Very Energetic Heavy Fragments from Relativistic Heavy-Ion Reactions*

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In bombardments of Au with 25-GeV ^{12}C ions we have studied the energy and angular distribution of fragments with $5 \leqslant Z \leqslant 9$ emitted at energies up to ~1000 MeV. Beyond ~150 MeV the spectra change from roughly exponential in energy and isotropic in some forward-moving frame to roughly inverse power law in energy (steepening with increasing Z) and strongly forward peaked in direction. Possible bumps in the angular and energy distributions suggest hydrodynamic effects.

From studies of collisions of relativistic heavy ions with heavy nuclei one hopes to infer the existence of phenomena such as shock waves and plasma oscillations, perhaps even to create ultradense or crystalline nuclei.

Toward this goal, we have been using Lexan track detectors to study the angular and energy distributions of fragments with $Z > 4$ emitted from a Au target bombarded with 2.1-GeV/nucleon heavy ions at the Bevatron. Our first experiments[1] showed that the yield of low-energy ($1 \leqslant E \leqslant 5$ MeV/nucleon) fragments is an order of magnitude higher and the energy distribution is broader when the projectiles are ^{16}O ions instead of protons. For both types of projectiles the angular distribution of fragments is nearly isotropic. It is customary to ascribe such low-energy fragments to "evaporation" from an excited residual nucleus, subsequent to the initial high-energy collision in which the projectile initiates an intranuclear cascade of mesons and nucleons.

We now wish to report the first observations of fragments with lab energies between those of evaporated fragments and those of fragments stripped from a projectile nucleus (the latter having recently been studied by Heckman *et al.*[2]). With a fluence of 10^{12} carbon ions of kinetic energy 2.1 GeV/nucleon, Au targets of thickness 0.05 and 0.4 g/cm^2, and Lexan plastic detector stacks 1.6 g/cm^2 thick, we have detected fragments of charge $5 \leqslant Z \leqslant 9$ with energies up to 75 MeV/nucleon. Their velocities range from ~$0.1c$ to ~$0.4c$, which probably includes the range of velocities of acoustic or plasma waves in nuclear matter. One might thus use such fragments as probes of nuclear hydrodynamic phenomena.

The Lexan stacks were arrayed around the Au targets so as to record tracks of fragments emitted at lab angles from ~20° to ~160°. Various sheet thicknesses, sequences of ultraviolet sensitization and etching in NaOH solution, and scanning by an ammonia method and by optical microscopy were used to resolve individual charges with $Z \geqslant 5$. The major source of background that had to be rejected consisted of light, low-energy fragments resulting from interactions of the penumbra of the carbon beam with those portions of Lexan sheets at nearly forward and nearly backward angles.

Figure 1 shows differential cross sections as a function of energy (not energy/nucleon) at 25° to the beam for fragments of boron, carbon, nitrogen, oxygen, and fluorine. The points at high-

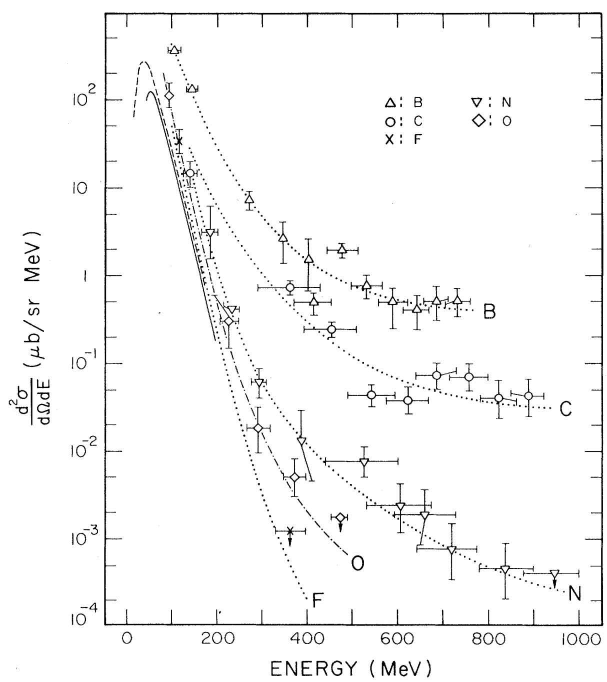

FIG. 1. Differential cross sections for production of fragments with $Z = 5$, 6, 7, 8, and 9 at 25° to the beam in reactions of 2.1-GeV/nucleon ^{12}C ions with a Au target. Where no events were seen (arrows), points indicate upper limits with confidence coefficient 0.84. Dashed curve and solid curve are for reactions of 5.5-GeV protons with a U target (Ref. 3), at 20° to the beam.

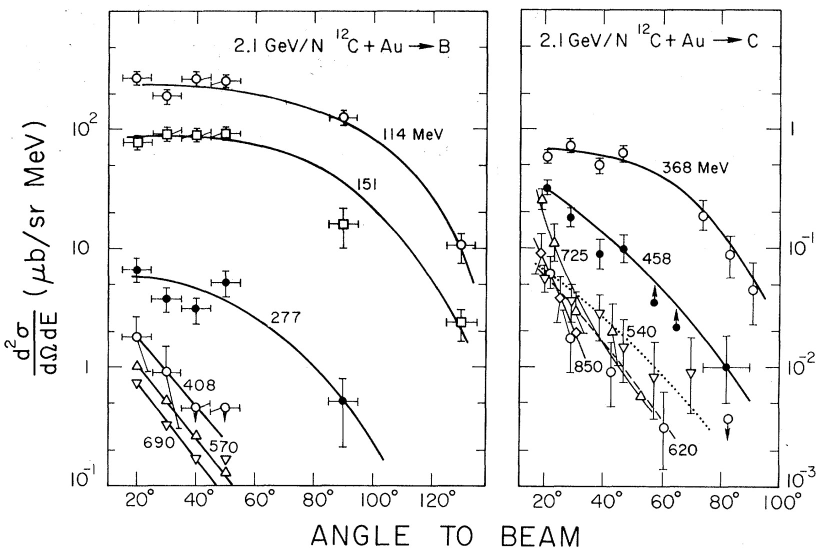

FIG. 2. Angular distribution of boron and carbon fragments with various lab energies.

