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I. STATUS REPORT FOR EXP SC 87 JUNE 1982

STUDIES OF TARGET FRAGMENTATION AT INTERMEDIATE ENERGIES

Berkeley - Corvallis - Studsvik Collaboration

II. PROPOSAL FOR CONTINUATION OF THE PROGRAMME

STUDIES OF TARGET FRAGMENTATION AT INTERMEDIATE ENERGIES
Berkeley[1] - Corvallis[2] - Mainz[3] - Studsvik[4] Collaboration

III. NEW PROPOSAL

STUDIES OF PIONIC FUSION IN NUCLEAR COLLISIONS

Berkeley[1] - Corvallis[2] - Mainz[3] - Studsvik[4] Collaboration

K. Aleklett[4], J.V. Kratz[3], B. Kraus, Jr[2], W. Loveland[2],
P.L. McGaughey[1], K. Moody[1], Y. Morita[1], G. Rudstam[4], and
G.T. Seaborg[1].

1. Lawrence Berkeley Laboratory
Nuclear Science Division
Berkeley, California 94720, USA

2. Oregon State University
Department of Chemistry
Corvallis, Oregon 97331, USA

3. Johannes Gutenberg Universität Mainz
Institut für Kernchemie
Postfach 3980, Fritz-Strassmann Weg 2
D-6500 Mainz, Federal Republic of Germany

4. The Studsvik Science Research Laboratory
S-611 82 Nyköping
Sweden

Summary of Status Report and Proposals

I. So far we have used the following heavy ion beams for experiment at SC.

85 MeV/A ^{12}C: a) Target fragment mass distributions, forward momentum and average kinetic energy from the interaction with Ho, Ta, and Au. b) Target fragment angular distributions from the interaction with Au and U (in collaboration with ISOLDE) c) Target fragment differential energy distributions from the interaction with Au.

45 MeV/A ^{12}C (degraded beam): Target fragment mass distributions, forward momentum and average kinetic energy from the interaction with Ho, Ta, Au, and U.

107 MeV/A ^{16}O: Target fragment mass distributions, forward momentum and average kinetic energy from the interaction with Ho, Ta, Au, and U.

94 keV/A ^{20}Ne: Target fragment mass distributions, forward momentum and average kinetic energy from the interaction with Au.

In the status report we only discuss results from completed data analysis.

II. In the continuation of the program we wish to address three issues: (a) how do the mechanisms of target fragmentation change in the projectile energy region from 18-85 MeV/u, (b) can we understand the physics of why target fragmentation phenomena appear to scale with total projectile kinetic energy (or momentum) rather than projectile velocity, etc. (c) can we understand the mechanism of multi-nucleon "transfer" reactions leading to trans-target species at projectile energies greater than 25 MeV/u.

III. Finally we propose a new radiochemical experiment at SC: "Studies of pionic fusion in nuclear collisions". We like to begin our studies with the reaction ^{208}Pb (^{3}He,π^-)^{211}At with the beam energies 85 MeV/u $\geq E_{lab} \geq$ 45 MeV/u. The lower energies by degrading the 85 MeV/u beam.

I. STUDIES OF TARGET FRAGMENTATION AT INTERMEDIATE ENERGIES

1. Introduction

One interesting aspect of heavy ion reactions at intermediate energies is the target fragmentation process, i.e., the process in which large, low energy fragments of the target nucleus are produced. Our group has devoted its efforts to studying this process in heavy nuclei. The direct study of the properties of these "spectators" of the collisions can reveal characteristics of the nucleus-nucleus interaction (such as the energy, momentum and mass transfer to the target nucleus) not easily probed by other measurements. The experimental measurements of the target fragment yields, energies, momenta, angular distributions, etc. can be compared directly with predictions of theoretical models of these collisions, such as the intranuclear cascade model or various hydrodynamical models, and thus test various features of these models. The comparison of the features of target fragmentation in nucleus-nucleus collisions to similar aspects of the relatively well-studied target fragmentation in p-nucleus collisions can offer significant insights into the latter reactions.

