WHAT CAN WE LEARN ABOUT FRAGMENTATION FROM COINCIDENCE EXPERIMENTS?

CONF-870410--29

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It has become clear that in order to characterize a complex process such as nuclear fragmentation more exclusive experimental measurements must be performed, i.e., the correlations between coincident fragments must be determined. Some types of correlations are readily interpreted in terms of specific mechanisms, for example, the angular correlation between two heavy fragments. Binary (fission-like) breakup results in relatively strong angular correlations, while no strong correlations are expected for a multi-body fragmentation mechanism. Data from coincidence measurements of the fragmentation of uranium and gold targets by relativistic projectiles are presented which illustrate these points. The interplay between such experiments and model calculations of fragmentation is discussed.

1. INTRODUCTION

Two modes of decay of excited heavy nuclei have been long known and are by now well characterized: spallation (statistical evaporation of nucleons and light nuclei from a system in thermal equilibrium), and binary fission, assumed to be fundamentally the same process as liquid-drop fission at relatively low excitation. A long-standing question is what other processes may occur at sufficiently high excitation energies, and the term fragmentation is generally used to refer to any such process by which a complex nucleus breaks into smaller pieces or emits nuclear fragments. In this paper I will discuss the data from several experiments in which I have participated¹⁻⁴, with special reference to the correlations between coincident fragments and what can be learned about fragmentation mechanisms from such measurements.

Models of fragmentation have commonly been used to account for inclusive (i.e., single-fragment) experimental data, such as mass and charge distributions of fragments and single-fragment energy spectra. Examples (not a complete list) include sequential statistical emission from an excited nucleus formed by an initial fast process⁵⁻⁶, statistical breakup (non-sequential) of an excited, compressed system during an expansion stage⁷⁻¹⁰, cold shattering of the struck target nucleus¹¹⁻¹², and cluster formation near the critical point¹³⁻¹⁴. Although the basic assumptions of the different models differ widely, they are all reasonably successful in reproducing the gross features of fragment mass distributions. Even the most minimal models, only involving the

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constraints of finite nuclear size plus maximal entropy, can reproduce the fragment mass distributions¹⁵⁻¹⁶.

We may draw one of two conclusions from this: (1) fragment mass distributions are insensitive to the details of the excitation/de-excitation process; or (2) the different models all share the same essential physics, such as phase space effects, which determines the final result. It should also be pointed out here that in general several distinct kinds of processes will contribute to the mass distribution, e.g., fission, spallation, etc., and that any agreement of a single reaction mechanism with the data may be accidental.

What about the more detailed information contained in the energy spectra of the fragments? Here again, models based on different physics seem capable of fitting the data (the term "fitting" is deliberate, since a parameterization of the data is usually done). Such fits have been demonstrated for a cold breakup model¹², a liquid-gas phase transition model¹³, and a thermal statistical model⁹. It is likely that the successful fits are due to a similarity in the essential physics of the models. The same data set of fragment energy spectra from the reactions of 30 MeV/A ^{12}C with Au could be well described both by a thermal hot-spot model and by a cold breakup model¹⁷. This was attributed to the fact that both models included two different velocity components, a random one and one directed along the beam axis, although the origin and mass dependence of the latter component differs between the two models.

In order to place more stringent constraints on the different models, more exclusive experimental measurements are now being done, in which the correlations between coincident fragments are measured. In the following, I discuss two such experiments, which illustrate some of the difficulties of interpreting coincidence data, and point out how these difficulties might be eased by more detailed model calculations.

2. URANIUM FRAGMENTATION BY RELATIVISTIC PROTONS

In this experiment¹, carried out at the Argonne ZGS, the masses and kinetic energies of coincident heavy fragments were measured at correlation angles close to 180 degrees. Figure 1 shows (a) the angular correlation and (b) the distribution in laboratory momentum ratio, p_1/p_2 , for three values of the total observed mass, $M_t = m_1 + m_2$. Both of these distributions are consistent with two-body breakup of a system moving with only a small fraction of the projectile's momentum, and while binary fission of an excited cascade residue is reasonable for the heavier mass systems, it seemed less likely for lighter systems. The characteristics of the events with "two-body kinematics", i.e.