est energy for boron and carbon correspond to events that penetrated to the final sheet of the 1.6-g/cm^2 Lexan stack. The uncertainty in energy associated with each point results from the finite target thicknesses. The uncertainty in cross section results both from low-counting statistics and from the rather crude methods of determining charges and detection efficiency. Included in the figure are representative curves for boron and fluorine fragments from 5.5-GeV protons on a U target[3]; in 1-GeV proton bombardments of U the curves are displaced downward by about an order of magnitude but have a similar shape.[4] Independent of bombarding energy, the energy spectra of fragments from proton bombardments are steeper than the spectra in our carbon bombardments.

Figure 2 shows the angular dependence of the differential cross sections for boron and carbon fragments at several energies. The data exhibit several striking features: (1) At energies above ~150 MeV the cross sections deviate strongly from the roughly exponential behavior characteristic of evaporation and fall off much more slowly, roughly as power laws E^{-n}. (2) In this power-law region the value of n increases from ~2.7 for boron to ~5 for oxygen, and the differential cross sections fall off very rapidly with fragment charge. In contrast, differential cross sections for all fragments are comparable in the exponential part of the evaporation spectrum and differ mainly in their peak values and in their cutoff energies.[5] (3) In the power-law region the angular distributions are very anisotropic, being increasingly forward peaked with increasing energy.

In addition to these three well-established features, there are hints of two more subtle features. They are probably not outside of systematic error in the present experiment, but they warrant a more detailed investigation with improved statistics and a lower background. The first is the possible existence of a local maximum in the angular distributions at a laboratory angle of about 50°, observed in data at lower energies in Fig. 2. Such a sideways peaking might be expected if fragments preferentially spall off along the directions of shock waves propagating at a Mach angle defined by $\arccos(v_s/V)$, with v_s the nuclear sound speed and V the projectile speed.[6]

The second is the possible existence of a local maximum in the yield of carbon fragments at energies of about 700 MeV (Fig. 1), particularly at small lab angles (Fig. 2). A possible analog in solid-state physics is the excitation of a plasma oscillation by impact of a multi-keV K^+ ion on a metal foil, followed by decay of the plasmon into an electron that is emitted from the foil with energy of up to $\hbar\omega_p - \varphi$, where ω_p is the frequency, φ is the work function.[7,8] In the nuclear case $\hbar\omega_p = \hbar(4\pi n g^2/M)^{1/2}$, a few hundred MeV, of the same order as the energy at the possible maximum for the carbon. Here n is the nucleon density, g^2 is the nucleon coupling constant, and M is the nucleon effective mass.

We have found it impossible to fit the angular and energy distributions of fragments with $E \gtrsim 150$ MeV using "thermal" models. Assumptions of such models—that the excited residual nuclei have some reasonable distribution of lab velocities and that fragments are evaporated isotropically in the rest frame of each moving nucleus—lead to energy distributions that decrease much too rapidly and angular distributions that are much too flat to reproduce the data. Our conclusion remains unchanged even if the temperature is allowed to increase with the momentum of an excited nucleus.[9]

We have also found that the kinematics of quasi-elastic processes cannot fit the data. Fragments in the observed kinetic energy interval of 150 to 1000 MeV are ejected primarily at lab angles larger than 45° by such processes. Further, it is difficult to imagine how our fragments can have been produced from the carbon projectiles by direct reactions such as charge exchange or pickup. During such reactions the transformed projectiles would have to lose typically almost 90% of their momenta.

We conclude that emission of very energetic heavy fragments in relativistic heavy-ion reactions is a nonthermal process characterized approximately by inverse power laws and strong forward peaking. Recently the spectrum of very energetic α particles emitted in interactions of heavy cosmic rays ($12 \lesssim Z \lesssim 26$) with Ag and Br in nuclear emulsions has been found[10] to follow a power law $E^{-1.8}$. This is consistent with our finding that the value of the negative exponent increases with the Z of the fragment. At the highest fragment energies studied in relativistic proton reactions with heavy targets,[11] the energy spectra of ^{6}Li, ^{7}Li, and ^{7}Be fragments deviate from "thermal" distributions but to a lesser extent than do fragments of the same energies in our relativistic heavy-ion reactions.

A Monte Carlo treatment of the intranuclear cascade has recently been used to predict the energy distribution of protons emitted in collisions of 29-GeV nitrogen on carbon (approximated as two interacting Fermi gases).[12] Given sufficient computer time (because cross sections are small), one could apply this program to our system and see if intranuclear cascades lead to power-law spectra of energetic fragments.

Finally, we note that there may be a macroscopic hydrodynamic analog to our experiment. In impacts of high-velocity projectiles with solid plates there is a range of supersonic impact velocities for which fragments of size comparable to the size of the projectile are spalled off the opposite side of the plate in a concentrated cone about the projectile direction.[13] It would be interesting to use a nonlinear hydrodynamic code to examine the angular and energy distribution of fragments emitted at the front of a shock wave in a spherical nucleus.

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