2. Experimental Techniques

We have used traditional radiochemical techniques to make single particle inclusive measurements of the yields, average energies and momenta of fragments with $24 \leq A < A_{target}$ in the fragmentation of Ho, Ta, Au and U nuclei by heavy ions of energy 45-107 MeV/u. These techniques are well suited to detect these low energy (typically < 0.1 MeV/u) fragments, especially those with $A < 140$. The use of modern chemical techniques allows the characterization of the properties of some 100-150 target fragments in a single reaction providing a good statistical basis for the studies. The measurements can be grouped into three principal types: (a) the measurement of the yield of fragments of a given z and A (which can be integrated to give information about total reaction cross sections) (b) the measurement of target fragment recoil properties (from which one can deduce, using the two-step model, the average energies and momenta of the fragments of given z and A) and (c) the measurement of individual fragment angular distributions and energy spectra.

3. Accomplishments

The general goal of our research project has been the study of the evolution with increasing projectile energy of the reaction mechanisms involved in target fragmentation. If we combine our 1^+ years of experimentation at the CERN SC synchrocyclotron with our 4 years experience at other accelerators, we can report that we have measured the target fragment yields in 50 projectile-(projectile energy)-target systems encompassing projectile energies from 7-2100 MeV/u, projectiles from C to Ar, and targets from Ho to U. Limiting fragmentation is observed to describe the target fragment yields from 250-2100 MeV with little change being observed in the relative yields of different fragments with increasing projectile energy. However, we find this not to be the case in reactions induced by heavy ions of energy <100 MeV/u. At these lower energies the relative fragment yields differ significantly from those observed at higher energies. The measured yields in reactions induced by projectiles of energy 84-2100 MeV/u are in general agreement with predictions of the intranuclear cascade model, and, at the higher energies (>250 MeV/u) are also well-described by other models, such as the firestreak and abrasion-ablation model, probably indicating the dominating influence of collision geometry upon these yields at the higher energies. Interestingly enough, the heavy fragment yields in heavy-ion induced reactions are similar to those in reactions induced by protons of the same total projectile kinetic energy. While some detailed differences exist between the yields from nucleus-nucleus collisions and p-nucleus collisions, especially at energies <100 MeV/u, a heavy ion and a proton of equivalent total kinetic energy produce generally similar fragment yield distributions even at projectile energies such as 84 MeV/u where limiting fragmentation is no longer valid.

A further testimony to the usefulness of the total projectile kinetic energy as a scaling parameter for target fragment yields is the variation of the light (A<50) fragment yields with projectile energy (Figure 1). The yields of these fragments increase linearly, in a statistically significant manner, with total projectile kinetic energy (or within the uncertainty of the data, with total projectile momentum) for 45-2100 MeV/u projectiles.

We have found that the total reaction cross section (as measured by the radioactive residue yields) for heavy ion-heavy target reactions is roughly constant for projectile energies from 10 MeV/u to 2100 MeV/u (Figure 2). This result is in good agreement with microscopic model calculations of DeVries and Feng[1] as shown in Figure 2. The physical point, sometimes not realized in naive discussions of nuclear transparency, is that nuclear transparency effects are due to interactions taking place in the nuclear surface and in a heavy nucleus such as Ta surface reactions are not a major portion of the cross section.

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 1 GeV and then decrease with further increases in the total projectile kinetic energy (Figure 3a). This behaviour is qualitatively similar to that observed[2] in the interaction of energetic protons of the same total kinetic energy with ^{197}Au (Figure 3b) 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[3] 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.

The two-step model[4] 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}, 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 4. 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 $80<A<120$ with A_{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[5] have shown in the context of a two step kinematic model that the recoil momentum of the target fragment, p_{11}, is given by

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

where β is the beam velocity, $\gamma = (1-\beta^2)^{-1/2}$ 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.

Heckman[6] has shown that the momenta of the lightest fragments (A<80) can be written as

$$P_{11} = \text{constant}$$

where the constant is 420, 200, and 45 MeV/c for reactions induced by projectiles of energy 8 GeV, 4 GeV and 25 GeV, respectively. Using data gathered at the CERN SC cynchrocyclotron, we confirm that this relationship describes the data for projectiles of energy 45 and 84 MeV/u with the values of the constants being 684±53 and 648±34 MeV, 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.

