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TARGET FRAGMENTATION IN INTERMEDIATE ENERGY HEAVY ION COLLISIONS

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Radiochemical measurements of target fragment isobaric yields, excitation functions, fission cross sections, fragment angular distributions, etc. are presented for the interaction of 10-100 A MeV light (C-Ne) heavy ions with heavy targets (Sm-U). The characteristics of various aspects of target fragmentation are summarized and the possibility of a new "fast fission" mechanism is suggested.

1. INTRODUCTION

One interesting aspect of intermediate energy nucleus-nucleus collisions is that of target fragmentation, the production of large ($20 \leq A \leq A_{CN}$), relatively slow-moving ($0.02 < E < 5$ A MeV) fragments of the initial target nucleus. This phenomenon is complementary to that of projectile fragmentation, although it is not studied as extensively due to the experimental difficulties of detecting these fragments. Nonetheless, there is a rich and complex array of phenomena associated with these processes that more than justify the efforts of various experimental groups engaged in studies of target fragmentation.

In this report, we shall discuss some aspects of a set of broad survey measurements of the general characteristics of the fragmentation of heavy targets induced by light (C,O) projectiles of intermediate (8.5 - 105 A MeV) energy. We shall focus on single particle inclusive measurements made using radiochemical techniques. The use of radiochemical techniques gives us the requisite sensitivity for detecting the high Z, slow moving target fragments along with the ability to study low probability processes. The simplicity of the experimental measurements allows studies to be performed at a variety of accelerators (LBL, CERN, MSU, in this case) whose beam energies span the region of interest. This simplicity has its price in that, like all single particle inclusive measurements, information about the correlations between observables is lost.

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2. TARGET FRAGMENT YIELDS

2.1 Evolution of target fragmentation mechanisms with increasing projectile energy.

In figure 1, we show the target fragment isobaric yields[1] for the interaction of various energy heavy ions with the n-rich, relatively non-fissionable ^{154}Sm. At the lowest energy (8.5 MeV/A), the fragment yield

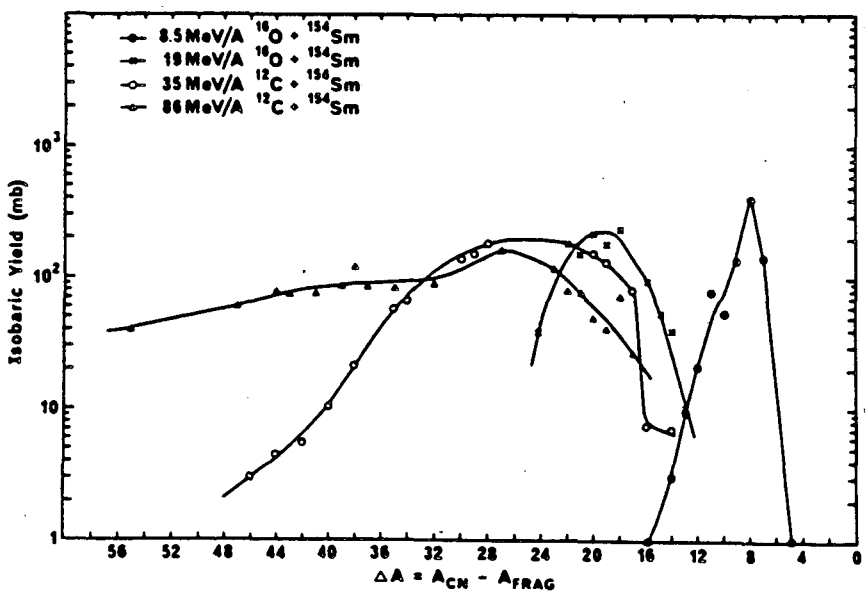

Figure 1
Fragment isobaric yield distributions for the reaction of various heavy ions with ^{154}Sm. The lines are to guide the eye through the data points.

distribution is sharply peaked at a mass number near that of the completely fused system, with most of the reactions proceeding via a complete fusion mechanism. (The velocity spectra of the fragments show > 95% of the events are due to complete fusion). As the projectile energy increases, so does the energy deposited in the target nucleus, leading to the production (after deexcitation) of fragments of lower and lower mass numbers. Correspondingly, the fragment isobaric yield distribution becomes broader - but the decrease in the mass transfer from projectile to target nucleus causes the isobaric yield distribution to be asymmetric with a steeper upper edge and a long"spallation-like" tail towards lower masses. (The fraction of reactions proceeding by complete fusion drops to ∿35% at 19 A MeV and is <5% at 35 A MeV). It is interesting to note that even at a projectile energy

of 85 MeV/A, significant formation of trans-target species is observed although with somewhat less probability than in the reaction of 85 MeV/A ^{12}C with ^{206}Pb, ^{209}Bi[2].

