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Publication Date
1982-05-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters

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May 1982

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

TARGET FRAGMENTATION AT INTERMEDIATE ENERGIES

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ABSTRACT

Target fragment yields and average momenta have been measured in recoil studies of the reaction of 12-84 MeV/u heavy ions with ^{197}Au. By comparison with other data, we find that the F/B ratios peak at ∿1 GeV total projectile kinetic energy. Fission-like events arise from a nearly constant excitation energy process for beam energies of 45-400 MeV/u while light fragment yields increase linearly with beam energy or momentum.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

In recent years there has been increasing interest in studying the evolution of nuclear heavy ion reaction mechanisms as the projectile energy increases from low ($\lesssim$ 10 MeV/u) to relativistic ($\sim$ 1 GeV/u) energies. Studies of projectile fragmentation have shown the onset of this phenomenon for projectile energies less than 20 MeV/u[1] with little observable difference[2,3,4] in the fragment yields at 42 and 2100 MeV/u. In this paper, we report measurements characterizing Au target fragmentation in the projectile energy range from 12-84 MeV/u, and by comparison with similar data for 380-2100 MeV/u heavy ion induced reactions, we can characterize the evolution of target fragmentation over a larger energy range. We observe a similarity in target fragmentation mechanisms from 45-2100 MeV/u and a difference between these mechanisms and those operating at 12-18 MeV/u. Furthermore, we see that the characteristics of target fragmentation appear to be governed by the total projectile kinetic energy over the range of 45-2100 MeV/u, thus extending earlier observations[5,6] at 400-2100 MeV/u.

The fission-like events, resulting in fragments with A = 80-120 from the Au target, appear to involve primary products whose excitation energy is relatively constant for the projectile energy range 45-400 MeV/u. The light fragment (A < 50) yields increase linearly with beam energy from 45-2100 MeV/u.

We have measured the target fragment yields and recoil properties (from which we deduced average fragment energies and momenta) for the interaction of 12.0 and 18.4 MeV/u ^{16}O and 45.4 and 83.8 MeV/u ^{12}C with ^{197}Au. The ^{16}O experiments were carried out at the LBL 88" cyclotron and the ^{12}C experiments were done using the CERN SC synchrocyclotron.

(The 45 MeV/u beam was obtained by degrading the primary beam). The radiochemical techniques used for the measurements of fragment yields[7] and recoil properties[8] were similar to those described previously. Target fragment radionuclides were assayed by off-line γ-ray spectroscopy. The Winsberg version[9] of the two-step vector model was used to deduce average fragment energies and momenta from the measured recoil properties.

A range-weighted measure of the extent of forward peaking of the fragment angular distributions is their F/B ratio, the ratio of the fraction of target fragments recoiling forward (F) from a thick target to the fraction of fragments recoiling backward (B). The F/B ratios for a typical high mass (^{167}Tm), intermediate mass (^{145}Eu), medium mass (^{74}As, ^{96}Tc) and light mass (^{46}Sc) fragments from the reaction of energetic heavy ions with ^{197}Au increase with increasing total projectile kinetic energy below $\sim$ 1 GeV and then decrease with further increases in the total projectile kinetic energy (Figure 1a). This behavior is qualitatively similar to that observed[11] in the interaction of energetic protons of the same total kinetic energy with ^{197}Au (Figure 1b) although the momentum transfer is 2-4x larger for a given fragment in the heavy ion reaction. If the physics of p-nucleus and nucleus-nucleus target fragmentation is similar, the emission of highly excited hadrons in the forward direction[12] does not explain the decrease in F/B with increasing projectile energy because at the velocities used in the heavy ion studies, such effects are negligible. Further experiments that measure the changes in transverse fragment momentum and the possible emission of forward going jets of nuclear matter in these collisions as a function of projectile energy might be useful.

