Onset of Damping in Energetic Heavy-Ion Interactions

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Measurements of longitudinal momenta transferred to mass-identified products of the fragmentation of Cu by ^{12}C ions give clear evidence for a change in reaction mechanism between 22 and 84 MeV/u. Results at 84 MeV/u are generally consistent with peripheral interactions. However, at 22 MeV/u large momentum transfers observed for near-target products suggest that strongly damped processes have become important. Limits to momentum transfer of the type reported by Galin *et al.* are shown to arise in a natural way from this transition.

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Considerable interest in nuclear reactions induced by intermediate energy (10–200 MeV/u) heavy ions stems from the fact that a transition from low- to high-energy behavior is expected in this region. Galin *et al.*[1] have inferred from studies of fission and low-energy proton emission that the longitudinal momentum transferred in reactions induced by 15–84-MeV/u ^{12}C ions does not exceed ~ 2 GeV/c. It has been suggested[2] that this saturation of momentum transfers is evidence for soliton formation in heavy-ion interactions near the velocity of sound in nuclear matter.

A rather different picture of reactions in this energy region is drawn from studies of the spectra of more energetic charged $Z \leq 2$ particles.[3] The deduced source velocities are a nearly constant fraction, ~ 0.5, of that of the projectile. Auble *et al.*[3] have concluded that such data show "no obvious discontinuities which one might expect to appear if drastic changes in reaction mechanism or saturation of a particular mechanism were to occur" between 7.5 and 147 MeV/u. This contrast with Galin *et al.*[1] can be understood at high energies in terms of the participant-spectator picture.[4] Collision times are sufficiently short that there can be little flow of energy into those regions of the target nucleus which were not directly involved in the initial collision. Fission or low-energy charged-particle emission probes the slowly moving spectator part of the target while energetic particles may arise from the highly excited participant region (fire ball). It is not clear why such a picture should hold at 7.5 MeV/u where collision times become long and there can be extensive mass and energy exchange between projectile and target.[5]

The present Letter reports measurements of mean longitudinal momenta, $p_{\parallel}$, transferred to mass-identified fragments of the interaction of 22- and 84-MeV/u ^{12}C ions with Cu. These new data provide an important connection between the intermediate energy region and the extensive data available for this target at higher energies[6]—up to 400 GeV. They permit comparisons with predictions[6] and observations[1] of upper limits on momentum transfer in target fragmentation processes and allow evaluation of the need for novel processes such as solitons[2] to account for changes in reaction dynamics.

The measurements utilized the same thick-target, thick-catcher technique which had been employed at higher energies.[6] A target stack consisted of a 47 mg/cm^2 Cu foil with 7 mg/cm^2 Mylar catchers on the upstream and downstream sides. An additional Mylar was included as a blank. One such stack was irradiated with $\approx 7 \times 10^{13}$, 84-MeV/u ^{12}C ions from the CERN synchrotron, another with $\approx 12 \times 10^{13}$, 22-MeV/u ^{12}C from the LBL 88-in. cyclotron. After irradiation, relative activities of various radionuclides in the four foils were determined by Ge(Li) spectroscopy on the basis of γ-ray energies and half-lives. Corrections for activation of Mylar was significant only in the case of ^{24}Na. Two quantities are derived from these measurements, FW and BW, where F and B are the fractions of the total activity of a particular isotope produced in the target which was observed in the forward and backward Mylar catchers, respectively, and W is the target thickness. FW and BW represent mean projected ranges in the forward and backward directions. Values of FW are plotted in Fig. 1(a) as a function of the number of nucleons which were removed from the target. For comparison with the new results, data[6] for 400- and 2100-MeV/u ^{12}C ions are also shown. A few of the results which were reported by Lund *et al.*[7] while the present experiment was in progress aid in defining the smooth curve at 84 MeV/u. There is good agreement between most of the other data points in these two independent experiments.