2.2 FISSION EXCITATION FUNCTIONS

A complementary study of the fragmentation of the more fissionable Au by 12.0 - 83.8 A MeV heavy ions[3] showed similar trends to those observed for ^{154}Sm with the additional feature that the fission cross section decreased from ∿50% of the total reaction cross section at 12 A MeV to ∿8% at 84 A MeV. Perhaps the most interesting fission excitation function comes from the interaction of various energy heavy ions with ^{165}Ho as shown in figure 2.

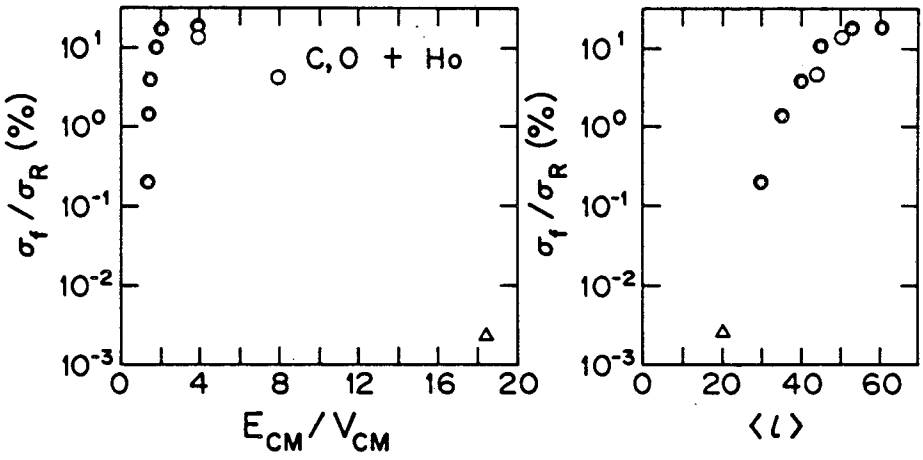

Figure 2.

(a) Fission excitation function from the reaction of ^{12}C and ^{16}O with ^{165}Ho
(b) Same data as (a) except σ_f/σ_R is now plotted vs. the average angular momentum of the fissioning system. Data from ref. 4 (solid points) and ref. 5 (open points).

For a nucleus like ^{165}Ho, which will only fission when made to rotate rapidly, one observes the fission exit channel to decrease in importance as the projectile energy is raised from 17 to 84 A MeV. The physics behind this observation is better shown in Figure 2b) in which σ_f/σ_R is plotted as the average angular momentum of the fissioning system, $\langle \ell \rangle$. This latter quantity was estimated using the simple approximate semiclassical relationships:

$$\langle \ell \rangle = 2/3 \left(\frac{\sigma_{fusion}}{\pi \lambda\!\!\!^{-2}}\right)^{1/2} \qquad E_{proj} < 10 \text{ A MeV} \quad (1)$$

$$\langle \ell \rangle = \ell_{crit} \, (P_{11}/P_{CN}) \qquad E_{proj} \leq 10 \text{ A MeV} \quad (2)$$

Values of ℓ_{crit}, and σ_{fusion} were taken from ref. 6. and the fractional transferred linear momentum was calculated using the semiempirical relationship[7]

$$(P_{11}/P_{CN}) = -0.092 \sqrt{\frac{E}{A}} + 1.273 \qquad (3)$$

It appears that by organizing the data as a function of the angular momentum of the fissioning system the essential physics is shown, i.e., that of a decreasing angular momentum transfer to the target nucleus as the projectile energy increases from 17 to 84 A MeV. The singular importance of angular momentum in determining rare earth fissionability can be further demonstrated by remembering that the fission cross section for the interaction of GeV protons (which deposit excitation energies of several hundred MeV) with rare earth nuclei is <10 mb.[8]

2.3 LIGHT FRAGMENT ($20 \leq A \leq 60$) EXCITATION FUNCTIONS

One of the most interesting aspects of target fragmentation are those reactions producing nuclear fragments that have $A_{fragment} \leq 1/3\ A_{target}$. At higher projectile energies ($E_{proj} \geq$ 2-3 GeV), such fragments are known[9]

