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NUCLEAR-BREAKUP MECHANISMS IN THE INTERACTION OF
RELATIVISTIC PROJECTILES WITH HEAVY TARGETS CONF-8206132--2

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I. INTRODUCTION

As new energy regimes were entered at high energy accelerator facilities, the interactions of the available projectiles with a variety of targets were investigated. These were primarily inclusive studies of reaction products utilizing radiochemical techniques. An extensive literature⁽¹⁾ on proton interactions up to 400 GeV has been generated, and more recently, pion and heavy-ion reactions have been studied. These data have provided a general phenomenology for the description of high energy interactions, but the inclusive character of the studies left important questions of the nature of and correlations with other fragments produced in the same event unanswered. Such information is vital to any interpretation of a reaction mechanism. Only a few fragment correlation studies have been carried out. One⁽²⁾ was concerned with the correlations in mass, energy, and angle of fragments over a broad mass range in the interaction of 11.5 GeV protons with U; the other,⁽³⁾ primarily on light

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fragment production and correlations with the emission of heavy fragment partners and fast charged particles in the interaction of p , α , and ^{20}Ne with U , Au , and Ag . The present work represents a combination and extension of these studies to higher projectile energies and is the most comprehensive study of multifragment correlations yet carried out.

The different detector systems utilized in this work provide information on different aspects of the fragment properties and correlations, and a selection of some of the extensive data obtained will be presented here.

II. EXPERIMENTAL APPARATUS

Figure 1 shows the experimental layout. A 1 m.-diameter, spherical, thin-walled (3 mm), Al vacuum chamber housed a double time-of-flight (TOF) system, utilizing two gas avalanche start detectors and two arrays of Si surface-barrier energy and stop detectors; and four gas ionization chambers, backed by Si detectors, for ΔE - E particle identification. The Si arrays were positioned near $+90^\circ$ and -90° to the beam direction and provided fragment correlation angles in the range 155° - 195° for masses in the range 10-140. The ΔE - E telescopes were centered at -30° , 62° , 113° , and 151° to the beam and extended the range of correlation angles measured for fragments with $Z = 6$ -20 in coincidence with partners in the Si arrays. The avalanche start counters could also be used as high geometry detectors to signal a binary event near 180° from a mass-identified fragment in the opposite time-of-flight arm.

An array of 80 scintillation paddles surrounded the forward hemisphere of the chamber and counted the number of fast charged particles associated with events recorded by the internal detectors.

Beams of 5 GeV p and α and 5, 8, 21 and 42/GeV ^{20}Ne were utilized at the LBL Bevalac for bombardment of a

500 $\mu\text{g}/\text{cm}^2$ Au target. The target was positioned at an angle of 15° to the beam, making it effectively thick for beam interaction, but thin for fragments emitted at $\theta \sim 90^\circ$.

III. DATA AND RESULTS

In the following sections data are presented on fragment energy spectra, the mass and kinetic energy correlations of the fragments, the associated fast charged particle multiplicities and the formation of light ($A = 10-30$) fragments.

A. Fragment Energy Spectra

Figure 2 shows energy spectra from the TOF system in three mass bins: $28 \leq A \leq 31$, $80 \leq A \leq 89$, and $120 \leq A \leq 139$. These data are summed over detectors at $\theta = 75^\circ-110^\circ$, over which no significant change in the spectra is observed. The solid circles are the unselected fragment cross sections. The triangles represent the spectra of events satisfying a binary veto requirement that uses the large area avalanche detector on the opposite side of the target to the emission of the measured fragment. The binary veto requirement is satisfied if there is no coincidence signal in the avalanche counter above a software-selectable, pulse-height threshold (in this case corresponding to a fragment of $A=30$). This veto eliminates binary fission and other processes exhibiting approximate two-body kinematics in the laboratory frame. The spectra of light fragments, typified by the mass bin $28 \leq A \leq 31$ in Fig. 2a, show that only a small fraction of the fragments are thus vetoed out, and that no particular part of the energy spectrum is associated with such binary events. This can be interpreted as an indication that such light fragments are not formed to any significant extent in two-body processes, a point which is discussed in more detail below. The binary fission component of the fragment

yield is seen as a peak in the spectrum of the intermediate mass fragments (Fig. 2b) at a kinetic energy of ~ 60 MeV.

B. Mass and Kinetic Energy Correlations

The fragment mass correlation is shown in Figure 3 for the 5 GeV p bombardment. The contour lines differ by factors of 2. A broad correlation is observed with increasing probability for symmetric fission near $M_1 = M_2 \approx 90$ and for light fragment pairs near mass 10-20. The total fragment kinetic energy is shown as a function of the total fragment mass in Figure 4 for the 5 GeV ^{20}Ne bombardment. A line representing the kinetic energy expected for the fission of a nucleus of given mass total is indicated. It is clear that below about total mass 120, the total kinetic energy of the fragments observed in the present work is higher than is expected from systematics for the fission of that mass.