The two-step model[9] was used to deduce values of p_{11}, the longitudinal component of the momentum transferred to the target fragment in the initial projectile-target interaction. As an aid to understanding the variation of p_{11} with fragment mass and projectile energy, let us define a parameter called the "inelasticity" as the ratio (expressed as a percentage) of the measured longitudinal velocity, v_{11} ($= \frac{p_{11}}{Af}$) to the maximum velocity that could be imparted to that fragment, the velocity of the hypothetical compound nucleus, v_{CN}. The variation of inelasticity with fragment mass and projectile energy is shown in Figure 2. One is immediately struck by the large momentum transfers occurring in the interaction of 45 and 84 MeV/u ^{12}C with ^{197}Au. The variation of inelasticity with fragment mass number appears to be similar from 45-2100 MeV/u suggesting a basic similarity in reaction mechanisms, but is different at 12 and 18 MeV/u, suggesting different mechanisms are operating.

The constancy of the inelasticity with fragment mass number (for $80 \leq A \leq 120$ with E_{proj} = 45-400 MeV/u) suggests a single origin for these fragments, an idea supported by the yield distributions at the two lowest energies which show these fragments to be part of a single continuous fission fragment-like bump. Masuda and Uchiyama[13] have shown in the context of a two step kinematic model that the recoil momentum of the target fragment, p_{11}, is given by

$$\langle p_{11} \rangle \approx \frac{(\gamma E_T^* + E_B^*)}{\beta\gamma} \qquad (1)$$

where β is the beam velocity, $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$ and E_T^* and E_B^* the respective excitations of target and beam nuclei. If we assume, in the absence of other information, that $E_B^* = 0$ MeV, then the values of E_T^* deduced for nuclei with A = 80 - 120 for E_{proj} = 45-400 MeV/u are roughly independent of E_{proj} and have the value of 292 ± 6 MeV. Other common assumptions about E_B* (E_B* = E_T*, E_B* = constant (0)) lead to similar conclusions with different values of E_T*. All of the above arguments support the conclusion that the fragments with A = 80 - 120 arise from a single, fission-like constant E* process which doesn't change with E_{proj} = 45 - 400 MeV/u. For the highest projectile energy (2100 MeV/u), the products in this region probably arise from both fission and deep spallation and thus there is a greater variation of inelasticity with fragment mass.

The yields of the lightest fragments (A < 50) increase linearly, in a statistically significant manner, with either the total projectile kinetic energy or total projectile momentum for 45-2100 MeV/u projectiles. Heckman has shown[6] that the momenta of the fragments with A ≲ 80 can be written as

$$p_{11} = \text{constant} \qquad (2)$$

where the constant is 420 and 45 MeV/c for reactions induced by projectiles of energy ∿ 8 GeV and 25 GeV, respectively. We confirm that equation (2) describes the data for projectiles of 45 and 84 MeV/u with the values of the constants being 684 ± 53 and 648 ± 34, respectively, thus extending the range of applicability of Heckman's correlation for heavy ion reactions by a factor of 9 in total projectile kinetic energy.

In summary, we find target fragmentation induced by heavy ions of energies ≥ 45 MeV/u to be mechanistically similar. The fission-like events arise from a single process whose characteristics appear to be largely invariant with respect to beam energy from 45-400 MeV/u. The light fragments appear to originate from another type of event in which large momentum (energy) is deposited in the nucleus.

We acknowledge the assistance of T. Lund in using the CERN irradiation facilities and R.J. Otto in making the measurements at LBL. The help of the health physics and operations staff of the LBL 88" cyclotron and the CERN SC synchrocyclotron is gratefully acknowledged. This work was supported in part by the U.S. Dept. of Energy and the Swedish Natural Science Research Council.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

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Figure Captions

Figure 1. The variation of F/B for selected products from the reaction of a) heavy ions with Au b) protons with Au (Ref. 11). The data for heavy ion projectile energies $\geq$ 4800 MeV are from Ref. 10.

Figure 2. Variation of inelasticity with product mass number for reactions of heavy ions with Au. The data for the three highest energies are from Ref. 10.