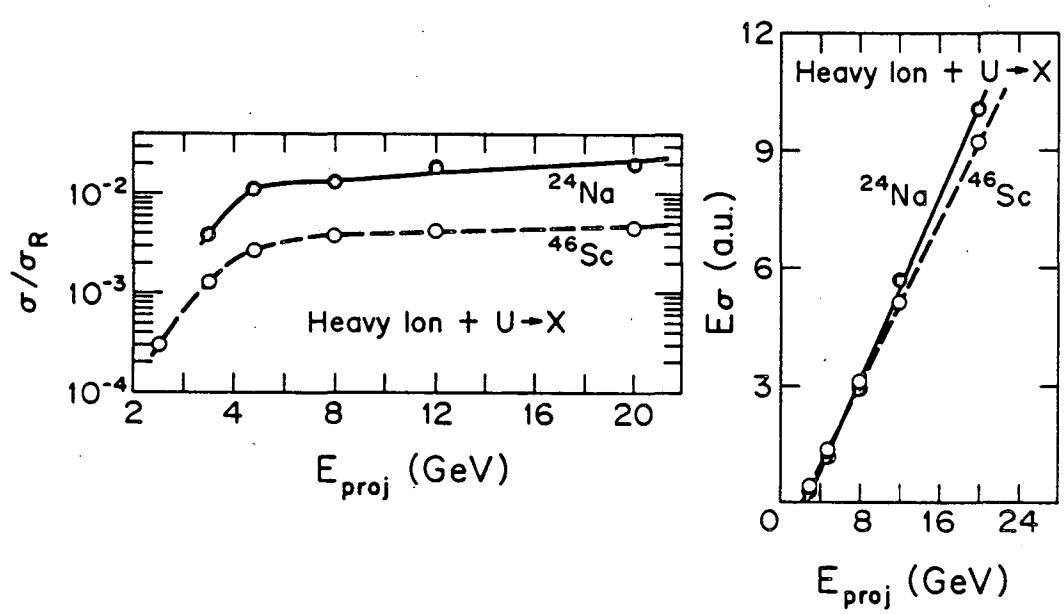

Figure 3.

(a) Excitation function for the production of 2 typical light fragments from the interaction of C and Ne with U. (b) Same data as (a) replotted to illustrate a simple functional form of the excitation function. Data from ref. 10.

to have fragment multiplicities greater than 1 and the process giving rise to these events is called "multi-fragmentation." Excitation functions for the production of these fragments can be parameterized in a simple manner (Figure 3) and show the threshold for the production of these fragments in light nucleus-heavy nucleus collisions to be ∿2-3 GeV. Firestreak model calculations of the maximum excitation energy of A = 200-240 nuclei after interaction with 2-3 GeV C ions show E_{max}^{*} ∿ 600-700 MeV, i.e., about 3 MeV/A, an estimate in agreement with theoretical estimates[11] of the excitation energy threshold for multifragmentation.

If we extend these measurements of light fragment excitation functions into the intermediate energy regime (Figure 4), we see evidence for a qualitatively different behavior of the light fragment excitation function at the lower energies in nucleus-nucleus collisions, indicative of a different mechanism for the production of light fragments. This finding is consistent with the observation of Lynen et al.[12] that the production of these fragments in intermediate energy reactions is a binary process rather than a multi-body breakup as observed at higher energies.

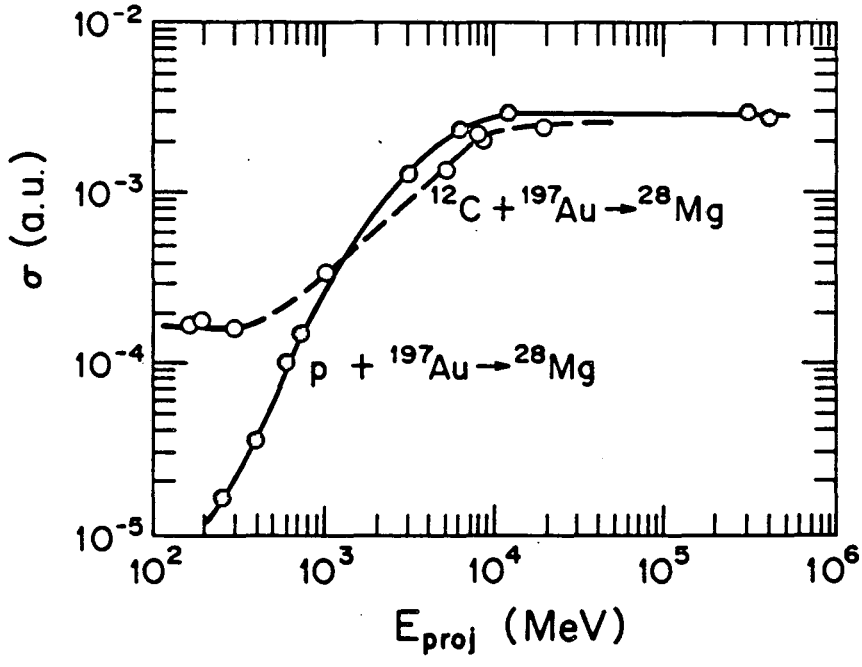

Figure 4

Excitation functions for the production of a typical light fragment, ^{28}Mg, in the interaction of ^{12}C and ^{1}H with ^{197}Au. The p + ^{197}Au data is from ref. 13.

