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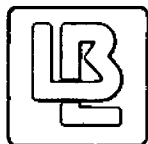
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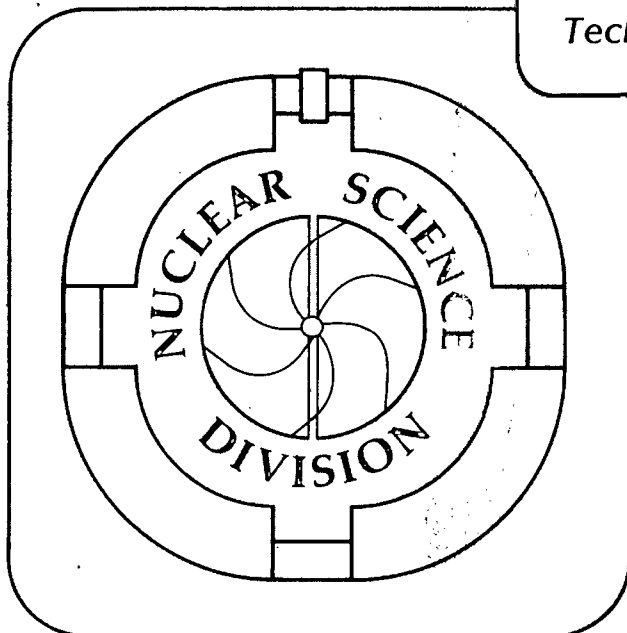
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TARGET FRAGMENTATION FROM 10 - 2100 MeV/ μ

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Abstract

The target fragment momenta were deduced from recoil properties measured for the interaction of 13 - 86 MeV/ μ heavy ions with ^{197}Au and compared to published higher energy data. The F/B ratios peak at ~ 1 GeV total projectile kinetic energy. At projectile energies of 50 - 86 MeV/ μ , 30 - 100% of the projectile momentum is transferred to the target fragments, depending on collision impact parameter. The projectile energy dependence of the target fragment longitudinal momentum, p_{11} , obeys the relationship $p_{11} = a + b \sqrt{1 - \beta^2}$ (β is projectile velocity in units of c) from 50 - 2100 MeV/ μ .

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In recent years there has been increasing interest in studying how the mechanism(s) in nuclear heavy ion reactions change as the projectile energy increases from low (~ 10 MeV/ μ) energies to relativistic (2100 MeV/ μ) energies. We thought that it would be valuable to use a single set of experimental techniques (radiochemical measurements of target fragment average energies and momenta) to characterize the changes in target fragmentation over this projectile energy regime. Accordingly, in this paper we compare the results of radiochemical measurements of target fragmentation in the reaction of ^{12}C , ^{16}O , and ^{20}Ne with ^{197}Au at seven different projectile energies from 13 - 2100 MeV/ μ . We report new data from studies of reactions induced by projectiles whose energies ranged from 13 - 86 MeV/ μ , showing unusually large momentum transfers to the target fragments. At the lower energies, our work complements that of Gelbke et al.¹ on projectile fragmentation and Dyer et al.² on target fragmentation, in which the target residue fissions. It is interesting to compare our data with that of Kaufman et al.³ who studied the interaction of 400 - 2100 MeV/ μ ^{12}C with ^{197}Au . The overall thrust of the combined data requires significant revision of our ideas on the energy evolution of nuclear heavy ion reactions.

As part of a larger general survey of heavy target fragmentation, we studied the interaction of 13 and 19 MeV/ μ ^{16}O with ^{197}Au , using the LBL 88-inch cyclotron, and the interaction of 50 and 86 MeV/ μ ^{12}C with ^{197}Au , using the SC synchrocyclotron at CERN. The 50 MeV/ μ beam was obtained by degrading the primary 86 MeV/ μ beam. We measured the thick target - thick catcher recoil properties of the fragments, from which we deduced average fragment momenta. The experimental techniques used have been described elsewhere.⁴

