barrier ($\approx 0.85E_C$) the ^{184}W, ^{184}W, induced-fission cross sections are a factor of 5 greater than the total ^{136}Xe + ^{238}U fission yield[6] which represents an upper limit for the Coulomb fission cross section in the latter system. The comparison indicates that the inelastic scattering followed by fission is strongly Z dependent as expected for a pure Coulomb interaction. Assuming a Z^n dependence, we can deduce $n \geq 5$ at 85% of E_C which is consistent with the calculations of Oberacker *et al.*,[3] who predict $n = 6$.

In conclusion, we have for the first time established that fission following inelastic scattering occurs at bombarding energies below the nuclear interaction barrier. We do not observe the large Coulomb-nuclear interference effects predicted for the excitation function. The observed strong Z dependence of the fission cross section at the lowest energies is consistent with a strong contribution of the Coulomb interaction inducing the fission process.

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Evidence for a New Reaction Mechanism in the Bombardment of ^{238}U with 11.5-GeV Protons

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The masses and kinetic energies of coincident heavy fragments emitted from a ^{239}U target bombarded with 11.5-GeV protons were measured as a function of the angle between the fragments. Fragments with nearly equal and opposite laboratory momenta are observed with a total mass as low as $\sim\frac{1}{2}$ that of the target and higher kinetic energy than expected from fission, providing evidence for a new reaction mechanism.

We report here on the correlations of mass, kinetic energy, and angle of coincident heavy fragments formed by the interaction of 11.5-GeV protons with ^{238}U. Previous studies of single-fragment spectra[1,2] in such reactions have shown that fission of ^{238}U by GeV-energy protons is a low-excitation-energy process, occurring late in the deexcitation chain of the primary cascade residues.

The most probable fragment mass is $A = 105$, attributed to symmetric fission of an $A = 210$ residual nucleus. The present fragment-fragment correlation studies give evidence of a new reaction mechanism involving two-body breakup, but distinct from fission.

In the present experiment, coincident fragments were detected by silicon surface-barrier detectors and their energies, velocities (hence masses), and angular correlations measured. A single detector was positioned 90° to the beam, and a linear array of four detectors on a movable arm of the scatter chamber was on the opposite side of the target. (Throughout this paper the subscript 1 refers to the fragment striking the 90° detector and the subscript 2 to the fragment striking any one of the array detectors.) The flight time of fragment 1 was measured between a thin-foil secondary-electron emitter, which provided the start signal, and the stopping detector. The same start signal was used to time fragment 2; a correction for the flight time of fragment 1 from the target to the secondary-emitter foil was applied to obtain the actual flight time of fragment 2. The uncertainties in this procedure resulted in significantly poorer mass resolution for fragment 2 (8% full width at half maximum for $m_2 = 100$) as compared to fragment 1 (3% full width at half maximum).

For each coincident event the pulse heights corresponding to the energies and flight times of the fragments were stored on magnetic tape, as well as information identifying the angle of fragment 2. In addition, fragment-1 events without coincident partners ("singles") were recorded for comparison with coincident events. Data were taken over a range of 155°–190° in correlation angle between the fragments, with the array detectors in the plane defined by the beam and detector 1; out-of-plane correlations were also measured, but we discuss only the in-plane data in this communication.

The most prominent features of the correlations are those suggesting two-body breakup of a slowly moving system, namely, an angular correlation peaked slightly forward of 180° and fragments of nearly equal momenta. These features are seen for all values of total mass, $M_t = m_1 + m_2$, from $M_t = 240$ to $M_t = 100$ and are shown in Fig. 1 for three values of M_t. Fission of nuclei close to the target is represented by $M_t = 240$, the most probable fissioning system by $M_t = 210$, and events having large mass loss by $M_t = 140$. The angular correlations are shown in Fig. 1(a),

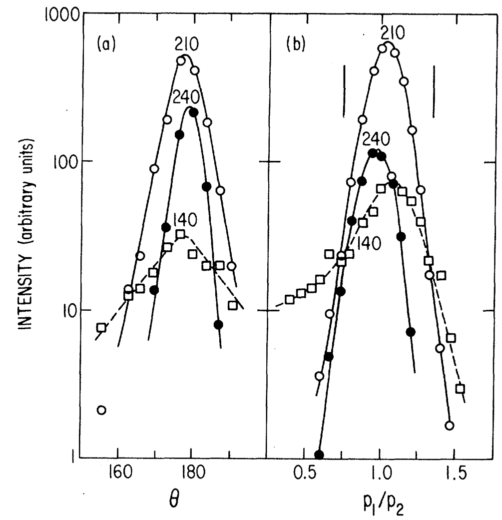

FIG. 1. (a) Angular correlation between fragments for three values of total mass: Filled circles, $M_t = 240$; empty circles, $M_t = 210$; empty squares, $M_t = 140$. (b) Distributions in p_1/p_2, laboratory momentum ratio, for the same values of M_t.