The mechanism for the production of these light fragments in the intermediate energy region is discussed further in Section 3.

2.4 COMPARISON WITH PHENOMENOLOGICAL MODELS

Although there have been several promising beginnings[14] to developing a phenomenological model capable of treating intermediate energy heavy ion reactions, there is, at present, no appropriate phenomenological model for target fragmentation in this energy region. Therefore, we have chosen to compare our experimental measurements with two different phenomenological models (appropriate for projectile energies either less than or greater than those used in this work) in hopes of discerning just what new physical features characterize intermediate energy target fragmentation.

Lower energy (< 10 A MeV) incomplete fusion reactions have been shown to be well-described by the generalized sum-rule model.[15] In this model, incomplete fusion reactions are described as binary reactions that are localized in l-space near the critical angular momentum for the complete fusion of the transferred cluster with the target nucleus. The transfer cross sections are also governed by phase space considerations given by the optimum Q value relation of Siemens et al.[16] (The implementation of this model for treating target fragmentation is given in ref. 1.)

At higher projectile energies (>250 A MeV), the interactions are well represented by the traditional "participant-spectator" picture. One particularly successful phenomenological model employing this picture is the nuclear firestreak model.[17] In this model, the interaction between colliding nuclei is localized to the overlap region, where co-linear tubes of nuclear matter from the target and projectile are assumed to undergo completely inelastic collisions (governed by an empirical transparency function). After two tubes have collided, they are assumed to fuse and equilibrate their kinetic and thermal energies. If the resulting kinetic energy of a fused tube is less than its binding energy in the target remnant, then it is captured and contributes to the remnant's energy, mass and momentum. (Thus both the sum-rule and firestreak models have a localized region of impact parameters leading to a given mass transfer).

In figure 5a, we compare the predictions of these two phenomenological models with the data of figure 1. As expected, the sum rule model generally describes the shape of the isobaric distribution at a projectile energy of 8.5 A MeV (apart from a small peak at A = 155 which, in the model, is due to α-transfer reactions). The data at 19 A MeV are qualitatively described but as the projectile energy increases, the model fails to account for the observed broadening of the isobaric yield distribution. This failure of

the sum-rule model is due to the overestimation of the complete fusion cross section at the higher projectile energies. As a consequence the model overestimates the extent of complete fusion, underestimates incomplete fusion and predicts a narrower isobaric distribution. The complete fusion cross section decreases faster than the $(\lambda)^{-2}$ dependence assumed in the sum rule model.

The firestreak model suffers from a similar difficulty. For example, the peak in the predicted distribution (Fig. 5, 86 A MeV ^{12}C + ^{154}Sm) at A ∿ 114 (which is <u>not</u> observed) is due to the de-excitation of the quasi-compound nucleus. (In the same distribution, the overestimate of the yields of fragments of high A shows that this model also does a poor job of predicting small mass transfers) .

