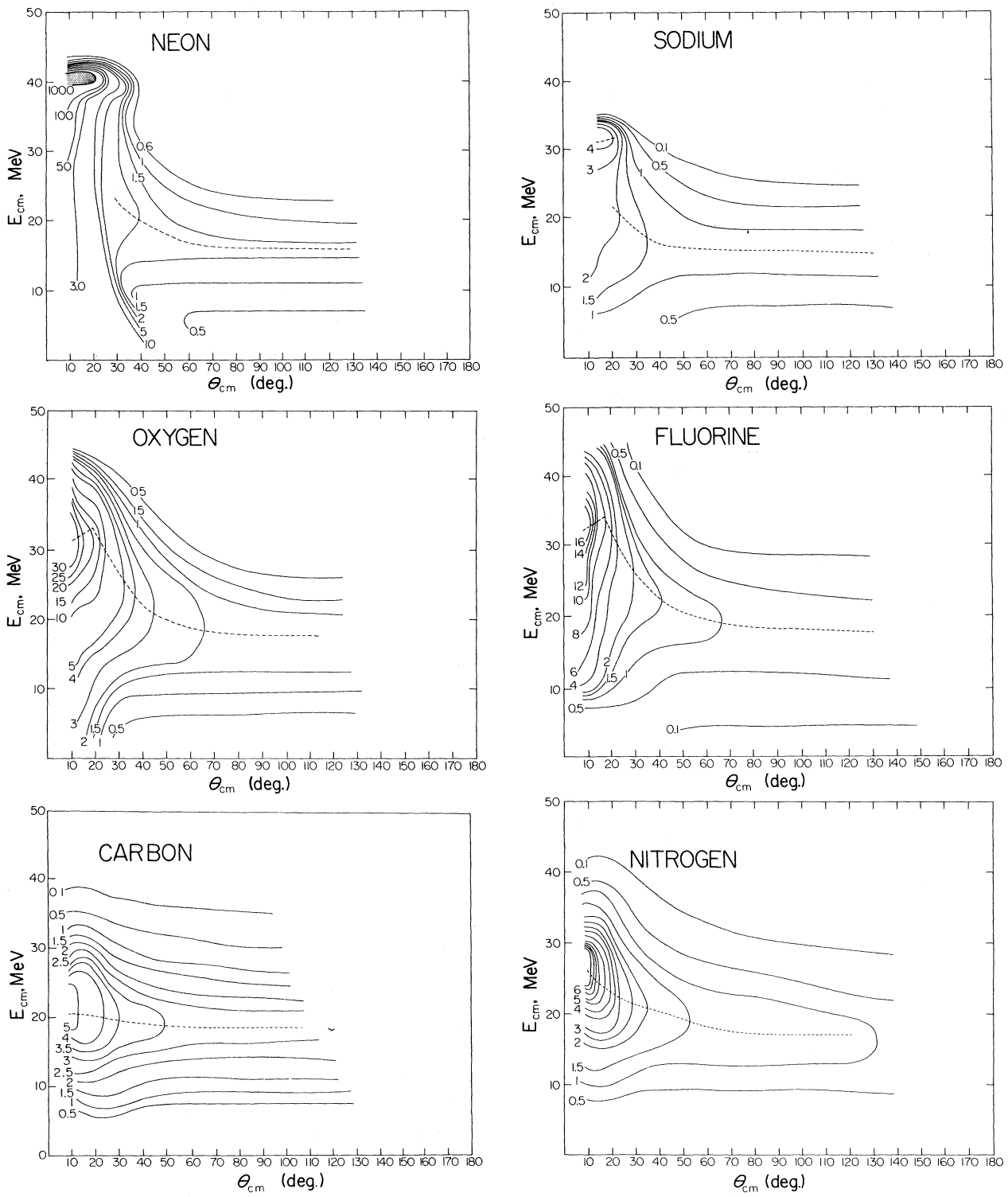

FIG. 1. Contours of $d^2\sigma/dE_{c.m.}\,d\theta_{c.m.}$ for elements produced in the reactions of 120-MeV ^{20}Ne with ^{27}Al. Increased damping of the projectile kinetic energy is seen as the charge transfer and/or angle of observation increase. The dashed lines indicate the most probable kinetic energies at each angle. The contour labels are millibarns per radian per 1.6 MeV.

ing is complete. In the following we shall focus our attention on these completely damped collisions.

The most probable energies of the reaction products will differ from those of the primary fragments if the fragments have sufficient excitation energy to lose mass through light-particle emission. The actual mass changes are a function of the excitation energy of the fragment. Recent measurements[10] of the γ de-excitation of the heavy partner resulting from deep inelastic reactions of 100-MeV ^{16}O with ^{27}Al indicate that the available excitation energy is in fact divided between the two fragments in the same ratio as the mass is divided. This result is consistent with the assumption of thermal equilibrium in the composite system. We have applied this result to the very similar $^{20}Ne + ^{27}Al$ reaction system studied in this work and have used the code ALICE [11] to calculate the evaporation losses expected for different primary mass splits. The typical calculated mass losses are about 2 amu for fragments with excitation energies of ~15 to 20 MeV. The fragment angular momenta are not expected to be large enough to perturb this result. The calculated losses have been used to correct the observed kinetic energies. The total kinetic energies for each mass division have been calculated by multiplying the corrected fragment energies by $47/A$ where A is the pre-evaporation mass of the partner of the observed product. These total kinetic energies are plotted in Fig. 2.

