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CORRELATIONS AMONG NUCLEAR FRAGMENTS IN RELATIVISTIC PROTON-INDUCED BREAKUP OF HEAVY NUCLEI

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Summary

The primary objective of the experiment is to characterize an unusual reaction mechanism involving the breakup of nuclei by relativistic projectiles into correlated fragment pairs covering a broad range of total mass and extending to a total mass as low as 1/3 that of the target. The masses of these coincident fragments are determined by a double time-of-flight technique. Two fast, gas avalanche counters, placed on opposite sides of the beam, provide the start signals and subtend two arrays of Si surface barrier detectors (14 detectors in each) which provide the stop and energy signals. Eight ΔE-E Si particle telescopes are distributed azimuthally in planes perpendicular to the plane of the beam and heavy fragment detectors. The multiplicity and distribution (but not identity) of energetic light, charged particles associated with heavy fragment events is determined by detection in an external array of 80 plastic scintillator paddles surrounding the forward hemisphere of a 1-meter diameter, thin-wall vacuum chamber. The correlations of the heavy fragment events with those in the particle telescopes and external scintillators will be determined as a function of the angle of the heavy fragment detector arrays with respect to the beam direction and as a function of the target mass. Thin ($\sim$500 $\mu g/cm^2$) targets of U, Au, and Ag will be used. Data runs totaling $\sim$400 hrs are requested at a proton intensity of $\sim 10^{11}$ protons/pulse, following a test period of about 10-14 days, during which intermittent beam will be utilized.

Scientific Background

Single-fragment, inclusive studies of the interaction of GeV protons with heavy nuclei (in particular, Au and U) have demonstrated that there are significant changes in the reaction mechanism which become apparent at bombarding energies of about 3 GeV. As the proton energy is increased above this value, the angular distributions of products change from forward- to sideward-peaked and the forward momentum transfer to the target decreases.[1] At 400 GeV the angular distributions of some products are not only sideward-peaked, but show an enhancement of yield in the backward direction.[2]

A study of correlations between pairs of heavy fragments formed in the interaction of 3, 6, and 12-GeV/c protons with U at the ZGS demonstrated the existence of an unusual reaction mechanism.[3] The kinetic energies, masses, and correlation angles of coincident heavy fragments emitted near 90° to the beam were measured. The fragment pairs were found to be very nearly collinear, and binary breakup (shown by equal and opposite momenta) occurred over a broad range of fragment masses, and included events in which the sum of the fragment masses was as low as 1/3 that of the target mass. Moreover, the total fragment kinetic energy for such events was higher than predicted for a statistical fission process leading to the same masses. A previous experiment at the ZGS had established that such fragments are formed in a relatively low state of excitation.[4]

Further studies of this reaction mechanism were recently carried out at the LBL Bevalac where the multiplicity pattern of charged, light particles associated with the binary heavy fragment events was investigated. Beams of 4.9-GeV p, 5.0-GeV α, and ^{20}Ne ions of 5.0, 8.0, 25- and 42-GeV were utilized in bombardments of Au and U. A large, multiparameter detector complement of 246 detectors provided extensive information on light, charged particle correlations with single and binary heavy fragment events. These data are presently being analyzed, but preliminary results confirm the existence of the two-body breakup mechanism observed in the ZGS experiment and indicate some differences in the associated multiplicity patterns with incident protons and heavy ions. A number of other interesting insights into the reaction mechanisms of relativistic heavy ions were observed, and these are discussed in connection with a companion proposal to the present one for further Fermilab studies.[5]

The reaction mechanism proposed to account for the observation of binary fragments with a total mass much lower than that of the target is not well characterized at present. One qualitative picture suggested[3] is that of a nearly central collision in which the projectile interacts collectively with the nucleons along its path. The latter are rapidly ejected 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 close together and relatively 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. Such a rapid breakup does not allow time for the transfer of much excitation energy to the newly formed fragments, accounting for the observation that they are not highly excited when formed. Such a picture is consistent with recent theoretical models such as the "collective tube model"[6] and the "effective target model".[7] These models, however, are concerned primarily with multi-particle breakup rather than a specific two-body breakup mechanism.