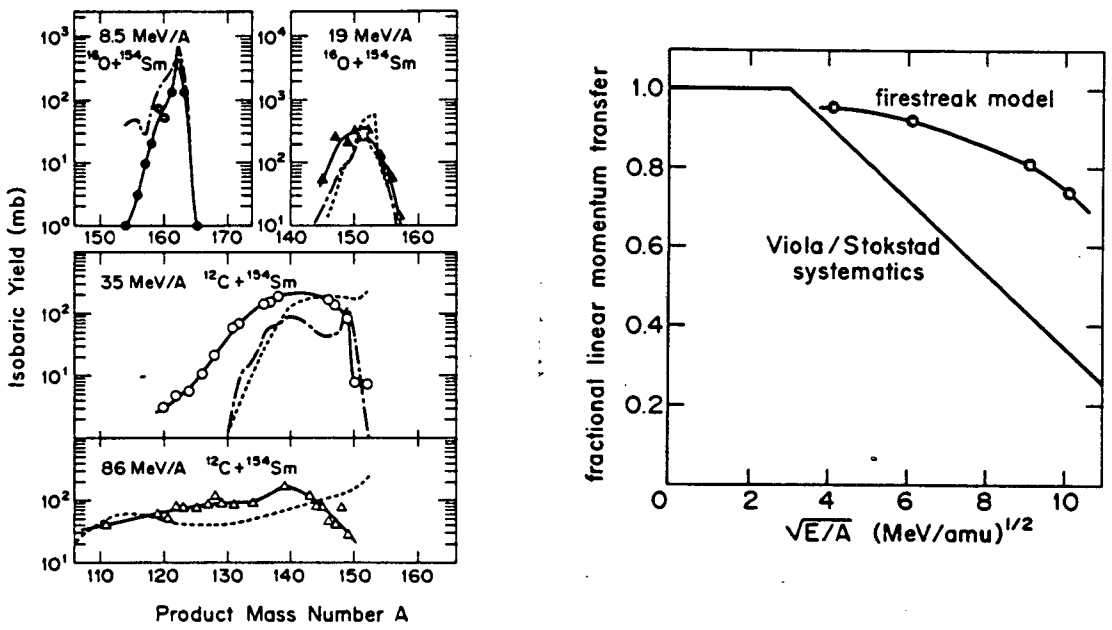

Figure 5

(a) Comparison of the measured isobaric yield distributions (solid line) with those predicted by the sum rule model (long-line-dash curve) and the firestreak model (dashed curve) (b) comparison of the known systematics (ref. 7) of fractional linear momentum transfer in intermediate energy heavy ion reactions with the predictions of the firestreak model.

This overestimate of complete fusion is shown most clearly in figure 5b where the measured fractional linear momentum transfer in intermediate energy reactions is shown to be far less than that predicted by the firestreak model. Among the physical phenomena that could account for the deficiencies in these models is the existence of qualitative changes in the nuclear transparency in this energy region not reflected in either model and/or substantial pre-equilibrium emission.

3. TARGET FRAGMENT ANGULAR DISTRIBUTIONS

One can show that for any moderate or highly excited, long-lived, intermediate species the angular distribution of emitted particles (or break-up products) in the frame moving with the velocity of the intermediate species must be symmetric about a plane normal to the direction of motion of the intermediate system. By the term "long-lived", we mean that the intermediate species lives long enough that the statistical assumption concerning level densities is valid, i.e., a statistically large number of overlapping levels with randomly distributed phases is populated so that interferences between them will cancel. In addition to this fundamental relationship of the fragment angular distribution and a gross measure of the time scale of the reaction, the angular distributions are also useful in defining certain features of the reaction mechanisms. With these ideas in mind, we wish to examine the results of measuring the angular distributions of 48 different target fragments[18] in the interaction of intermediate energy (85 A MeV) ^{12}C with ^{238}U and 78 different fragments[19] from the 84 A MeV ^{12}C + ^{197}Au reaction.

For these reactions, the isobaric yield distributions have been measured.[3,10]

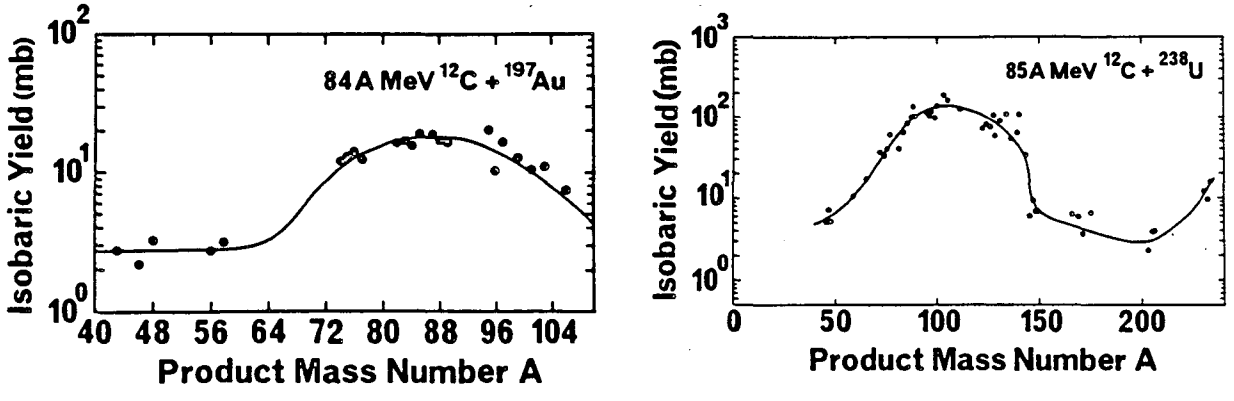

Figure 6

Target fragment isobaric yield distributions for the interaction of 84-85 A MeV ^{12}C with ^{197}Au (ref. 3) and ^{238}U (ref. 10).