FIGURE 1

(a) Fragment angular correlations for three values of total mass in reactions of 11.5 GeV protons with ^{238}U . (b) Distributions in fragment momentum ratio¹.

FIGURE 2

Correlation between coincident fragment masses for ^{238}U fragmentation¹.

FIGURE 3

Correlation between total kinetic energy and total mass for ^{238}U fragmentation. The full line indicates the path of most probable values, the dashed line the relation expected for binary fission¹.

those with $0.75 \leq p_1/p_2 \leq 1.33$, are shown in terms of the correlation between fragment masses in Fig. 2 and the correlation of total kinetic energy and total mass in Fig. 3. The most probable event corresponds to symmetric fission of a cascade residue with $A=210$ to give a pair of $A=105$ fragments. There is a long tail of events extending to low values of fragment masses, with the most probable mass division being symmetric. However, for any given mass of one fragment, there is a broad distribution of partner masses, with the most probable value corresponding to an asymmetric division.

The broken line in Fig. 3 shows the average total kinetic energy expected from the Viola¹⁸ fission systematics if these events arose from fission of an excited target residue with $A = M_t$. The solid line indicates the most probable kinetic energy of the data, which is considerably larger than that expected for fission. A model for such a two-body fragmentation process was suggested, in which the projectile ejected a number of nucleons from the target in a fast process, thereby causing a "cleavage" of the residual nucleus. The resulting two fragments are closer to each other than would be the case for fission, with its stretched scission configuration, thus resulting in the higher total kinetic energies observed. This picture corresponds closely to the cold breakup model of fragmentation of Hufner and co-workers¹¹⁻¹².

What is the probability of this two-body fragmentation mode? From Fig. 2, the probability of observing an $m_1 = m_2 = 60$ event is about 4% of the most probable binary fission event, so we could use that as a rough estimate of the magnitude of this process. Alternatively, one can ask what fraction of all fragments of mass 60 are formed by this process? To answer that we must consider the experimental thresholds, acceptances, etc. Coincidences were taken between a single detector fixed at 90 degrees to the beam and four movable detectors on the opposite side, covering correlation angles between 155 and 190 degrees. Data were also taken at out-of-plane angles of 5 and 10 degrees. By integrating over all coincident partners of a given mass fragment (m_1) in the fixed detector, and over the range of correlation angles (interpolating over gaps in the experimental data), we obtain the energy spectrum of a fragment with a coincident fragment near 180 degrees for comparison with the corresponding spectrum for singles events.

Figure 4 shows energy spectra for fragments in three mass ranges; the smooth curves show the single-fragment inclusive spectra and the points the coincident spectra. The coincidence cross section for light fragments in the mass range $m_1 = 52-60$ is only 20%-40% as large as the singles cross section, depending on fragment energy; the spectra have similar shapes. Fragments around the most probable mass, $m_1 = 100-108$, have a much higher coincidence efficiency, approaching 100% above a fragment energy of 100 MeV. In the heavier fragment group, $m_1 = 132-140$, the energy spectra have a narrow distribution characteristic of low-energy fission, and the coincidence and singles cross sections are nearly the same above about 50 MeV. The heavier, higher energy fragments clearly are formed by binary fission of near-target residues at fairly low excitation energies. The low-energy threshold of 30 MeV for the fragment detector cuts off a significant fraction of the spectrum for the heavier fragments. An estimate of the spectrum shape at low energies

FIGURE 4

Energy spectra for uranium fragmentation. The points are for coincident fragments, the solid curves are the singles spectra. The dotted curve in (c) is an estimate of the spectrum at low energies.

for $m_1 = 132-140$ is shown in Fig. 4(c) by the dotted curve, which was estimated from radiochemical measurements¹⁹ of the recoil range distribution of the neutron-deficient nuclide ^{131}Ba .