II. PROPOSED CONTINUATION OF EXPERIMENTAL PROGRAM

Based upon the results described in Section 1 we would like to propose continuation and re-direction of our experimental program. We wish to address three issues: (a) how do the mechanisms of target fragmentation change in the projectile energy region from 18-45 MeV/u, (b) can we understand the physics of why target fragmentation phenomena appear to scale with total projectile kinetic energy (or momentum) rather than projectile velocity, etc. (c) can we understand the mechanism of multi-nucleon "transfer" reactions leading to trans-target species at projectile energies greater than 25 MeV/u. We shall discuss these questions independently, describing the proposed experiments and beam time requirements, although the results from one experiment may bear on answering another question.

Because of the apparent large change in target fragmentation mechanisms seen in the projectile energy range from 18-45 MeV/u (Figure 4), we wish to focus a portion of our present and future efforts to studying these changes using the CERN SC synchrocyclotron (and in a complementary program, the MSU superconducting cyclotron). Beams of these energies can be obtained at the SC machine by degrading the primary beam either directly in front of the ISOLDE irradiation facility of upstream from it with subsequent magnetic analysis to remove secondary particles from the beam. Our experiments with 45 MeV/u ^{12}C described previously were carried out using the former method and we have made some preliminary measurements using the latter method. (It would be helpful in this regard if some beam development work could be done to optimize the optics of this magnetic analysis system to improve the beam focus). Because of the freedom from secondary particles in the beam, the latter method of achieving lower energy beams is preferred. (An even better means, of course, would be the direct acceleration of lower energy heavy ion beams in the SC machine, a program whose goals we fervently support). As a method of attack upon the problem of learning more about the changes in target fragmentation in this energy region, <u>we propose to measure the target fragment yields, average energies and momenta (using recoil techniques) for the interaction of 25 and 35 MeV/u ^{12}C with Ta, Au and U, a group of heavy target nuclides of varying fissionability</u>. Special attention will be given to the low mass target fragments (A<40), possible products of a nuclear disassembly process, whose production mechanism seems to vary most drastically in this energy region. These measurements will require 2 shifts of beam time. Integration of the data from these measurements with the data discussed previously should give a more detailed picture of the evolution of target fragmentation mechanisms with projectile energy.

While information on <u>average</u> target fragment energies and momenta are useful in describing reaction mechanisms, a more useful (and more difficult) single particle inclusive measurement is that of the fragment angular distributions and energy spectra. Such measurements give model-independent kinematic information about the system under study. To gain further information about reaction mechanisms in the 18-45 MeV/u energy region, we propose to measure the fragment angular distributions and energy spectra for the interaction of 25 and 35 MeV/u ^{12}C with Au and U. This measurement should require 6 shifts of beam time. Based upon similar arguments, we have already begun the process of measuring fragment angular distributions and energy spectra for the interaction of 45 and 84 MeV/u ^{12}C with Au and U. The taking of data appears to be complete and analysis of data is in progress.

Another scientific issue we wish to address is that of "transfer" reactions. Upon first examination, the radiochemical study of transfer reactions induced by projectiles whose energy is > 25 MeV/u might seem futile, since any captured nucleons might be expected to deliver to the capturing system enough excitation energy to cause emission of more nucleons than were initially captured, producing target fragments whose z and A were similar to those of fragments produced by other processes. However, in the interaction of 20 and 86 MeV/u ^{12}C with heavy nuclei, several multi-nucleon transfer products were observed (Kudo, et al., Molzahn, et al.) and their yields measured. Apparently, large pieces of the incident projectile can be captured by the target nucleus and furhtermore, the excitation energy of the trans-target species can be dissipated without substantial loss of nucleons. We would like to further extend the studies of these "transfer" reactions using rare earth targets instead of heavy targets where the fission de-excitation of the primary reaction products can obscure the initial product distributions. While the measurement of the yields of the trans-target species is valuable, we feel that a deeper understanding of the reaction mechanism involved will come from knowing the product angular distributions and energies. Accordingly, we propose to measure the yields, energies and angular distributions of trans-target species produced in the interaction of 50 and 86 MeV

^{12}C with a neutron-rich, separated rare earth isotope either ^{160}Gd or ^{154}SM). The rare earth targets have been chosen so that transfers of ^{4}He or ^{8}Be will produce products whose radioactivity is easy to detect. This measurement is anticipated to require 6 shifts of beam time.