One of the expected features of such a reaction mechanism is that the light particles and clusters formed in the hot reaction zone adjacent to the projectile path will be shielded from emission in the direction of the two heavy fragments and will, in fact, be focused by Coulomb forces, in an azimuthal plane perpendicular to the heavy fragment direction. It was not feasible in the LBL Bevalac experiment to combine a search for such events with the other correlations that were investigated. In the present proposal eight ΔE-E particle telescopes will be distributed in the chamber to identify these events. Since the mechanism proposed is characteristic of high bombarding energies, it is especially desirable to search for the expected effects at the highest energy available, where the mechanism should be most prominent.

In the previous ZGS and LBL Bevalac experiments the heavy-fragment detector arrays were concentrated near 90° to the beam on opposite sides of the target. It is of particular interest to establish whether these directions are unique in any way. Other orientations of the heavy-fragment detector arrays are proposed to investigate this dependence.

The charged particle multiplicity distributions associated with binary heavy fragment events will be observed with an external 80-paddle, plastic scintillator array, and, if possible, other particle detectors will be placed downstream to determine the small angle emissions.

Sideward emission of nuclear matter in heavy-ion collisions with heavy nuclei at high incident energies has been explained in a fluid-dynamical model.[8] For near central collisions, this model predicts the formation of a strongly compressed, highly excited head shock which pushes matter sidewards and initiates a strong, sideward-traveling compression (shock) wave. The angular distribution of emitted fragment is peaked at the Mack shock-wave angle of 70°. No analogous model for proton interactions has been proposed, but it would be of interest to search for any shock phenomena by examining the fragment emission and possible correlations at the expected Mach angle of ∿70°.

Research Goal

The primary goal of the experiment is to characterize the reaction mechanism leading to the breakup of heavy nuclei by relativistic projectiles into correlated fragment pairs whose total mass is as low as 1/3 that of the target. Several aspects of the interaction will be examined: (1) The identification and angular correlation of particles and clusters emitted in coincidence with correlated fragment pairs; (2) The multiplicity and distribution of other fast, light charged particles associated with the early stages of such events; (3) Evidence for preferred emission of fragments at the Mach angle of 70°, indicative of a shock-wave phenomenon in central collisions and (4) The dependence of the correlated phenomena on the target mass. Targets of U and Au are chosen as a representative fissionable and relatively non-fissionable species, respectively, and for which a large body of data on high energy interactions has been accumulated. A silver target is chosen as a relatively light species for which a large body of emulsion data is available for comparison and interpretation.

Although our primary concern is with binary heavy fragment events, some single fragment data will also be obtained in the course of the experiment, since a few detectors will be used in a singles mode to serve as beam monitors for normalizing the various runs. An extensive study of single heavy-fragment events is proposed in a companion effort utilizing much of the same apparatus as the present proposal.[5]

Experimental Apparatus

The experiment will be carried out in a spherical 1-meter diameter, thin-wall (3 mm) aluminum vacuum chamber. A schematic diagram of the apparatus is given in Figure 1. Heavy fragments will be mass-identified by a time-of-flight method. Two, thin gas avalanche counters (placed on either side of the target at a distance of ∿10 cm) will provide the start signal for the time-of-flight measurement and 2 Si surface-barrier detector arrays (of 14 detectors each, placed ∿40 cm from the target) will provide the stop and total energy signals. The avalanche counters and Si-detector array will be placed on moveable arms which can be oriented with respect to the beam direction. Eight particle-identification telescopes, each consisting of a ΔE Si transmission detector and a thick Si stopping detector, and capable of resolving Z and A of fragments with $1 \leq Z \leq 4$ will be distributed within the chamber in azimuthal planes perpendicular to the plane of the beam and heavy fragment detectors. These will be placed at a distance of ∿10 cm from the target. The multiplicity, but not identity, of fast charged particles will be detected in 80 plastic scintillator paddles external to the chamber and distributed over the forward hemisphere. If possible, additional plastic detectors will be placed downstream of the chamber to detect forward directed particles. The targets will be thin ($\sim$500 $\mu g/cm^2$) foils of Au, UF_4, and Ag, mounted on a target frame accommodating three targets, any one of which can be readily positioned in the beam.

The apparatus required is essentially the same as that utilized at the LBL-Bevalac and is available for use at Fermilab.

