Momentum Transfer to Target-Fragmentation Products in the Reactions of 25-GeV ^{12}C with Au

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The thick-target–thick-catcher technique has been used to determine average kinetic properties of a number of target-fragmentation products formed in the reactions of 25-GeV (2.1-GeV/nucleon) ^{12}C ions with Au. The forward momentum transferred to the target as a function of product mass is essentially identical to that for 28-GeV protons, but quite differenct than that for 1.0- and 3.0-GeV protons, suggesting that the total projectile kinetic energy is the significant parameter governing limiting fragmentation rather than the energy per nucleon.

Many aspects of the interactions of relativistic heavy ions with complex nuclei can be interpreted in terms of the limiting-fragmentation hypothesis.[1] Fragments of the projectile, identified by their emission at small angles to the beam direction with velocities nearly equal to that of the projectile, have cross sections and momentum spectra (in the projectile rest frame) which are independent of target mass and projectile energy in the 1–2-GeV/nucleon range.[2,3] Similarly, target fragmentation may be characterized by products which are emitted nearly isotropically with low energies in the target rest frame (laboratory). Fission-fragment angular distributions showed[4] that momentum transfer to the target was small for 29-GeV ^{14}N ions and similar to that for 28-GeV protons. The cross-section systematics of target fragments has been studied for various projectile-target combinations[5-10] and found to be nearly independent of projectile for a given target, with the possible exception of U targets.[10]

In general, the reaction characteristics described above result from peripheral collisions, in which little transfer of momentum and energy takes place. Nearly central collisions, in contrast, result in a high multiplicity of light fragments emitted at forward angles in the laboratory with no clear distinction between projectile and target fragmentation.[11-13]

The determination of the mechanisms leading to the residual nuclides observed in the cross-section measurements[5-10] requires more detailed study of their energy and angular distributions. Although present beam intensities at the Lawrence Berkeley Laboratory (LBL) Bevalac preclude such studies with relativistic heavy ions, some insight into the kinematic properties of the products may be gained from thick-target–thick-catcher recoil studies.[14] One such study has been recently reported[15] in which the mean recoil properties of several spallation products were measured for both 25-GeV ^{12}C and 28-GeV protons reacting with Cu. The results showed a small difference between the two projectiles which was interpreted as indicating that the region of limiting target fragmentation had not yet been reached with the 2.1-GeV/nucleon ^{12}C projectile.

We report here on a study of the recoil properties of a large number of residual nuclei formed by the reaction of 25-GeV ^{12}C with Au. This target was chosen because of the extensive measurements made using the same technique with protons of 1–300 GeV.[16] The distinctive changes observed with changing proton energy in that work can serve as a useful standard of comparison for the heavy-ion interactions. The experimental technique was the same as that described in the proton work.[16] Targets of 25-mg/cm^2 Au foils were sandwiched between 18-mg/cm^2 Mylar foils and vacuum sealed in a Mylar envelope. The target assembly was exposed to $\sim 8\times10^{12}$ 25-GeV ^{12}C ions at the LBL Bevalac. Following the irradiation the forward Mylar catchers, backward catchers, and Au targets were separately assayed with a Ge(Li) detector. Additional Mylar foils, which served as activation blanks, exhibited negligible activity levels.

The analysis of the data has also been described[16]; it is based on the resolution of the velocity distributions into two components, a forward-directed $v_{\parallel}$ resulting from the initial projectile-target interaction, and a velocity V, isotropic in the moving system, which arises from the deexcitation of the excited fragment. These two steps are equivalent to the abrasion-ablation steps in a model for relativistic heavy-ion reactions.[17,18]

The results are shown in Fig. 1 where they are compared with the results for the same product nuclides from proton reactions with Au.[16] In Fig. 1(a) the values of $\beta_{\parallel}$ ($v_{\parallel}/c$) for each nuclide are

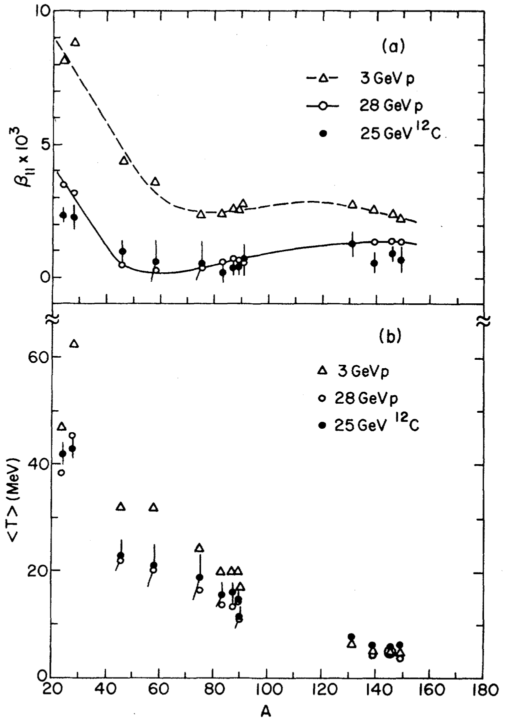

FIG. 1. (a) Forward velocity component $\beta_{\parallel}$ ($=v_{\parallel}/c$) for nuclides formed by the interaction of 25-GeV ^{12}C, 28-GeV protons, and 3-GeV protons with Au. (b) Mean kinetic energies $\langle T \rangle$ in the moving system of the same nuclides.

shown as a function of product mass number A. It is clear that the forward velocities of these target fragments from 25-GeV ^{12}C reactions are essentially the same as those of 28-GeV proton reactions. They differ considerably from those due to protons of 1-3-GeV energy (although not shown, results for 1-GeV protons are similar to those for 3-GeV protons).