and the distribution of the laboratory momentum ratio, p_1/p_2, in Fig. 1(b). The most probable angle between fragments is somewhat smaller for $M_t \leq 210$ than for $M_t = 240$, but still only slightly forward of 180°. The width of the angular correlation increases with decreasing M_t. The most probable momentum ratio (summed over the angular correlation) shows a slight increase with decreasing M_t, but remains close to unity. Again, the distribution broadens with decreasing M_t.

While the binary fission of a residual nucleus following an intranuclear cascade is a reasonable mechanism for the processes with $M_t \gtrsim 200$, it seems much less likely for the smaller values of M_t, since fission of such lighter nuclei becomes improbable. In order to characterize the process leading to these events, we have selected out of the entire in-plane set of data those events which satisfy "two-body kinematics," i.e., those with $0.75 \leq p_1/p_2 \leq 1.33$; these limits are shown by vertical lines in Fig. 1(b). This rather broad range around the two-body momentum ratio of unity is necessary to include the dispersions caused by our mass and kinetic-energy resolution, the effect of target thickness, and any particle evaporation following the binary breakup. The events included represent > 75% of all coincident events at $M_t = 140$ and > 95% at $M_t = 210$–240.

The correlation between m_1 and m_2 is shown as a contour diagram in Fig. 2, where we have

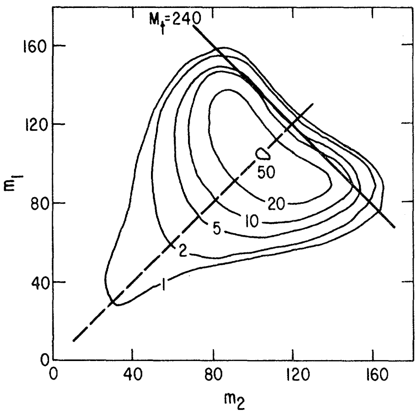

FIG. 2. Contour plot of the correlation between fragment masses. The dashed line is for symmetric breakup, $m_1 = m_2$. The contours beyond $M_t = 240$ show the effect of dispersions in the mass measurements.

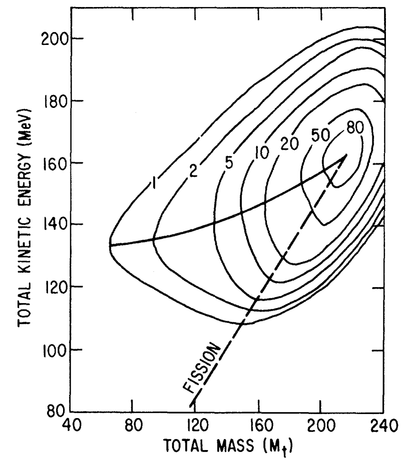

FIG. 3. Contour plot of the correlation between total kinetic energy and total mass of binary fragments. The full line indicates the path of most probable values, the dashed line the relation expected for fission (see text).

summed over all in-plane angles under the two-body kinematic restriction. The most probable event is that for $m_1 = m_2 = 105$, namely, symmetric fission of a cascade residue with $A = 210$.[1,2] The contours extending past the $M_t = 240$ line show how the mass resolution disperses the data. The dashed line is the $m_1 = m_2$ line; it is clear that for any given value of M_t the most probable mass division is the symmetric one. Thus, for example, for $M_t = 140$, the most probable pair of fragments is $m_1 = m_2 = 70$. However, for a given mass m_2 the most probable partner corresponds to an asymmetric division, for example, $m_2 = 70$ and $m_1 = 120$. The distributions in that case are quite broad.

An estimate of the probability of such two-body breakups as a function of fragment mass can be obtained by comparing coincident events with fragment-1 singles. We find that the coincident-to-singles ratio is constant (and maximal) for $85 \leq m_1 \leq 135$, which is the mass region dominated by binary fission. Normalized to that ratio, the ratio at $m_1 = 70$ is 0.50 and at $m_1 = 50$ is 0.17; we take these ratios to be approximations of the contribution of the two-body breakup mechanism at those mass numbers.