In both reaction systems, there is a significant probability for fission with the fission peak in the yield distribution being much broader for the U system. For the reaction with ^{197}Au, the fragments with $40 \leq A \leq 50$ are not part of the fission peak while they do appear so for the ^{238}U reaction system. Similarly the fragments with $A \sim 150$ appear to be part of the fission product distribution for the U reaction system, while they are typical "spallation" products for the ^{197}Au system.[3]

Representative laboratory frame angular distributions are shown in Figure 7. For the ^{197}Au reaction system, the typical light fragment (^{46}Sc) has a strongly forward-peaked distribution with a lesser but discernible backward peak. The typical fission fragment (^{83}Rb) distribution is less forward-peaked than the light fragment distribution but has a roughly similar shape. The heavy fragment distribution (^{169}Yb) is very strongly forward-peaked. For the ^{238}U reaction system, the angular distributions are less forward-peaked than for the ^{197}Au reaction system, consistent with previous observations[12] of lower momentum transfer in U target fragmentation. The small backward peaks observed in the Au target fragment distributions are absent in the U target fragment distributions.

These laboratory frame angular distributions were transformed into the moving frame of the target residue following the initial projectile-nucleus encounter (Fig. 8) The parameter $\eta_{||} = (v_{||}/V)$ used to make the transformation

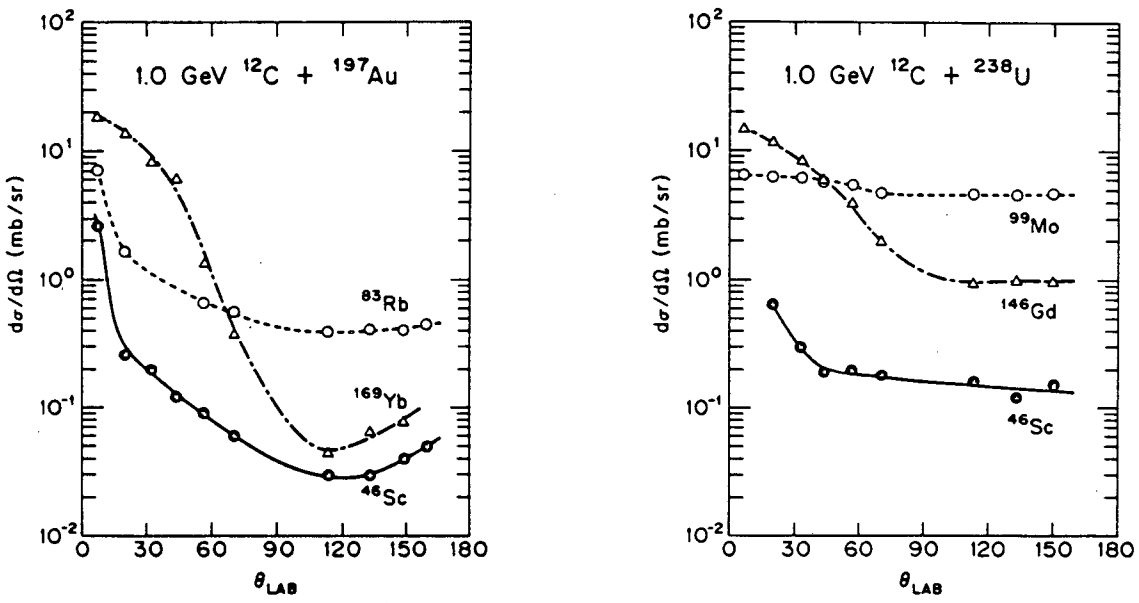

Figure 7

Representative target fragment laboratory frame angular distributions for the reaction of 85 A MeV ^{12}C with ^{197}Au and ^{238}U. (Ref. 18, 19).

(where $V_{||}$ is the longitudinal velocity of the moving frame and V is the velocity of the fragment in the moving frame) was determined in two ways (which gave the same answer within experimental uncertainties): (a) from moving source fits to measured fragment velocity spectra (b) from integrating the angular distributions to give F and B, the fraction of fragments recoiling forward and backward from the target ($\eta_{||}$ = (F-B)/(F+B)).