A range-weighted measure of the extent of forward-peaking of the fragment angular distributions is the 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 typical high mass (^{167}Tm), intermediate mass (^{146}Gd), medium mass (^{96}Tc), and light mass (^{46}Sc) fragments from the reaction of energetic heavy ions with ^{197}Au increase with total projectile kinetic energy until ~ 1 GeV and then decrease with further increases in the projectile energy (Figure 1a). It is interesting to note that this behavior is qualitatively similar to that observed⁵ in the interaction of energetic protons with ^{197}Au (Figure 1b). This decrease in F/B with increasing proton energy (for higher energies) has been qualitatively explained⁶ as a consequence of time dilation. In this explanation, one postulates that the interaction of the incident proton with a nucleon in the target nucleus results in an excited state of the proton whose lifetime in the laboratory frame will increase, due to time dilation, with increasing projectile energy. The increased lifetime leads to an increased probability of decay outside the nucleus or with small amounts of energy given to the nucleus. Thus the momentum of the struck target nucleus ($\propto \text{F/B}$) will decrease with increasing projectile energy. According to a model for this process suggested by Feshbach,⁶ this phenomenon becomes dominant at an incident projectile energy of ~ 7.5 GeV/ μ . If similar mechanism(s) are operating in heavy ion reactions as in proton-induced reactions (as suggested by Figure 1), the model suggested by Feshbach must be inapplicable because this process seems to occur at projectile energies of 86 MeV/ μ .

The two-step vector model⁷ was used to deduce values of p_{11} , the longitudinal component of the momentum transferred to the target frag-

ment 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 of the measured p_{11} value for a given fragment to the maximum momentum that could be imparted to that fragment: $p_{11}/(p_{cn} \times A_f/A_{cn})$. This is the momentum the fragment would receive when the projectile and target nuclei fused, followed by a breakup into that fragment. 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 0.6 and 1.0 GeV ^{12}C (50 and 86 MeV/ μ) with ^{197}Au . The magnitude of these momentum transfers indicates that the generalized critical angular momentum model⁸ does not correctly describe incomplete fusion at these energies since it predicts no significant momentum transfer to the target fragments can occur at projectile energies greater than ~ 20 MeV/ μ . The variation of inelasticity with product mass number appears to be different below 50 MeV/ μ as compared to the higher energies. The fragment inelasticities appear to vary smoothly and decrease continuously with projectile energy from 50 MeV/ μ to 2100 MeV/ μ , indicating a continuous evolution of reaction mechanism(s) in this energy regime.

If one examines the variation of the absolute value of p_{11} with projectile energy, one would find that p_{11} increases from ~ 10 to 20 MeV/ μ and decreases at higher energies. The actual decrease in p_{11} from 50 to 2100 MeV/ μ is described by a remarkably simple relationship:

$$p_{11} = a + b \sqrt{1 - \beta^2}$$

where a and b are constants and β is the projectile velocity in units of c (Figure 3). This relationship is valid (linear correlation coefficient $r > 0.95$) for all ten fragments from ^{24}Na to ^{149}Gd , where data are available at the five projectile energies used in Figure 3.

The constants a and b smoothly decrease and increase, respectively, with increasing fragment mass. The negative value of the intercept, a , implying preferential backwards emission of the fragments at the highest projectile energies, is consistent with the observed trends in proton-nucleus collisions.¹⁰ The catholic nature of this correlation, encompassing a wide range of projectile energies and fragment masses, is most puzzling. In the limit of high energies (where $(\beta_\gamma)^{-1} \simeq (1-\beta^2)^{\frac{1}{2}}$), the relationship is simply due to reaction kinematics,⁸ but the reasons for its validity at lower energies are not clear. While the assumption of a velocity-independent interaction time between projectile and target will cause a prediction of the $\sqrt{1-\beta^2}$ dependence of the fragment momentum, it is difficult to account for the negative value at the intercept, a .

We gratefully acknowledge the assistance of R.J. Otto in making the measurements at projectile energies of 13 - 19 MeV/ μ . One of us (PLM) gratefully acknowledges the support of CERN for the period of the experiments there, while KA and WL wish to thank their respective home institutions for overall support. This work was supported in part by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Dept. of Energy under Contract W-7405-ENG-48 and the Swedish Natural Research Council.