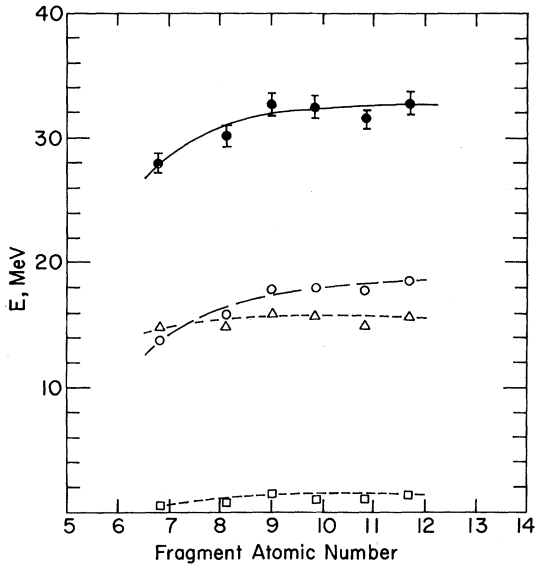

FIG. 2. Kinetic energies for completely damped deep inelastic reactions of ^{20}Ne with ^{27}Al. The energies are plotted against the evaporation-corrected average atomic number of the parent of the detected fragment. The total kinetic energies are indicated by the solid circles. The contribution to the total from Coulomb repulsion (open circles) and from rotation of the system (open triangles) have been calculated using Eq. (1). The negative of the small nuclear attraction term is also plotted (open squares).

For the symmetric division of the ^{47}V nucleus, a kinetic energy of 32.8 MeV is indicated. This may initially be compared with the recent calculations of Davies, Sierk, and Nix[12] which indicate a value of about 19 MeV for fission of a ^{47}V nucleus with zero angular momentum. It is not expected[13] that the scission configuration of the rotating ^{47}V nucleus should be more compact than that of the nonrotating nucleus, and therefore it would appear that the much larger kinetic energy observed in this experiment cannot be solely attributed to Coulomb repulsion at the time of scission.

Since the strongly damped collisions under consideration presumable occur for angular momenta just above those leading to fusion, the scissioning nuclei are expected to have angular momenta of $\sim 35\hbar$. If we assume that the system may be represented as a nuclear molecule in rigid rotation, the kinetic energy of the system at scission may be represented as

$$E = \frac{Z_1 Z_2 e^2}{d} + \frac{f^2\hbar^2 J(J+1)}{2\mu d^2} + V_{\mathrm{nuc}}, \qquad (1)$$

where Z_1 and Z_2 are the fragment atomic numbers, J is the angular momentum, μ is the reduced mass, d is the distance of separation between mass centers, V_{nuc} is the nuclear attraction energy, and f is the ratio of the moment of inertia of the composite system to the total moment of inertia including rotation of the individual fragments, i.e., $f = \mu d^2/(\mu d^2 + \mathcal{I}_1 + \mathcal{I}_2)$.

For elongated scission configurations, V_{nuc} is expected to be small and is usually neglected for heavy nuclei. We approximate it in our calculation by using the nuclear potential of Ref. 7. Since the total energy is known, Eq. (1) may be solved for the separation distance, d, and the relative contributions to the final kinetic energy from each of the terms in the equation may be determined. The results of this calculation are also indicated in Fig. 2.

In particular, for the symmetric division, the model indicates a separation of 10.2 F between mass centers, a kinetic energy of Coulomb repulsion of 18.6 MeV, a kinetic energy from rotation of 15.6 MeV, and a nuclear attraction contribution of −1.4 MeV. Thus in this calculation

almost one-half of the observed kinetic energy results from the rotation of the scissioning system.

This result may be compared with more sophisticated liquid-drop-model calculations including angular momentum effects if we assume that for such light systems the saddle-point configuration is a good approximation to the scission-point configuration. For a ^{47}V nucleus with $35\hbar$, the liquid-drop-model calculations[14] indicate a dumbbell-shaped saddle-point configuration with the mass centers separated by 10.9 F and a moment of inertia which is 4.15 times that of the spherical ^{47}V nucleus. Using this information, we estimate the total Coulomb plus rotational contributions to the kinetic energy at scission to be 30.5 MeV. Of that energy 17.4 MeV would result from Coulomb repulsion and 13.1 MeV from rotation. These numbers are in good agreement with the comparable quantities extracted using Eq. (1).

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Time-Dependent Quantum Treatment of Heavy-Ion Scattering*

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It is shown that using a quantum time-dependent method one can account for the angular distribution in strongly damped collisions between very heavy ions. The theory is applied to the study of the angular distribution of the reaction ^{84}Kr + ^{209}Bi at 600 and 700 MeV.

The purpose of this Letter is to determine the angular distribution for strongly damped collisions in heavy-ion–induced reactions. Experimentally it is observed that for very heavy projectiles like krypton and copper, and with use of a target such as bismuth, the angular distribution is highly peaked near the grazing angle.[1] Also these reactions exhibit a considerable amount of energy transfer from the relative motion into internal degrees of freedom. The first attempts to account for the energy loss and angular distribution were based on classical considerations[2-4] where the energy dissipation is simulated by the introduction of frictional forces. In Ref. 2 only the position of the peak in the angular distribution was determined; according to the results of Refs. 3 and 4, one obtains angular distributions which are considerably narrower than the experimental distribution. This is a common feature of all classical calculations which exhibit a very marked and narrow peak near the rainbow angle. To have a better treatment, one certainly needs to consider quantum mechanical effects. Broglia, Dasso, and Winther[5,6] have suggested an approach