Perhaps one of the most puzzling findings with respect to target fragmentation has been the scaling of various characteristics of the reactions with total projectile energy. Despite some differences, there are amazing qualitative similarities between the outcome of reactions induced by protons, alpha particles, ^{12}C, etc. having the same total kinetic energy.

It is obvious that this scaling must be limited at the low energy end somewhere close to the Coulomb barrier. Comering from this low energy end it is an open question wether it is sufficient to provide excitation energies in excess of several hundred MeV for target fragmentation into A<50 fragments to occur or wether it is an additional requirement that this energy is rapidly deposited in the target for example with a projectile velocity exceeding the average Fermi velocity. In order to shed some lights on these questions we propose to investigate angular distrubutions and recoil velocities of Au target fragmentation products produced by (fast) ^{18}O or ^{20}Ne beams of 49 MeV/u and 85 MeV/u using thin target stack foils techniques as well as the conventional thick catcher techniques. These detailed measurements require 5 shifts of beamtime at each energy. We then intend to compare this data with previous results involving 85 MeV/u ^{12}C and with results of Au fragmentations in (slow) Au+Au collisions, which are being studied concurrently at tha UNILAC accelerator at 20 MeV/u. The later collision either provide the system with the same total energy above the barrier as 85 MeV/u ^{18}O+Au or it provide the same maximum excitation energy per Au nucleus as 49 MeV/u ^{20}Ne+Au, this is, however, a projectile velocity well below the Fermi velocity.

As mentioned above, we have found that various characteristics of target fragmentation is scaling with total projectile energy. So far, 94 keV/u ^{20}Ne is the heavy-ion beam with the highest total beam energy that has been accelerated at SC (1.9 GeV total energy). The intensity of the extracted beam was 4 x 10^9 particles/s. At the end of the beam test we got the possibility to use the beam during 4 hours for a test irradiation with ^{197}Au. The data analysis gives that the irradiation was not long enough for a complete experiment, but we can conclude that specially light fragments have different properties than compared with 1.0 GeV ^{12}C. We therefore propose to measure the target fragment yields, average energies and moments (using recoil techniques) for the interaction of 94 MeV/u ^{20}Ne with Au and Ta to learn more about target fragmentation at 1.9 GeV total beam energy. These measurements will require 2 shifts of beam time.

The following table summarizes our beam time requests for the next years:

Projectile	E(MeV/u)	Nr shifts	Experiment
^{12}C	25	1	Frag. yields, energies
^{12}C	35	1	"
^{12}C	25	3	Frag. ang. dist.
^{12}C	35	3	"
^{12}C	85	3	Transfer reactions
^{12}C	50	3	" "
^{18}O	85	5	Frag. ang. dist.
^{20}Ne	50	5	Yields, energies, ang. dist.
^{20}Ne	94	2	Frag. yields, energies
		26	