The origin of abundant low-mass symmetric fragments with equal and opposite laboratory momenta is difficult to explain using the conventional picture of the intranuclear cascade followed by an evaporation-fission competition. A large fraction of the target mass is missing, but does not cause a momentum imbalance, thus eliminating a ternary fission mechanism. Fission of a highly excited $A \approx 200$ nucleus, with the fragments boiling off ~ 30 nucleons each (including α particles and other light nuclei) is a possible picture, but there is strong evidence[2] against the primary fragments having such high excitation energy. A third possibility, fission after a very long evaporation chain in which about 100 nucleons are lost, seems unlikely because of the low fissionability of medium-mass nuclei.

Further evidence about the mechanism is found in the correlation of fragment kinetic energies with mass. In Fig. 3 is shown a contour diagram representing the correlation of total kinetic energy, $E_1 + E_2$, with total mass, M_t, for all in-plane events satisfying the two-body kinematics criterion. The full line in this figure shows the (approximate smooth) locus of the most probable total kinetic energy as a function of M_t. For comparison of the data with a possible fission mechanism, the dashed line labeled "fission" represents the average total kinetic energy for a fissioning nucleus of mass M_t and a Z corresponding to 1–2 charge units to the neutron-deficient side of the β stable valley, based on fission systematics.[3] It is clear from this diagram that for $M_t \lesssim 180$ the events observed here have appreciably higher kinetic energies than expected from fission, thus ruling out the third hypothesis above.

We suggest the following picture, which in many respects is similar to recent models[4-6] of relativistic hadron-nucleus and nucleus-nucleus collisions, to account for these observations. A nearly central collision of a highly relativistic proton with a heavy nucleus may act collectively with the nucleons along its path, in contrast to a peripheral collision which results in a conventional intranuclear cascade. These nucleons are rapidly ejected from the nucleus in the forward direction, carrying off most of the incident momentum and inducing a cleavage of the nucleus. Additional nucleons and clusters may be emitted from the surface of the zone of excited nuclear matter adjacent to the projectile path. Such a process would leave two fragments of the target relatively close and unaffected by the rapid event. These "spectator" fragments have almost none of the beam momentum, and because they are formed suddenly in closer proximity than would be the case for a fission process (with its stretched scission configuration), their final kinetic energies are larger than that for fission. The fast time scale of this process leads to preferential emission of the fragments at 90° to the beam, an effect which has been seen in fragment angular distributions.[7-9] Such a rapid breakup does not allow much time for the transfer of excitation energy to the newly formed fragments, accounting for the observation[2] that they are not highly excited when formed.

In summary, we have observed the breakup of a heavy nucleus by relativistic protons with the characteristics of a two-body process in which a large fraction of the target mass is missing. Moreover, the residual fragments are ejected with higher kinetic energy than expected for the fission of a mass equal to the sum of the fragment masses. The missing mass is assumed to carry with it most of the incoming energy and momentum.

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β-Ray Angular Distribution from Aligned ^{12}B and ^{12}N

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The coefficients $\alpha_\mp$ in the alignment-correlation terms $\mathfrak{A}\alpha_\mp EP_2(\cos\theta)$, in ^{12}B and ^{12}N decays have been determined; $\alpha_-(^{12}\text{B}) = +(0.006 \pm 0.018)\%/\text{MeV}$ and $\alpha_+(^{12}\text{N}) = -(0.273 \pm 0.041)\%/\text{MeV}$. The sign of $\alpha_+(^{12}\text{N})$ was determined for the first time, by use of an NMR method and measurements on β-γ correlation in aligned ^{12}N. The $\alpha_- - \alpha_+$ result is consistent with strong conservation of vector currents without second-class currents and the $\alpha_- + \alpha_+$ result gives unique information on the time component of the axial-vector current.

Research works on β decay have recently focused on "recoil-order" experiments designed to determine the limits of validity of conserved-vector-current (CVC) theory and to search for the possible second-class currents (SCC) in the fundamental β-decay interactions. We have previously reported[1] measurements of the anisotropy coefficients α_- and α_+ in the β-ray angular distributions from aligned ^{12}B and ^{12}N. The results were compared with the available data for tests