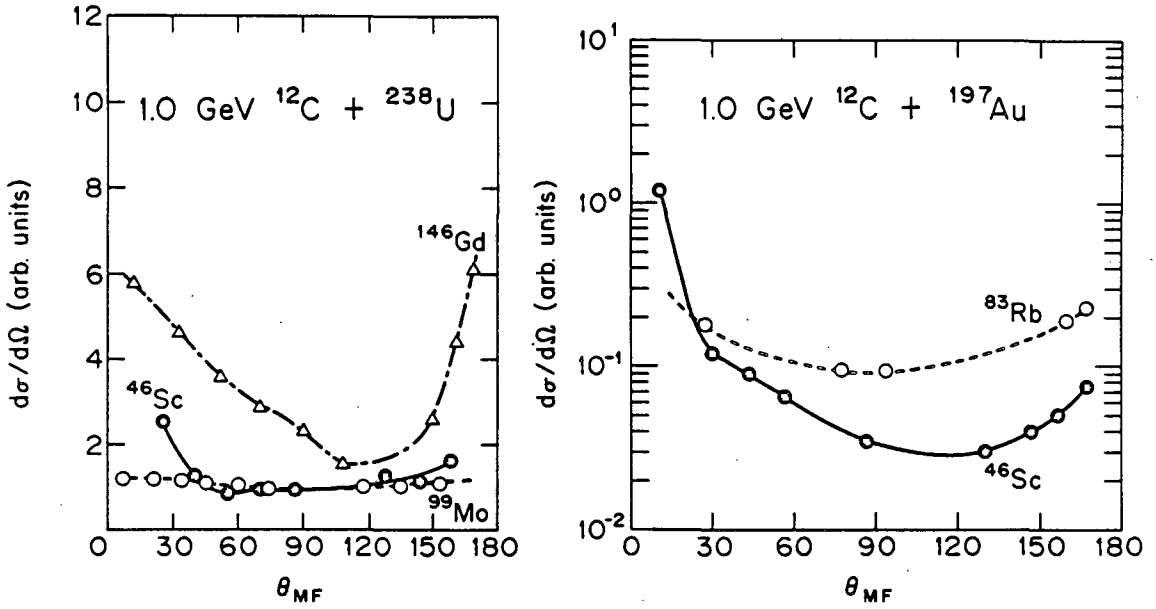

Figure 8.

Moving frame angular distributions for the fragments shown in figure 7.

The resulting "normal" fission fragment distributions are symmetric about 90° in the moving frame, indicative of a "slow" process in which statistical equilibrium has been established. The light fragment distributions are asymmetric in the moving frame indicative of their production in a "fast" process without the establishment of statistical equilibrium. (This latter conclusion was investigated further by varying the value of $\eta_{||}$, the transformation parameter, and by using a distribution of $\eta_{||}$ values to make the transformation rather than a single value. In no case was it possible to symmetrize the light fragment moving frame distribution). For the Au reaction system, it was not possible to find a moving frame in which the heaviest fragment distributions were symmetric about 90°, but for many cases, the range of moving frame velocities included values that were so large as to cause ambiguous, double-valued results for the lab to moving frame transformation. In these cases, the transformations could not be made and no definitive conclusion could be reached about the symmetry

of the moving frame distributions. However, for the U reaction system, because of the lower initial transferred momentum, no such ambiguities exist. For the U reaction system the heaviest fragments (A = 139-169) had moving frame distributions that were asymmetric, indicative of a "fast" production mechanism.

In view of the observation of Lynen et al.[12] that the production of light fragments was a binary process at these projectile energies, we thought it would be interesting to see if we could find, amongst our data, the heavy fragment complements to these light fragments. For the Au reaction system, we were unable to find any evidence for the existence of these complementary fragments because of the large yield of heavy fragments from spallation processes which "masked" the low probability events in which light fragments/heavy fragment complements were produced.

With the U target, the situation is different. The target fragments that can be clearly identified with spallation-like processes appear to be restricted to A > 200 (fig. 6). In fact, we show (in figure 9) the general similarity between the ^{146}Gd moving frame distribution and the calculated distribution for the complementary fragment to ^{46}Sc. It would be indeed fortuitous in an experiment such as we have performed to find among the half dozen or so heavy fragments, whose angular distribution we have measured, the exact kinematic complement of light fragment distribution. Furthermore a single-particle inclusive experiment such as this is not the best way to look for kinematic complementarity. Nonetheless, the similarity between the ^{146}Gd distribution and the calculated "^{46}Sc-complement" distribution is quite striking. Further support for this idea is seen in Figure 6 where we show the A = 46 and A = 146 fragments to occupy approximately complementary positions in the fission-like portion of the mass yield curve, and the $\eta_{||}$ values of A ∿50 and A ∿150 fragments which are consistent with complementarity.