C. Associated Fast Charged Particle Multiplicities

The array of 80 scintillators surrounding the chamber provides a measure of the number of fast charged particles emitted in coincidence with the heavy fragments detected inside the chamber. The term "multifoldedness" (M) is used to represent the number of scintillators hit in a single event. Since the array is composed of discrete elements covering only part of the solid angle, this quantity is detector dependent. The multifoldness distribution $P(M)$ associated with a variety of triggering fragments can be studied. An example is shown in Figure 5 for the mass bin $28 \leq A \leq 31$ with three bombarding projectiles. In Figure 6 a contour plot of fragment yield as a function of fragment energy and multifoldedness is shown for the mass bin $80 \leq A \leq 89$. Two components are seen - a high energy, low multifoldedness one due to fission and a lower energy, high multifoldedness one associated with more violent collisions.

The fast particle multiplicity (which is a measure of the violence of the collision) increases dramatically with increasing projectile energy, but this is not reflected in any major change in the fragment energy spectra. However, at a given projectile energy, the more violent (high multiplicity) collisions lead, on the average, to the production of lighter fragments than do the gentler, low multiplicity collisions.

D. The Formation of Light Fragments

A number of different correlations of light fragments ($A \sim 10-30$) point to the fact that they are not formed in the binary breakup of target residues, but rather, are most likely formed in a multi-fragment, target breakup mechanism. If, for example, the light fragment were evaporated from an excited target residue, an approximate 180° correlation would be expected between the evaporated fragment and recoil directions in the residue rest frame. This would be detected in the large area avalanche detector on the side of the target opposite to the direction of the measured light fragment. No such correlation is observed.

Other data on the mass, angular and kinetic energy correlations of light fragments with coincident partners indicate the following:

(1) Light fragments are formed in coincidence with a broad mass range of partners, with the probability of formation decreasing with increasing partner mass.

(2) The correlation between light fragments is independent of the laboratory angle between them. Figure 7 shows the angular correlation between fragment pairs with total mass (M_t) in three regions for the 8 GeV and 42 GeV ^{20}Ne bombardments. For $M_t > 160$ a narrow correlation peaking near 180° is seen, as expected for a binary fission process. This correlation broadens with decreasing M_t , and for $M_t < 100$,

essentially no correlation is observed. Some forward peaking, due to beam momentum transfer, is noted in the 8 GeV ^{20}Ne case. The trends noted here are confirmed in the extension of the angular correlation coverage over the range 55° - 300° , provided by coincidences between a fragment in one of the particle telescopes with a partner in an array detector.

(3) The kinetic energy of a light fragment is independent of the mass of its partner and is the same as for unselected (singles) events. The dependence of the mean fragment kinetic energy on the mass of its coincident partner is shown in Figure 8 for the 42 GeV ^{20}Ne bombardment. Various mass bins for the fragment are shown. For fragments of mass 10-20, the kinetic energy is independent of partner mass. As the fragment mass increases, a dependence on partner mass becomes more apparent, as expected for a binary breakup process.

(4) The charged particle multiplicity is highest for events leading to light fragments.

These data indicate that none of the kinematic correlations expected from a binary breakup origin for light fragment production are observed. They suggest an origin in a violent, multi-fragment breakup of the target.

IV. SUMMARY

The breakup of a Au nucleus under bombardment with relativistic p, α , and ^{20}Ne has been investigated in an extensive, multi-detector study. The present discussion addresses some of the many aspects of the experimental results. A broad distribution of coincident fragment masses is observed, with the total fragment kinetic energy being higher than expected for a fission mechanism for total fragment mass ≤ 120 . The formation of light fragments is shown to be inconsistent with a binary breakup mechanism, and a multi-fragment target breakup is suggested.

In general, the results indicate a broad spectrum of violence in the collisions, from gentle, leading to the production of heavy spallation products and fission, to essentially explosive, leading to multi-fragment breakup into light mass products. These aspects of the reactions represent a late-stage breakup of the target residues and are positively correlated with the violence of the initial fast stage of the collision as measured by the charged particle multiplicity.

V. REFERENCES

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Figure 1. Schematic diagram of vacuum chamber and detector layout.

Figure 2. Double differential cross sections for fragments in three mass bins: Top (Figure a) $20 \leq A \leq 31$; middle (Figure b), $80 \leq A \leq 89$, and bottom (Figure c), $120 \leq A \leq 129$.

Figure 3. Fragment mass correlation for 5 GeV p bombardment of Au.

Figure 4. Contour plot of total coincident fragment kinetic energy as a function of total coincident fragment mass for 5 GeV ^{20}Ne bombardment of Au.

Figure 5. Fast charged particle multifoldedness distributions associated with fragments in the mass bin $28 \leq A \leq 31$ at $\theta = 90^\circ$.

Figure 6. Contours of fragment yield against associated multifoldedness and fragment energy for the reaction 250 MeV/u Ne + Au producing fragments in the mass bin $80 \leq A \leq 89$.

Figure 7. Angular correlations (summed over out-of-plane angles) between coincident fragments in three bins of total mass for two of the reactions studied.

Figure 8. Mean kinetic energy of fragments in various mass bins as a function of the coincident partner mass for the 42 GeV ^{20}Ne bombardment.