III. STUDIES OF PIONIC FUSION IN NUCLEAR COLLISIONS

1. Introduction

The coherent production of pions well below the quasi-free nucleon-nucleon pion production threshold has recently been observed in collisions of complex nuclei. Of particular interest is the doubly coherent production[7-10)] of pions in a cooperative reaction of the type $A_1 + A_2 \rightarrow B(J) + \pi$ where the projectile (A_1) and the target (A_2) form an united nucleus B in some bound state $J>$. In contrast to the usually observed thermalization process the total free energy of the entrance channel is converted into a fast pion. Because of those two properties these reactions have been termed "pionic fusion"[11)]. The most interesting questions associated with this new type of reaction are i) the nature of the mechanism that couples the kinetic energy of the entrance channel to the pion field and ii) the selection rules for different entrance channel fragmentations that determine the population of (a specific state of) a given final nucleus. Klingenbeck et al.[11)] have discussed question i) in terms of the creation of one or multiple N^* excitations in nuclei and question ii) as related to the similarity of the structure of the populated final state with the entrance channel fragmentation. More specifically, pionic fusion proceeds[11)] through internal excitation of a <u>bound</u> nucleon. This configuration propagates coherently through the whole nucleus B, until, in a last step, it decays into the final nuclear state B(J) by emitting a pion. Due to the very limited body of experimental data it is not clear, at present, what is the relevance of the entrance channel fragmentation in determining the cross section for the population of the final nucleus B. Thus, it seems attractive to investigate the formation of the same nucleus B with different target/projectile combinations. Secondly, pionic fusion has so far been observed with $A \leq 3$ projectiles only. An open question is whether more complex projectiles like ^{12}C still lead to measurable cross sections. Thirdly, it is of importance to learn about the physical nature of the intermediate excitations by measuring excitation functions.

2. Proposed Research

Ward et al.[10)] studied the $^{208}Pb(^{3}He,\pi^{-})^{211}At$ reaction at ^{3}He laboratory energies of 158,200, and 230 MeV by off-line chemical separation of astatine and α-particle spectroscopy. (^{211}At decays by α-particle emission of 5.87 MeV with a half-life of 7.2 h). This way, pionic fusion involving the emission of a negative pion can uniquely be detected. Preliminary cross sections are reported[10)] to be on the order of several nanobarns near threshold.

We propose to begin our studies with the same reaction and degraded ^{3}He beams ($85.2\ MeV/u \geq E_{lab} \geq 45\ MeV/u$) in order to check the technique and to study possible background problems (3 shifts). With SC-beam intensities of 10^{13} $^{3}He^{+}/s$ a 10 mg/cm^{2} ^{208}Pb target and a bombarding time of ∿8 hours we expect a count rate of 100 α-particles/h for ^{211}At. If the $(^{3}He,\pi^{-}xn)$ products are populated with the same cross section we expect count rates of 10 h^{-1} and 40 h^{-1} for ^{209}At and ^{207}At, respectively. In order to measure the $^{208}Pb(^{3}He,\pi^{-}xn)^{211-xn}At$ excitation function six bombardments of 8 hours duration each at 45, 50, 55, 60, 70, and 85 MeV/u are required (6 shifts). The influence of the entrance channel fragmentation is to be checked by additional ^{3}He bombardments of mass separated ^{206}Pb and ^{207}Pb targets where ^{207}At and ^{209}At are again produced in $(^{3}He,\pi^{-}xn)$ channels (6 shifts). For the same reason it would be highly desirable to then extend these studies to ^{4}He bombardments with special emphasis on a comparison of the $^{208}Pb(^{3}He,\pi^{-})^{211}At$ excitation function with that for the $^{207}Pb(^{4}He,\pi^{-})^{211}At$ reaction.

Therefore, we would like to ask the SC staff to seriously check the possibility of accelerating ^{4}He-ions (10^{-12}-$10^{13}s^{-1}$) to ∿50 MeV/u. We are presently negotiating with the Jülich cyclotron staff for the same purpose, however, it looks like both the available intensities and the maximum energy are marginal there. Subsequently, we are interested in an extension of the programme to the use of heavier ions such as ^{12}C. Here the $^{198}Pt(^{12}C,\pi^{-}xn)^{210-xn}At$, the $^{198}Pt(^{12}C,\pi^{0})^{210}Po$, and the $^{197}Au(^{12}C,\pi^{0}xn)^{209-xn}At$ reactions are most attractive. Near threshold measurements would require $^{12}C^{3+}$ beams of > 10^{12} particles/s degraded from 49 MeV/u to about 20 MeV/u.

The programme is anticipated to be started at the end of 1982 and to continue through 1983 and 1984.

Summary of requested beam time:
^{3}He (various energies) 15 shifts.

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Figure captions

Figure 1. Variation of the light fragment yields with total projectile energy.

Figure 2. Total reaction cross section for ^{20}Ne reactions with ^{181}Ta. The solid line is the microscopic model calculation of DeVries and Peng$^{1)}$.