The general pattern of Fig. 1(a) suggests that

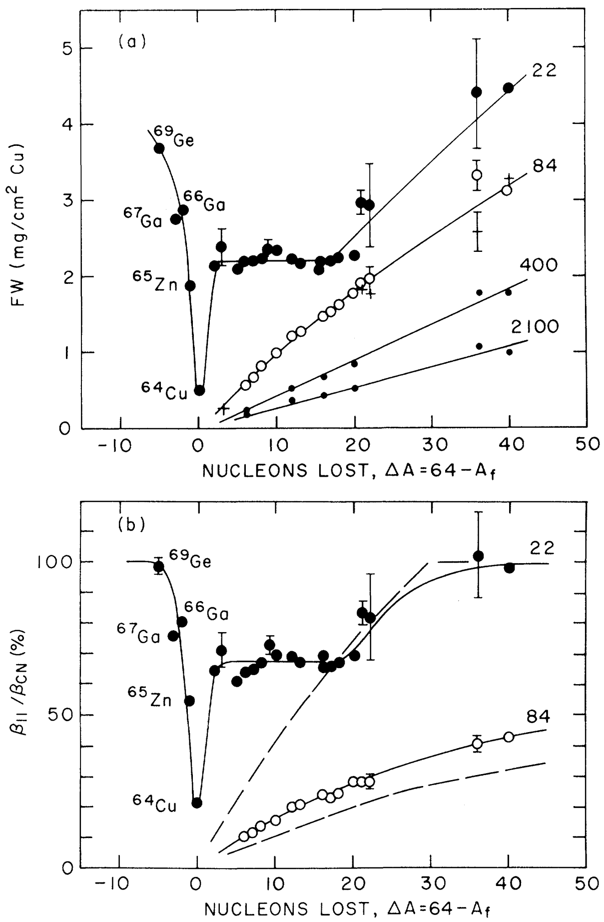

FIG. 1. (a) Dependence of mean forward projected range on number of nucleons removed from a Cu target. Solid curves show general trends for incident ^{12}C ions at the indicated energies. Sources of the points are: large open circles and filled circles—the present work; plusses—Ref. 7; and small filled circles—Ref. 6. (b) Fractional velocity or momentum transfer as a function of number of nucleons removed. Dashed curves are predictions of a peripheral model discussed in the text.

interactions at 84 MeV/u involve the same peripheral mechanisms as are operative at the higher energies. However, as the projectile energy decreases below the Fermi energy for Cu, 36 MeV,[8] the onset of more strongly damped interactions is seen. At 22 MeV/u, *FW* for many near-target products is markedly increased and several products ($^{66,67}Ga$ and ^{69}Ge) resulting from transfer of mass and charge to the target become easily detectable. At higher energies, such products are formed only in small yields by secondary reactions.[9]

For further analysis, the reaction leading to a particular product is assumed to occur in two steps; an initial projectile-target interaction which leads to an excited prefragment moving forward with velocity $\beta_\parallel$, and a subsequent de-excitation step which adds an additional isotropic component, V. In the limit of full momentum transfer, the prefragment is the compound nucleus moving with $\beta_\parallel = \beta_{CN}$. Derivation of $\beta_\parallel$ and V from measured mean ranges employed the same general procedure as had been used previously.[6] It was modified, however, to include a Maxwellian distribution of recoil energies corresponding to V, the same distribution as was assumed by Lund *et al.*[7] We also explored a broader distribution as well as a unique value of V. Although $\langle V \rangle$ could be changed by ~40% by such modifications, variations in $\beta_\parallel$ were < 5%.