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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 and (b) protons with Au (Ref. 5). The data for heavy ion projectile energies ≥ 400 MeV/ μ are from Ref. 3. (XBL 818-1118)

Figure 2. Variation of inelasticity with product mass number for reactions of various heavy ions with Au. The data for the three highest energies are from Ref. 3. (XBL 818-1120)

Figure 3. Variation of p_{11} with $\sqrt{1-\beta^2}$ for typical light, medium, and intermediate mass products from heavy ion reactions with Au. β is the projectile velocity in units of c . (XBL 818-1119)

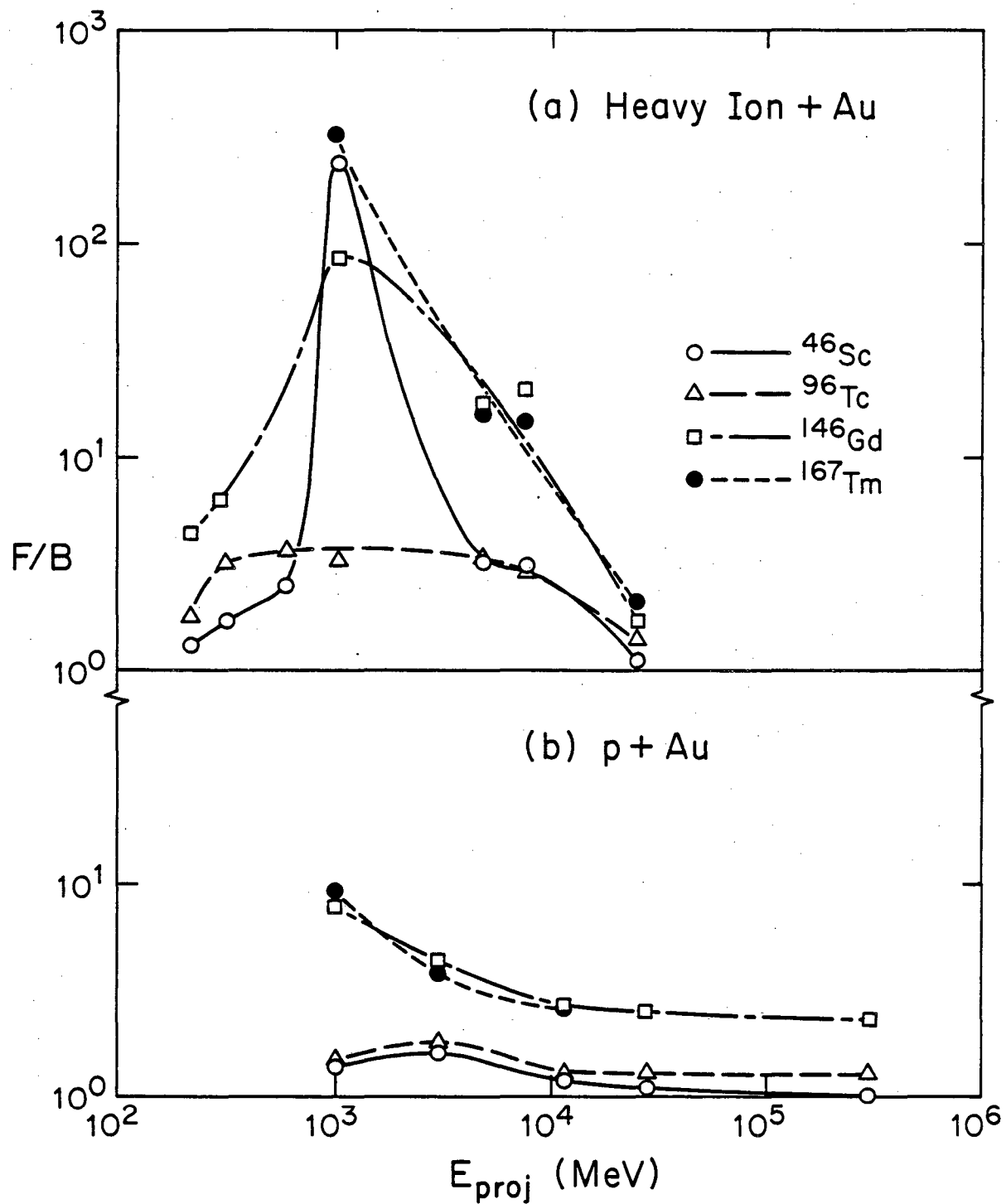


Figure 1

XBL 818-1118

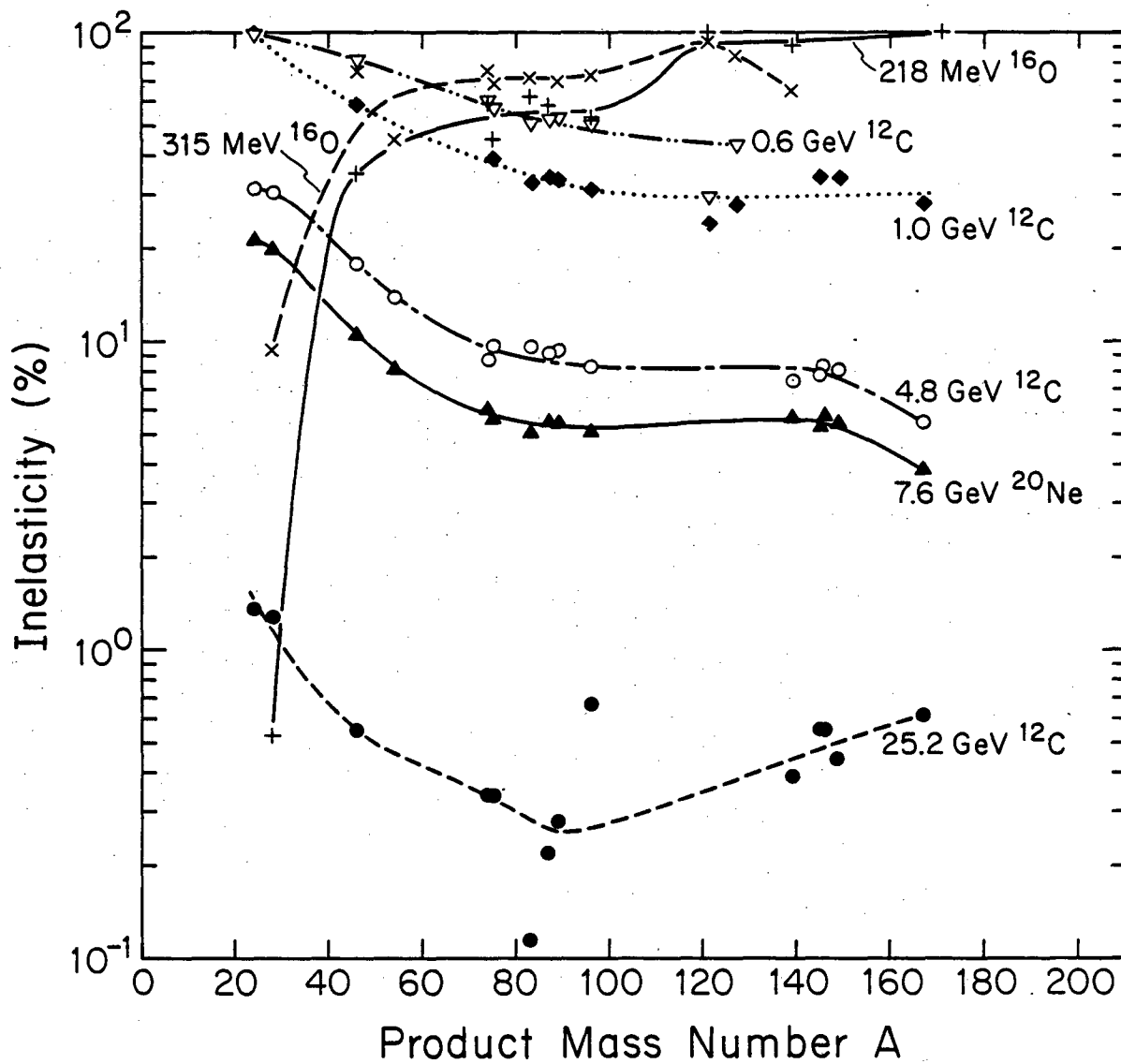


Figure 2

XBL 818-1120

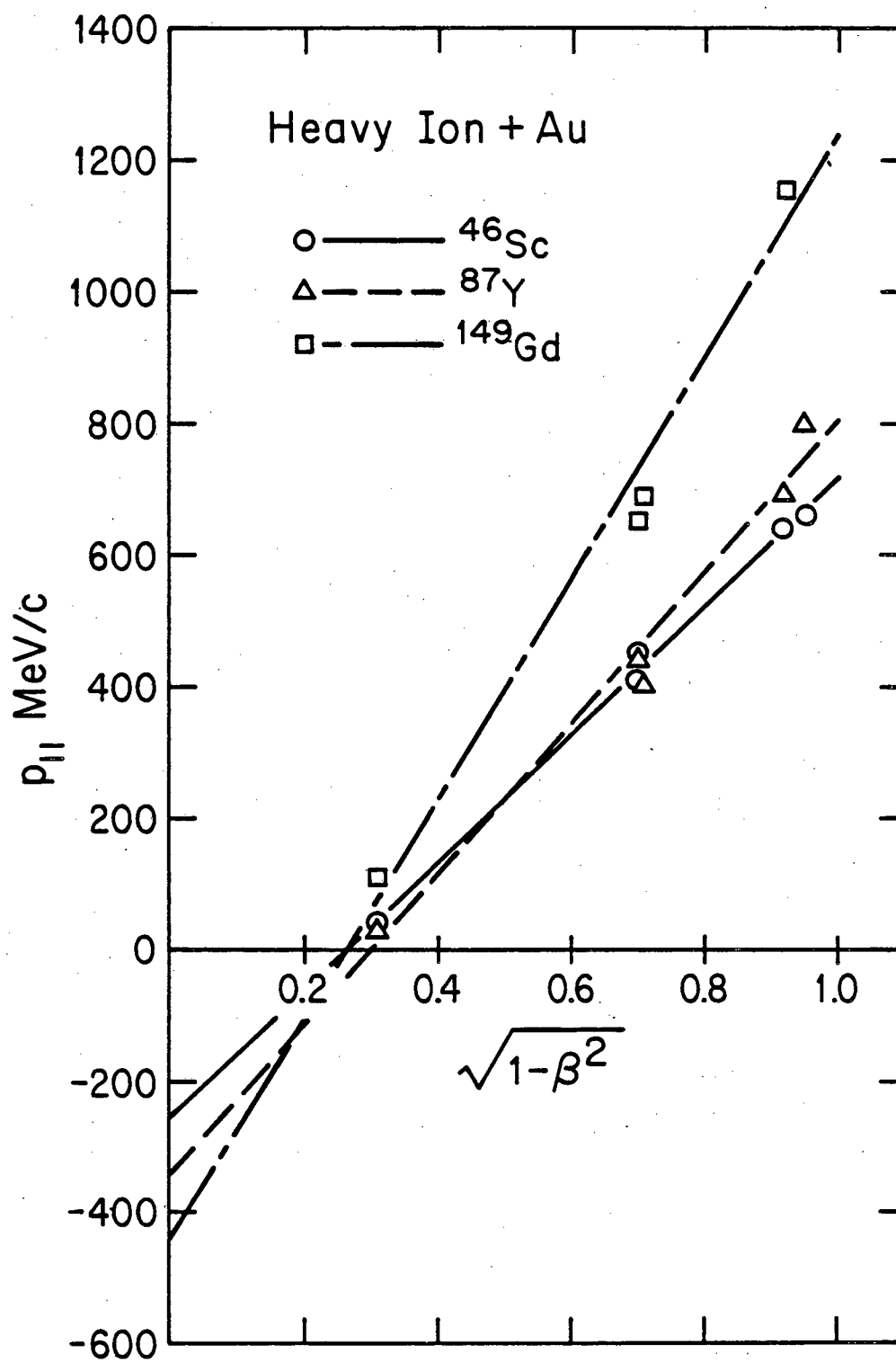


Figure 3

XBL 818-1119

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