Figure 3. The variation of F/B for selected products from the reaction of a) heavy ions with Au b) protons with Au.

Figure 4. Variation of inelasticity with product mass number for reactions of heavy ions with Au.

Group Leader in Matter of Safety

J.V. Kratz, Mainz

Scientific Spokesman

K Aleklett, Studsvik

Contactman

G. Rudstam, E.P. Division, CERN

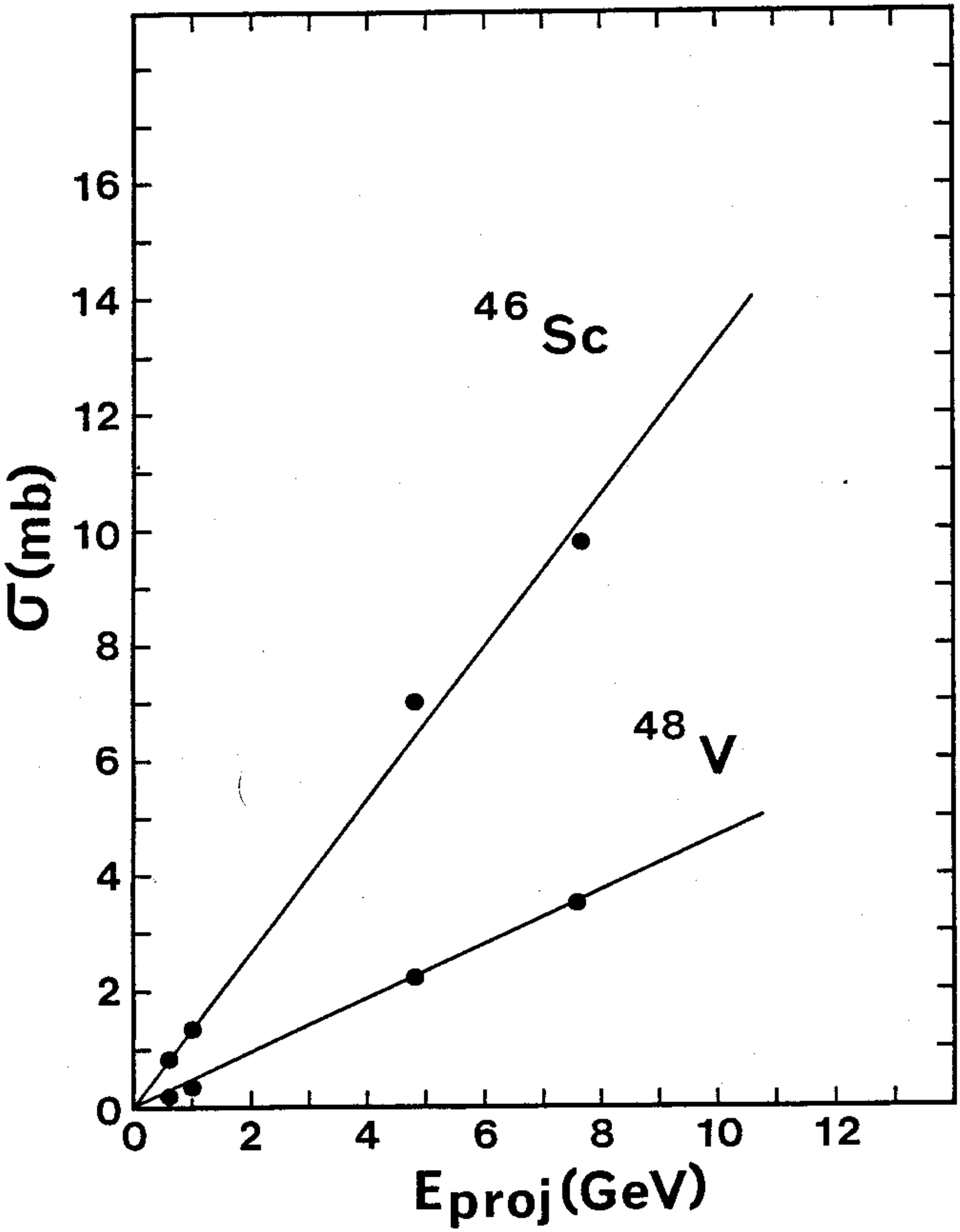

Fig. 1.