Since our primary interest is in momentum transfers we will not discuss V further, but display the derived values of $\beta_\parallel/\beta_{CN}$ in Fig. 1(b). For reference, momenta of ^{12}C ions are 2.44 and 4.85 GeV/c at energies of 22 and 84 MeV/u, corresponding to $\beta_{CN} = 0.035$ and 0.068, respectively. The highest momentum transfers, ~2.4 GeV/c for ^{69}Ge, ^{28}Mg, and ^{24}Na at 22 MeV/u, and ~2.1 GeV/c for ^{24}Na at 84 MeV/u, are in reasonable agreement with the limit set by Galin *et al.*[1] There is no evidence in Fig. 1(b) for the rapidly moving sources ($\beta_\parallel/\beta_{CN} \sim 3$) which were inferred from the spectra of energetic $Z \leq 2$ particles.[3] Evidently the source of these particles is not strongly coupled to the precursors of the observed heavy fragments at either energy. The two sorts of experiments are complimentary and appear to examine different aspects of the interactions.

Treating a peripheral reaction at high energies as a quasi-two-body process leads[6] to a relationship of the form

$$p_\parallel = \Delta E[1 + k(1 - \beta^2)]/\beta \qquad (1)$$

for the dependence of longitudinal momentum transfer on ΔE, the energy transferred to the fragment precursor, and the projectile velocity β. The parameter k determines how rapidly $p_\parallel$ increases above its asymptotic value, ΔE, as β decreases. For a peripheral process, k is expected to be small. Experimentally, $k \approx 1$ for the fragmentation of Cu[6] and $k \approx 0$ for the fission of Au.[10]

Shown as dashed lines in Fig. 1(b) are predictions for 84 and 22 MeV/u obtained from Eq. (1) with $k = 1$ and ΔE values determined by measurements at higher energies.[6] While the dashed curve at 84 MeV/u has the same shape as the experimental data, it falls ≈30% below the points.

Such disagreement was not unexpected as the approximations underlying Eq. (1) were expected to become poorer at low energies. Considering the wide range of energies covered (see Fig. 2), we consider the 30% agreement and, particularly, the monotonic dependence of $\beta_{\parallel}/\beta_{CN}$ on ΔA which follows from the linear dependence of $p_{\parallel}$ on ΔE in Eq. (1), as indicating that target fragmentation at 84 MeV/u proceeds largely via the same peripheral mechanisms which are operative at higher energies. This complements a similar conclusion[11] that the observable characteristics of projectile fragmentation at 43 MeV/u have also become identical to those at gigaelectronvolt-per-nucleon energies.

The calculated curve at 22 MeV/u correctly predicts that products with $\Delta A \geq 30$ are associated with full momentum transfer. However, large deviations for products closer to the target signal the onset of low-energy processes such as compound-nucleus formation, massive transfers, deep-inelastic reactions, and few-nucleon transfer reactions. Particle evaporation from a completely fused system would lead to a broad product distribution centered at $\Delta A \sim 5$. While mean momentum transfers [Fig. 1(b)] in this mass region are high, they fall appreciably below full transfer. The momentum deficit for products with $2 \leq \Delta A \leq 20$ corresponds, on the average, to the failure to capture one alpha particle. Such large but incomplete momentum transfers are a well-known feature of low-energy reactions.[12-14] In the case of 19.4-MeV/u ^{16}O incident on Ti they have been ascribed[13] to the prompt emission of energetic light particles, rather than deep-inelastic reactions. The peculiar position of ^{64}Cu in Fig. 1 reflects significant contributions from single-neutron transfer reactions which are expected to involve small momentum exchanges. Although momentum transfers increase for products heavier than ^{64}Cu, formation cross sections decrease rapidly. Observed yields are in the approximate ratios, ^{58}Co:^{66}Ga:^{69}Ge:^{72}As::100:11:0.7:<0.07. However, evaporation calculations predict a still more rapid decrease and the interpretation of the full momentum transfer determined for ^{69}Ge is not clear. While the present results give strong evidence that a variety of low-energy processes are involved in reactions at 22 MeV/u, detailed experiments are needed to resolve the relative contributions of different mechanisms.