The data in Fig. 4 illustrate two of the problems in interpreting a typical coincidence experiment investigating fragmentation: the efficiencies and thresholds of the detectors, and the (usually) limited angular coverage. What is the low coincidence rate at mass 60 relative to the singles rate due to? If data were available for a much wider range of correlation angles, how much would the coincidence rate increase? Are many heavy partners with low energies, coming from a very assymmetric breakup, missed because of the detector threshold? Experiments with greatly increased angular coverage and lower energy and mass thresholds are necessary in order to answer these questions; only with such increased acceptance can one measure a true multiplicity of associated fragments as functions of mass or charge, and thus distinguish multi-fragmentation processes from binary ones. The m_1 - m_2 correlation would

probably be strongly dependent on correlation angle; the change from Fig. 2 at angles away from 180° probably would be to eliminate the binary fission peak and to greatly broaden the distribution for light masses. Changes in the correlation between total kinetic energy and mass with angle are also likely, but less predictable.

3. GOLD FRAGMENTATION BY RELATIVISTIC HEAVY IONS

In this Bevalac experiment²⁻⁴, the detector geometry was also restricted to correlation angles close to 180 degrees, but two additional detector systems were used: four gas ΔE - Si E telescopes were placed at in-plane angles well away from 90 degrees to the beam, and a multiplicity array of plastic scintillators covering most of the forward hemisphere detected energetic $Z = 1-2$ particles. The latter array allowed the events to be classified by the violence of the interaction, based on the number of particles detected. In this way a clear separation between fission and deep spallation events for medium-mass fragments was shown. Beams of 5 GeV protons and He ions, and Ne ions of 0.25, 0.40, 1.05, and 2.1 GeV/A bombarded a thin ^{197}Au target, one of the objectives of the experiment being the study of the dependence of fragmentation on projectile mass and energy.

Figure 5 shows the angular correlations for fragments in three ranges of M_t for beams of 5 GeV protons and 42 GeV Ne. For $M_t = 170-180$ the correlations are fairly narrow and peaked a few degrees forward of 180° , consistent with formation by binary fission of excited near-target residues. An analysis³ of the dependence of the mean correlation angle on mass loss and projectile velocity showed that the data are consistent with a simple model of peripheral interactions, and that the momentum transfer in such interactions decreases with increasing projectile velocity. The angular correlations are much wider for smaller values of M_t , however, and clearly extend well beyond the region around 180° . This is in contrast with the data for uranium shown in Fig. 1, for which the angular correlation remains narrow even for events whose total mass loss is nearly one-half the target mass. The fragmentation process evidently changes significantly in character for a rather small change in nuclear size; it may be that the suggested cleavage mechanism sets in rather suddenly for the heaviest targets. Further experiments are clearly desirable to confirm this effect.

Some information about the angular correlations away from 180° can be obtained from coincidences between the gas ΔE - Si E telescopes and the Si arrays near 90° , although the number of such events was small. In order to eliminate the angular dependence of the light fragment cross sections from the

FIGURE 5
Angular correlations for ^{197}Au for three ranges of total mass.

correlation, we use the differential mean multiplicity of light fragments in coincidence with a 90° fragment, defined as

$$\frac{d\langle M_1 \rangle}{d\Omega_1} = \frac{d^2 \sigma_{12}(m_1, Z_2)}{d\Omega_1 d\Omega_2} \bigg/ \frac{d\sigma_2(Z_2)}{d\Omega_2} \quad (1)$$

where fragment 1 is detected at 90° and fragment 2 at angle θ_2 . These mean multiplicities are shown in Fig. 6 for 5 GeV protons and 42 GeV Ne, for two mass bins of fragment 1, summed over the entire range of $Z = 6-27$ of fragment 2. There is a general tendency for higher multiplicities near $\theta_2 = -90^\circ$

FIGURE 6
Differential mean multiplicity (Eq. 1) of fragments of mass m_1 at $\theta_1 = +90^\circ$ in coincidence with $Z = 6-27$ fragments at angle θ_2 .

($\sim 180^\circ$ from the trigger fragment), and lower multiplicities at $\theta_2 = +30^\circ$, close to the trigger, especially for $m_1 = 40-60$. The effect is not a strong one, however, and there is little evidence for a predominantly two-body break-up process for the Au target, the overall angular correlations for light fragment coincidences being approximately isotropic.