Electronics and Data Handling

The associated electronics is essentially the same as that used at the Bevalac and is available for the proposed experiments. Data handling and storage will require the use of a standard PDP 11/45 computer and tape drive. These are requested to be supplied by Fermilab.

Experimental Runs

The experiment includes a study of three targets (UF_4, Au, and Ag) at several orientations of the detector arrays:

1) Si detector arrays placed at 90°, on opposite sides of the beam. This is essentially the same orientation in which the reaction mechanism under investigation was first observed. Correlations will be observed with particles and clusters identified in particle telescopes azimuthally distributed within the vacuum chamber and with the multiplicity and distribution of fast, light charged particles detected in the 80-scintillator paddles distributed externally over the forward hemisphere of the chamber.

2) Si detector arrays placed at 45° and 225° to the beam direction to examine the correlation of binary events with the beam direction.

3) Si detector arrays placed at the Mach angles (70° and 290°) to search for any shock-wave phenomena. This orientation would be used for only two targets - the heaviest (UF_4) and the lightest (Ag).

In addition a short, blank run with no target in the beam will be carried out to ensure that no extraneous events are being detected.

Beam Requirements

The proposed experiments will require a clean proton beam at 400 GeV with an intensity of $\sim 10^{11}$ protons/pulse in a slow ($\sim$1 sec) spill. This intensity represents a compromise between an acceptable data rate for ternary fragment events and a rate of selected singles events that will not impose too large a dead-time on the computer processing of data. Higher intensities may be utilized (with a concomitant reduction in beam time) for the Au and Ag targets if the halo associated with such an increased intensity does not affect the detectors close to the beam adversely and introduce extraneous events that will increase the dead-time. For the UF_4 target, an increased intensity is not feasible owing to the limitations on dead-time introduced by the binary fission events which are not of prime interest. Greater than 90% of the beam should be concentrated in a spot size of <0.5 cm diameter at the target and the beam halo should not extend beyond $\sim$5 cm from the beam. Space for the possible installation of detector arrays downstream of the chamber is desired. An area of at least 10 meters in length and 4 meters in width is requested.

These experiments involve only a minimum of material in the beam path (very thin targets and 5-10 mil metal windows on the vacuum chamber). Thus, other experiments could utilize the relatively undisturbed beam downstream of our chamber.

Beam Time Estimates

Set-up Time

A period of two months will be required for the installation of the vacuum chamber in the beam line and the cabling, set-up, testing and calibration of detectors and electronics.

Test Runs

About ten days to two weeks of testing and adjustments will be required with intermittent full intensity beam.

Data Runs

For U, Au, and Ag Targets:

1.	Si-detector arrays at 90° and 270° to the beam	-	6 shifts
2.	Si-detector arrays at 45° and 225° to the beam	-	6 shifts
	Total	-	12 shifts
	Total for 3 Targets	-	36 shifts

For Ag and U Targets:

3. Si detector arrays at 70° and 290° to the beam	-	6 shifts
Total for 2 Targets	-	12 shifts
Blank (Background) run with no target in beam	-	1 shift
Total Data Running Time	-	49 shifts (or about 400 hrs)

These estimates were arrived at from the following considerations:

The LBL-Bevalac experiment with a Au target indicates a binary heavy fragment coincident rate of ∿10 events per 10^{11} protons. About 20% of these events are in the interesting total mass range of 80-120. We, therefore, expect ∿2 events per 10^{11} protons in this mass range.

Previous ZGS studies indicated that about 6-7 α particles are associated with heavy fragments in the mass region of ∿60. About 1/2 of the events leading to masses in this region are binary events. Therefore, we expect ∿3 α-particles per binary.

The particle telescopes will be placed 10 cm from the target and have a sensitive area of 450 mm^2, subtending a fractional solid angle of $\frac{4.5}{4\pi \cdot 10^2} = 3.6 \times 10^{-3}$.

Assuming, conservatively, that the α particles are emitted isotropically, the probability of detection is $(3)(3.6 \times 10^{-3})$ or 0.0108.

The expected ternary coincidence rate of binary heavy fragments with an α is, then $(2)(0.0108) = 0.0216$ per telescope per beam pulse of 10^{11} protons.