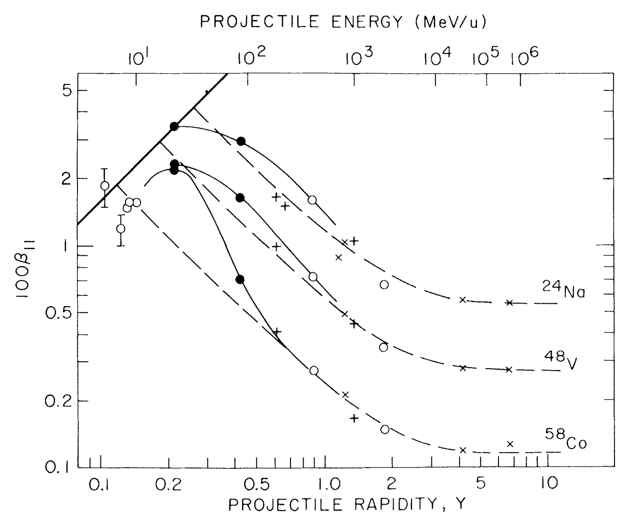

FIG. 2. Dependence of precursor velocity on projectile rapidity for selected products of the fragmentation of copper by ^{12}C (open circles and filled circles), ^{4}He (pluses), and ^{1}H (crosses). Filled circles are from the present work, others from Refs. 6 and 14. The dashed curves are least-squares fits to Eq. (1) for $Y > 0.6$. Solid curves show the general trends for ^{12}C ions. The heavy solid line is the momentum-transfer limit.

To place the present experiment in broader context, values of $\beta_{\parallel}$ for three representative species, ^{58}Co, ^{48}V, and ^{24}Na, are displayed in Fig. 2 for a wide range of projectile types and energies. The abscissa here is the projectile rapidity $Y = \tanh^{-1}\beta$. The asymptotic approach of $\beta_{\parallel}$ for a particular product to a lower limit at very high energies is a characteristic feature of a peripheral process.[6] As rapidities decrease, momentum transfers initially rise in general agreement with Eq. (1).

The heavy line cutting across the upper left-hand corner of Fig. 2 shows values of $\beta_{\parallel}$ for compound nucleus formation by ^{12}C ions. The intersection of a dashed curve with this line sets an approximate upper limit for momentum transfer

$$P_{max}^2 = (1+k) m_p \Delta E, \qquad (2)$$

which depends on ΔE for that reaction and the projectile mass, m_p. Such an abrupt transition is cleraly an oversimplification. Solid curves in Fig. 2 suggest more realistic behavior consistent with the changes in reaction mechanisms discussed above. It does not appear that all products will ultimately reach the full transfer limit. Unpublished data[15] for ^{58}Co formation from Cu by 5- to 10.5-MeV/u ^{12}C ions, shown in Fig. 2, indicate that even at 10 MeV/u, many near-target reactions proceed via large but not full momentum transfer processes. However, the general agreement between the experimental data and the simple model for products involving the largest momentum transfers, e.g., ^{24}Na, suggests that Eqs. (1) and (2) will be useful in discussing overall limits to longitudinal momentum transfer of the sort reported by Galin *et al.*[1] For example, upper limits to momentum transfer observed in an inclusive study of some particular class of reactions can now be related to an upper limit on energy transfer in those reactions. Identifying the observed transfers for ^{24}Na formation from Cu with the Galin *et al.*[1] limit based on low-energy proton spectra implies that $\Delta E_{max} \sim 320$ MeV, a substantial fraction of the total binding energy, 560 MeV.

In summary, results from the present study of the interaction of 22- and 84-MeV/u ^{12}C with Cu when combined with existing data permit tracing the evolution of reaction mechanisms over a wide energy range. Limiting momentum transfers appear as a natural consequence of the transition from peripheral to more- strongly- damped processes and the fact that a target nucleus cannot support very high levels of excitation and still give rise to massive target residues or fission products. The similar behavior observed with light-ion projectiles[16] suggests that hydrodynamical processes such as soliton generation[2] are not involved.

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