Returning to the data set of near- 180° coincidences, it is clear from the angular correlations of Fig. 5 that these data are representative of all coincidences only for total mass within about 30 mass numbers of the target, corresponding to binary fission. For events with larger mass loss, it is likely that only a fraction of the total cross section is included, and that for the lightest masses the fraction is small. To the extent that the included fraction is similar for the different projectiles, however, it is nevertheless interesting to compare the different correlations, especially since these are the only such data available.

FIGURE 7
Fragment mass correlations for ^{197}Au . The number of counts per bin varies from 64-127 (largest symbol) to 1-2 (smallest).

The fragment-mass correlations are shown in Fig. 7 for three of the projectiles, illustrating the differences. Within this restricted angular range, it appears that many more light fragment pairs relative to the fission events are produced by protons than by Ne ions of the same kinetic energy, 5 GeV. Increasing the Ne energy to 42 GeV considerably enhances the light fragment production, and there is a definite increase in events with $m_1 = m_2 = 20-40$, as compared to the lower energy projectiles. An interesting difference between proton and neon beams in the mass correlations for light fragments is shown in Fig. 8, where the mass distribution of fragments in coincidence with a partner of $m_1 = 20-40$ is shown for these three projectiles. While the most probable partner for a light fragment in reactions of Ne ions is another light

FIGURE 8
Fragment mass distributions in coincidence with a partner in
the mass bin $m_1 = 20-40$.

fragment, that is not the case for proton reactions, with both Au and U targets, for which the most probable partner is a medium-mass fragment. One might speculate that multifragmentation, in which a number of light fragments are formed, is more probable with the heavier projectile.

In Ref. 4 we estimated the mean multiplicity of fragments with Z in the range $Z = 2-27$ associated with a trigger fragment with $m_1 = 20-40$ at 90° , by integrating distributions such as Fig. 6. It was found that this multiplicity was approximately the same ($\sim 4-6$) for all projectiles used. This conclusion would seem to conflict with the above data, which seems to show much larger light fragment yields for 42 GeV Ne projectiles. The data are not easily comparable, however, since one set refers to fragments only close to a 180° correlation, while the other is representative of a much larger angular range. In addition, most of the yield in the range $Z = 2-27$ is for $Z \leq 6$, and thus the quoted multiplicity refers mainly to fragments below the mass threshold of the coincidence data.

FIGURE 9
Correlation between fragment total kinetic energy (TKE) and total mass (M_t). The line shows the dependence expected for binary fission.

Finally we show the correlation between the total kinetic energy (TKE) and M_t of the fragments for 5 GeV protons and 42 GeV Ne in Fig. 9, along with the dependence expected¹⁸ for binary fission. The most probable TKE is close to the fission line for M_t values greater than about one-half the target mass, with a tail extending to higher energies. For greater mass losses from the target the events lie well above the fission TKE. These low mass, high fragment energy events are similar to those observed for uranium fragmentation (Fig. 3), but represent a smaller fraction of the data, as might be expected considering the broader angular correlations for the lighter target.

4. INTERPLAY OF EXPERIMENT AND THEORY

With improvements in detector design it is now possible to detect most of the charged particles emitted in a fragmentation reaction, covering a much wider range of mass/charge and energy than did the experiments discussed above, and in addition covering a much larger fraction of the solid angle, even approaching 4π . With such increased experimental sensitivity and acceptance many of the open questions about fragmentation may be answered, but only with the help of more detailed theoretical calculations. Most of the models of fragmentation up to now have been applied to the calculation of single-fragment inclusive properties, especially mass or charge distributions. What is now needed are calculations of multi-fragment correlations in order to interpret the kind of data discussed above. In particular, one would like to

subject the results of the calculations to a filter based on the experimental acceptance and efficiency.

Theory can also help in suggesting simple observables which characterize different decay mechanisms and can serve to distinguish among them, and to guide the experimenter in what quantities to measure in the limited beam time available. Even with the greatly increased efficiency anticipated using the new multi-detector systems one would still like to use selective event triggers to enrich the fraction of "interesting" events recorded, and here again one needs theoretical guidance.

This work supported by the U. S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

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