Several hundred ternary coincidences are required to obtain significant statistics. For 300 ternary coincidences, we need $300/0.0216 = 1.39 \times 10^4$ pulses. At a pulse rep rate of ∿5 pulses/min, this corresponds to ∿46 hours, or ∿6 eight-hour shifts.

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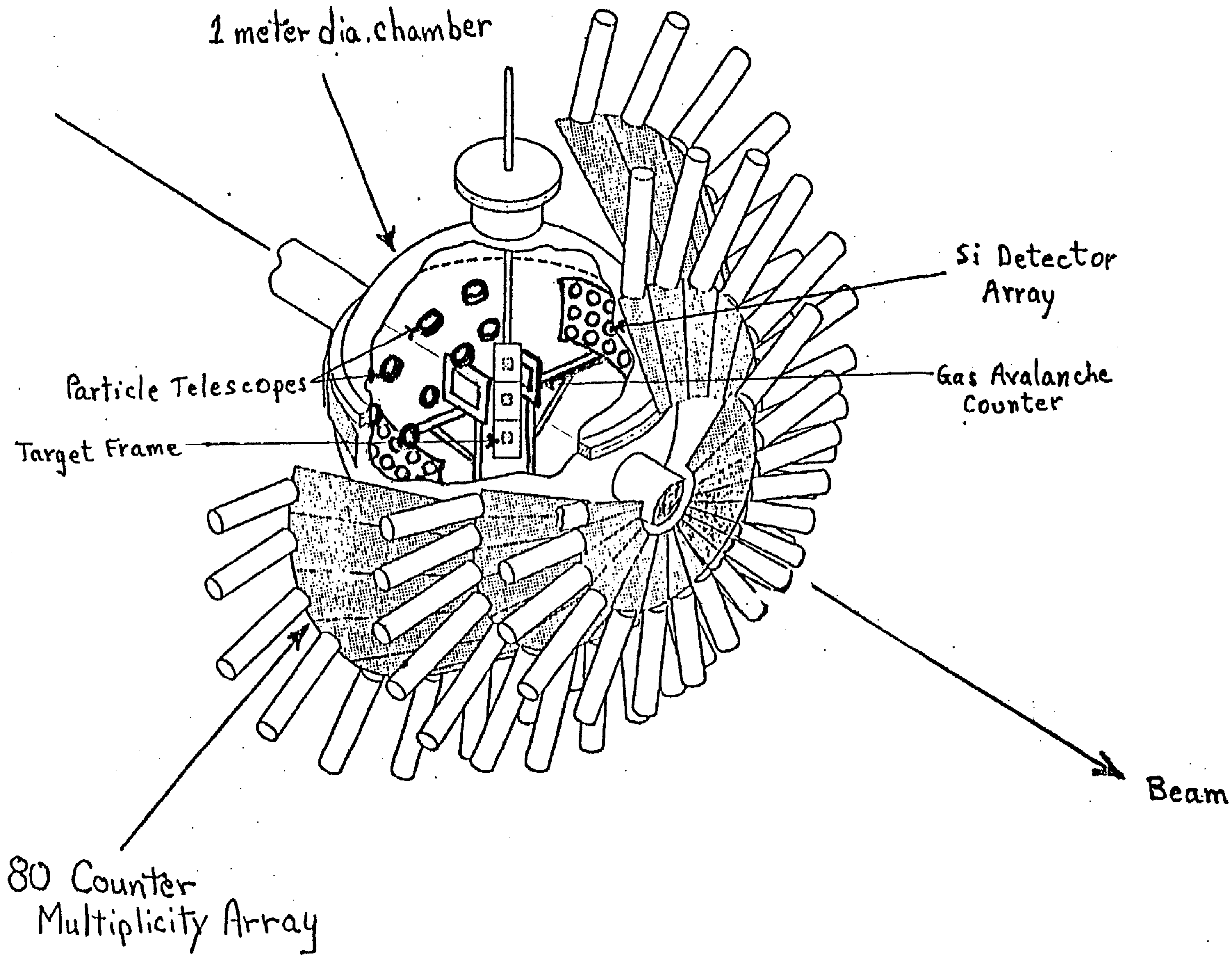

Fig. 1. Diagram of Apparatus