These data are a striking confirmation that the limiting-fragmentation hypothesis is valid for heavy-ion projectiles as well as for more "elementary" particles,[1] and that the asymptotic region appears to have been reached at an energy of 2.1 GeV/nucleon for a heavy target such as Au. Thus there appears to be a target-mass dependence in the approach to the asymptotic region, which is reached at a lower projectile energy for Au than for Cu. It is also noteworthy that the total kinetic energy of the projectile, rather than the energy per nucleon, appears to be the significant variable for comparing different projectiles. In that connection the measurements of Katcoff and Hudis[4] on the angular distributions of fission fragments in ^{14}N-ion-induced fission are of interest. They found that at 29 GeV very little momentum was transferred to the target, in agreement with the present data. However, at 2.0 and 3.0 GeV there was evidence of considerable momentum transfer, as shown by large forward-to-backward ratios. This suggests that considerably larger $\beta_{\parallel}$ values would be found for the present system with ^{12}C ions of 1-3-GeV kinetic energy, and that the dependence of $\beta_{\parallel}$ on projectile energy may be similar for all projectiles. Confirmation of this for a variety of projectiles and targets would be of fundamental significance for theories of relativistic heavy-ion reactions.

The small magnitude of $\beta_{\parallel}$ ($<3\times10^{-3}$ for the products measured here) is consistent with target fragmentation, in that such products are considered to be formed from an excited spectator fragment of the target which is nearly at rest in the laboratory following the first (abrasion) step. The second (ablation) step leads to kinetic energies, $\langle T \rangle = \frac{1}{2}AV^2$, in the system moving with velocity $\beta_{\parallel}$, which are shown in Fig. 1(b). Again, it is seen that these data resemble those of 28-GeV protons more than 3-GeV protons. The decrease in kinetic energy with increasing proton energy for products in the mass range $46 \leq A \leq 90$ is due to a decreasing proportion of binary fission in their formation.[16]

In summary, we find that the forward momentum transferred to target fragments by 25-GeV ^{12}C ions is small and nearly identical to that for 28-GeV protons. It is much smaller than that due to protons of 1-3 GeV, suggesting that the total kinetic energy of the projectile, rather than the kinetic energy per nucleon is the important parameter. The limiting-fragmentation hypothesis for heavy ions appears to be confirmed by these results.

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Observation of Focusing of Neutral Atoms by the Dipole Forces of Resonance-Radiation Pressure

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For sodium atoms in an atomic beam, we demonstrate focusing, defocusing, and steering caused by the transverse dipole forces exerted by the radial intensity gradient of a superimposed and co-propagating resonant cw light beam. Dipole radiation-pressure forces differ from the forces due to spontaneous emission and are needed to achieve optical traps for neutral atoms.

We have observed that a cw laser beam superimposed upon and co-propagating with a beam of neutral atoms can cause substantial changes in the atomic trajectories when the light frequency is tuned near an atomic resonance. The atoms can be confined, ejected, or steered by the light beam. This new effect, the focusing of atoms by light, results from the same physical mechanism (momentum exchange) responsible for self-focusing of light in atomic vapors.[1] These deflections are caused by the transverse *dipole* resonance-radiation-pressure forces exerted on an induced dipole by an electric field gradient. Deflection of neutral atoms by dc field gradients is well known[2] and the deflection of neutral molecules by gradients of resonant microwave fields has been observed.[3] The analogous effects in atoms caused by resonant fields have not previously been observed, but they have been discussed lately in applications of light pressure.[4,5] Indeed, transverse dipole forces are important in proposed optical traps for neutral atoms.[5] Since the effects we observe are quite strong, other applications will also be apparent.

Dipole resonance-radiation pressure arises from stimulated light-scattering processes and exists only in optical field gradients; it thus differs fundamentally from spontaneous resonance-radiation pressure[6] which arises from spontaneous light scattering and which exists even in uniform resonant light fields. Spontaneous forces have been observed and discussed in many situations, for example, deflection of atoms,[6,7] cooling of atomic vapors,[8] induced density gradients in a vapor,[9] and isotope separation.[10] Recently, they have been used to cool ions contained in ion traps.[11] Both pressures, of course, derive from light momentum. However, the dipole force can be made the larger of the two forces.

A diagram of our experiment is shown in Fig. 1. Light from a continuously tunable, single-mode cw dye laser was superimposed upon an effusive atomic beam of neutral sodium using a 3-mm-thick dielectric-coated mirror with a 230-μm-diam hole in it. The light was focused by a 75-cm lens to a focal spot size $w_0 = 100$ μm situated 25 cm from the mirror. The laser spot size on the mirror was 500 μm and the confocal parameter of the beam was 10 cm. Because the mirror was in the far field of the light, the dark spot in