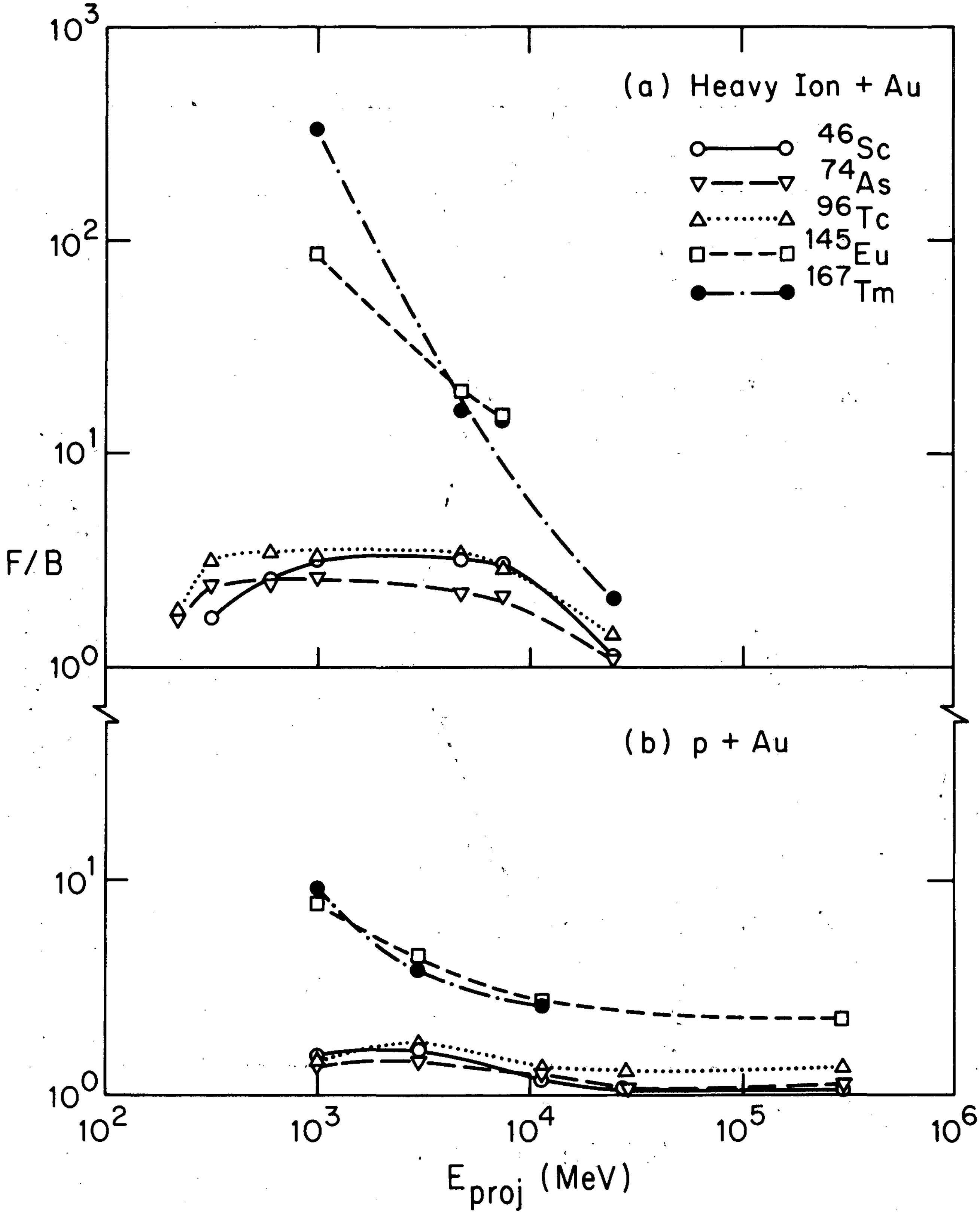
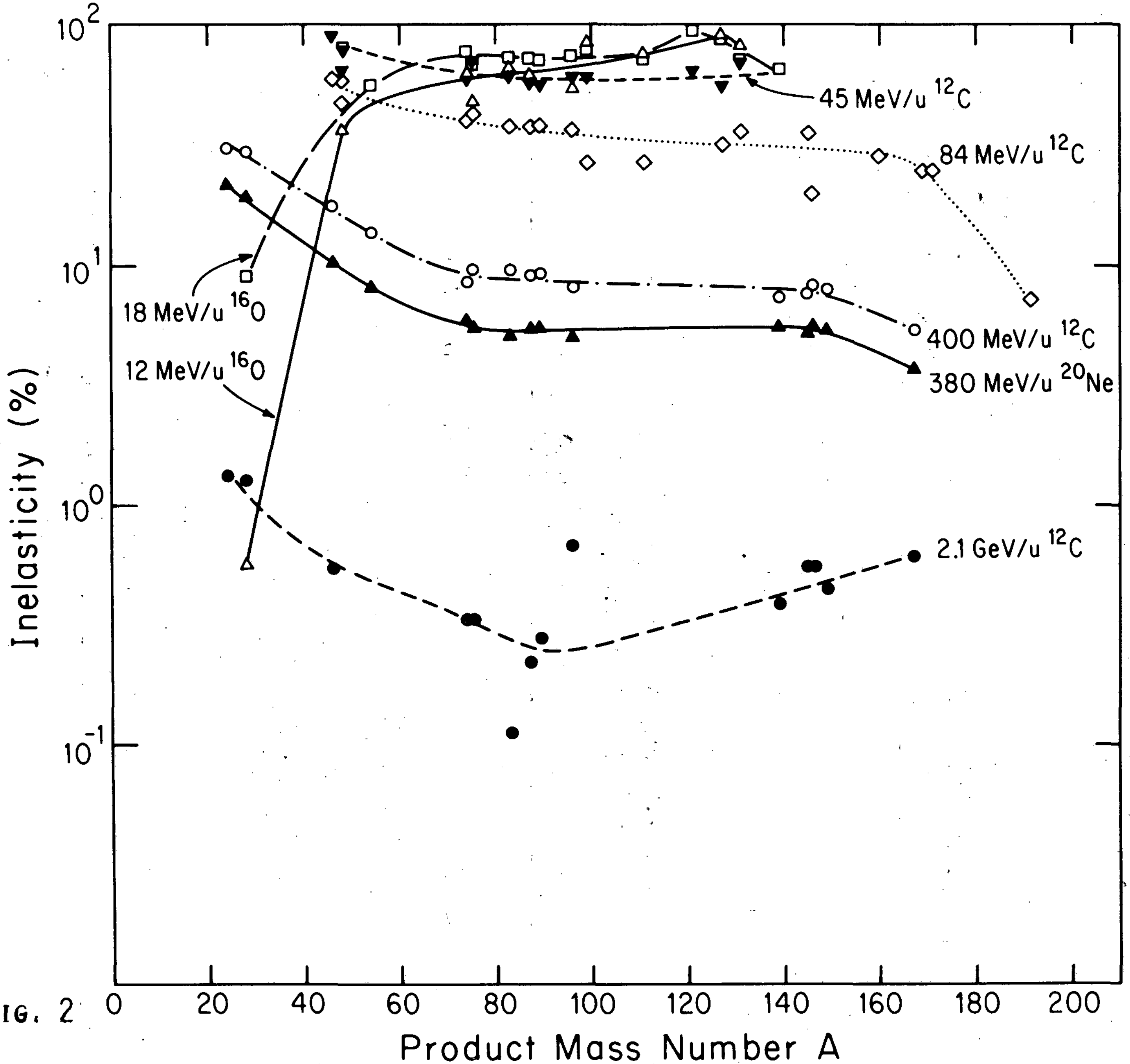

(a) Heavy Ion + Au
46Sc
74As
96Tc
145Eu
167Tm
(b) p + Au
F/B
10^3
10^2
10^1
10^0
10^1
10^0
10^2
10^3
10^4
10^5
10^6
E_{proj} (MeV)

FIG. 1



Inelasticity (%)
Product Mass Number A
45 MeV/u 12C
84 MeV/u 12C
18 MeV/u 16O
12 MeV/u 16O
400 MeV/u 12C
380 MeV/u 20Ne
2.1 GeV/u 12C

FIG. 2

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