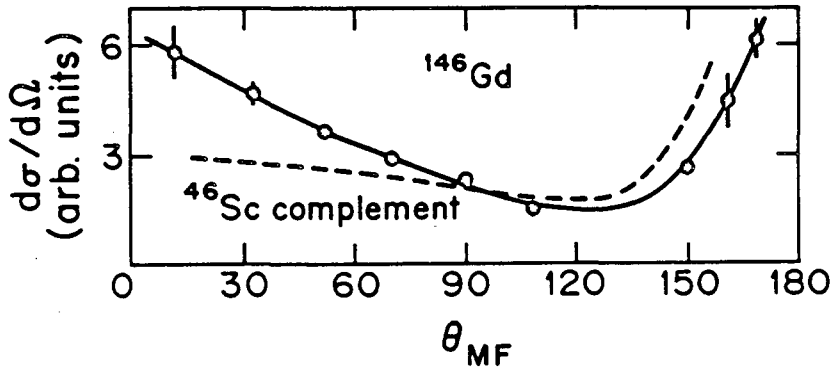

Figure 9
A comparison of the ^{146}Gd fragment moving frame angular distribution and that calculated for the heavy fragment complement of ^{46}Sc. The reaction is 85 A MeV ^{12}C + ^{238}U.

Therefore we conclude that due to: a) the apparent complementarity of A ∿46 and A ∿146 in the mass-yield curve, b) the similarity between the shapes of the ^{146}Gd moving frame distribution and that for the heavy fragment complement of ^{49}Sc and c) the fact that the $\eta_{||}$ values for A ∿50 and A ∿150 are consistent with complementarity, it is plausible (but not proven) that these fragments are kinematic complements.

Thus it becomes interesting to speculate that we may have observed a new intermediate energy heavy ion reaction mechanism, a "fast", non-equilibrium, very asymmetric fission. (The actual process could very well be characterized by a very broad symmetric mass distribution that is "hidden" under the more abundant "normal" fission distribution and only becomes visible to us in the low and high mass tails of the distribution).

Two fission processes with "fast" characteristics have been noted as occurring in different energy regimes. At lower projectile energies, a number of observers have reported a significant increase in the width of the fission mass distribution when the angular momentum of the projectile-target composite system exceeds the rotating liquid model limit, i.e., when the fission barrier becomes zero due to angular momentum. Current theories[20] of this "fast fission" process point to a system where the total interaction potential has a pocket ($Z_1 \cdot Z_2 < 2500$-3000) and $\ell_{Bf} \leq \ell \leq \ell_{crit}$ where ℓ_{crit} is the critical angular momentum for fusion. While the first condition ($Z_1 \cdot Z_2 < 2500$) is satisfied in the reaction under study; the second is not[6] in that $\ell_{crit} = 61\hbar$ while $\ell_{Bf} = 78\hbar$. Thus there are no "bound" partial waves that exceed ℓ_{Bf}.

If A ∿ 46 and A ∿ 146 fragments are complementary fragments, then a large amount of mass has been "lost" from the system in the fission process without disturbing the two body kinematics. Similar types of "fast" fission processes with large mass loss prior to fission and broad mass distributions have been observed in high energy p-nucleus collisions.[21, 22] In these events, the fission fragment kinetic energies were observed to be larger than those expected for fission. But these fragments were also observed to have large transverse momentum and be preferentially emitted at 90° to the beam axis, a condition not observed in our studies.

Thus we conclude that our results are suggestive of a new intermediate energy reaction process, a fast, non-equilibrium, binary division of the nucleus unlike processes seen at lower or higher projectile energies. The process is apparently accompanied by a large mass loss. Since the interaction potential has pockets for partial waves up to $\ell = 61$, and the "normal" fission involves lower partial waves, (based on previous estimates of the mean J

of the fissioning system to be 25-35ħ) one is further tempted to associate this process with the higher "bound" partial waves.

4. SUMMARY

What have we learned about the general nature of target fragmentation in intermediate energy (10-100 A MeV) nucleus-nucleus collisions? Among the answers to this question are the following statements:

(1) There is an evolution of target fragmentation mechanisms with increasing projectile energy with complete fusion being replaced by incomplete fusion and eventually spallation and fragmentation.

(2) Fission becomes less important as a reaction exit channel as the projectile energy increases. In the case of a Ho fissioning system, this decrease in fission probability appears to be due to a decreasing transferred angular momentum while in the case of Au fissioning systems, the dominant effect is one of a decreasing excitation energy.

(3) There is not a good phenomenological model whose predictions explain the observations. Both the "low energy" sum rule model and the "high energy" firestreak model fail to explain the observed data due, in part, to an overestimate of the number of events in which the projectile is stopped in the target.

(4) The production of light ($A < 60$) fragments from heavy targets ($A \sim 200$) is a "fast" process without the establishment of statistical equilibrium.

(5) For the 85 A MeV $^{12}C + ^{238}U$ reaction, evidence is presented for the possible occurrence of a new "fast fission" mechanism.

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