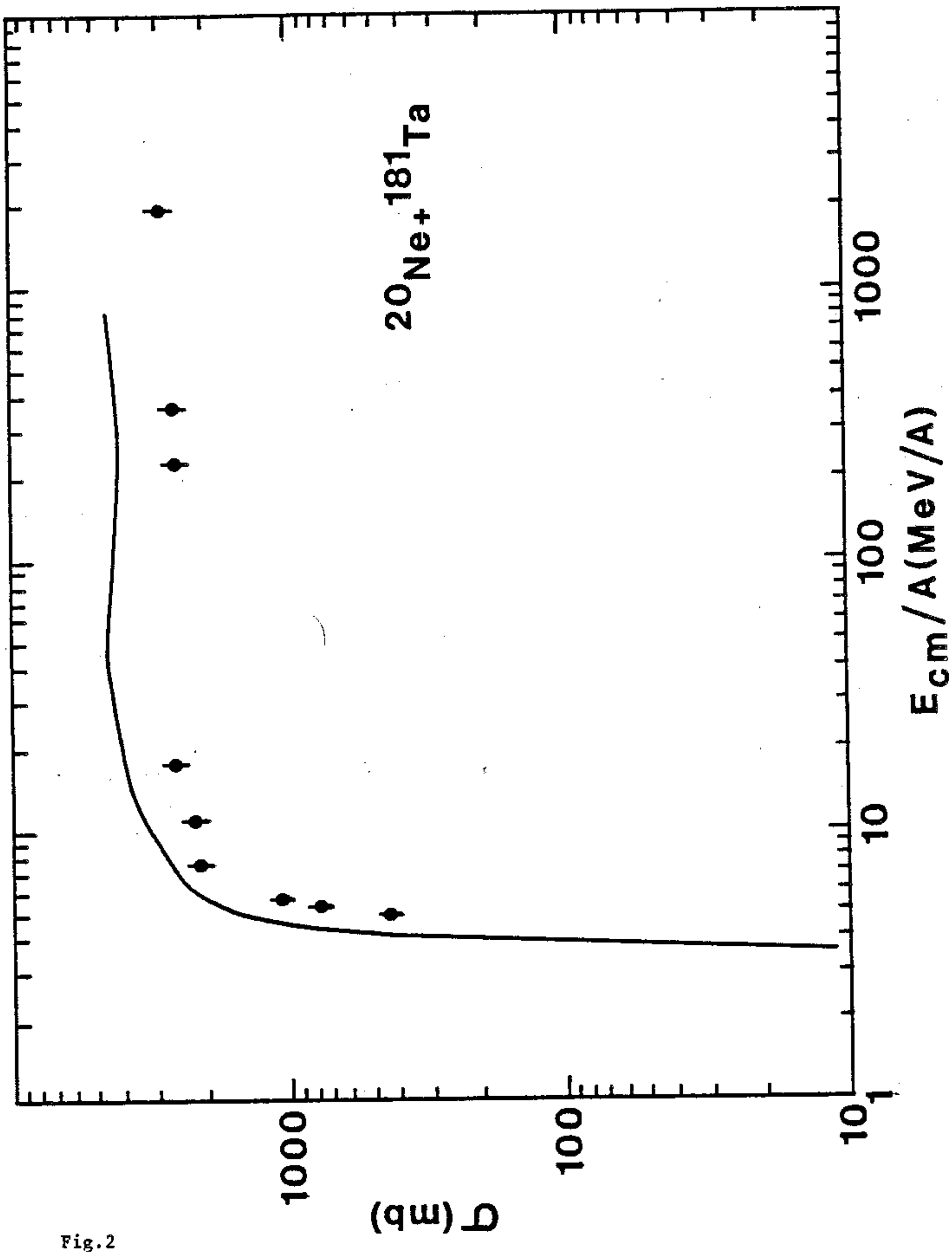

Fig.2

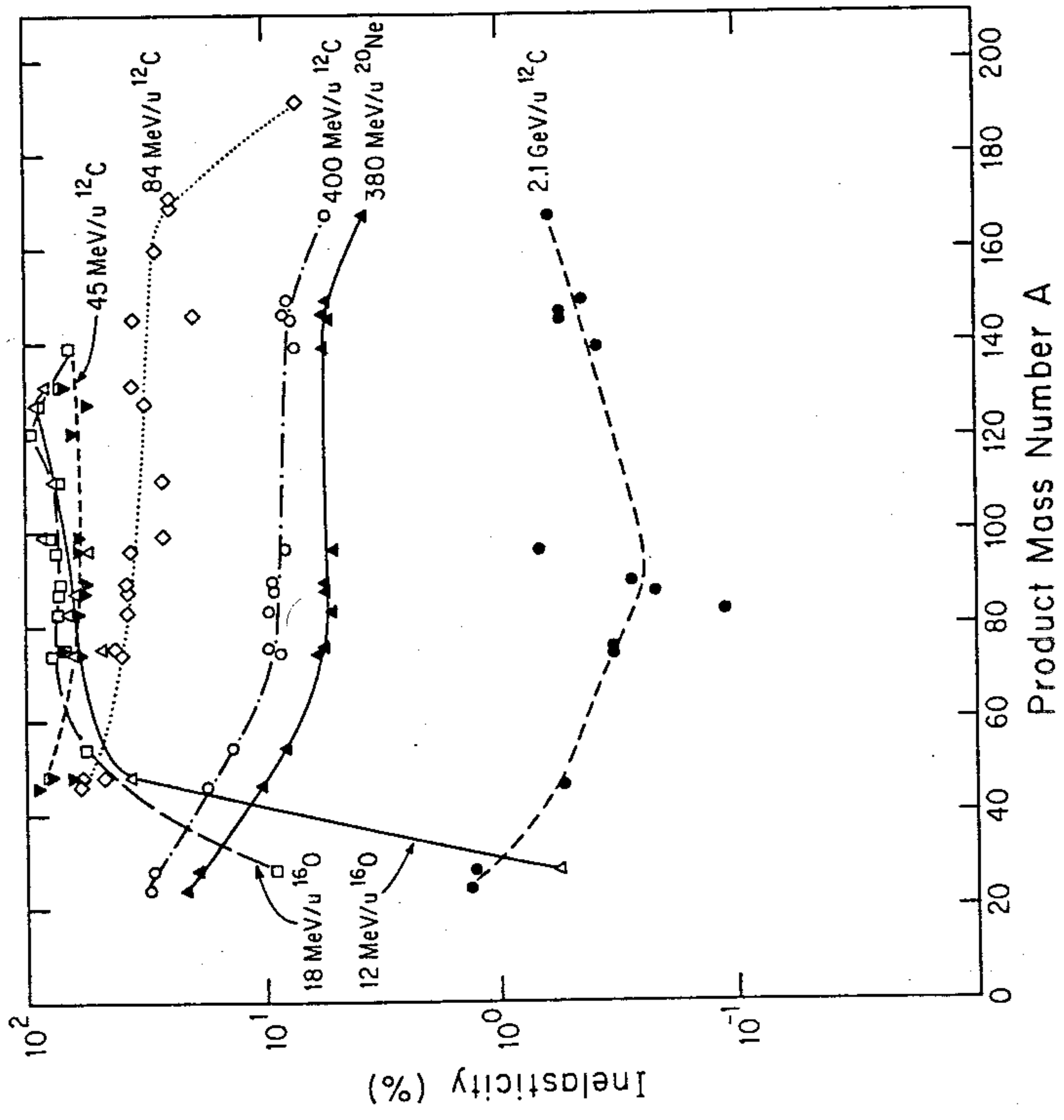45 MeV/u ^{12}C
84 MeV/u ^{12}C
400 MeV/u ^{12}C
380 MeV/u ^{20}Ne
2.1 GeV/u ^{12}C
18 MeV/u ^{16}O
12 MeV/u ^{16}O
Inelasticity (%)
10^2
10^1
10^0
10^{-1}
Product Mass Number A
0
20
40
60
80
100
120
140
160
180
200

Fig. 3.

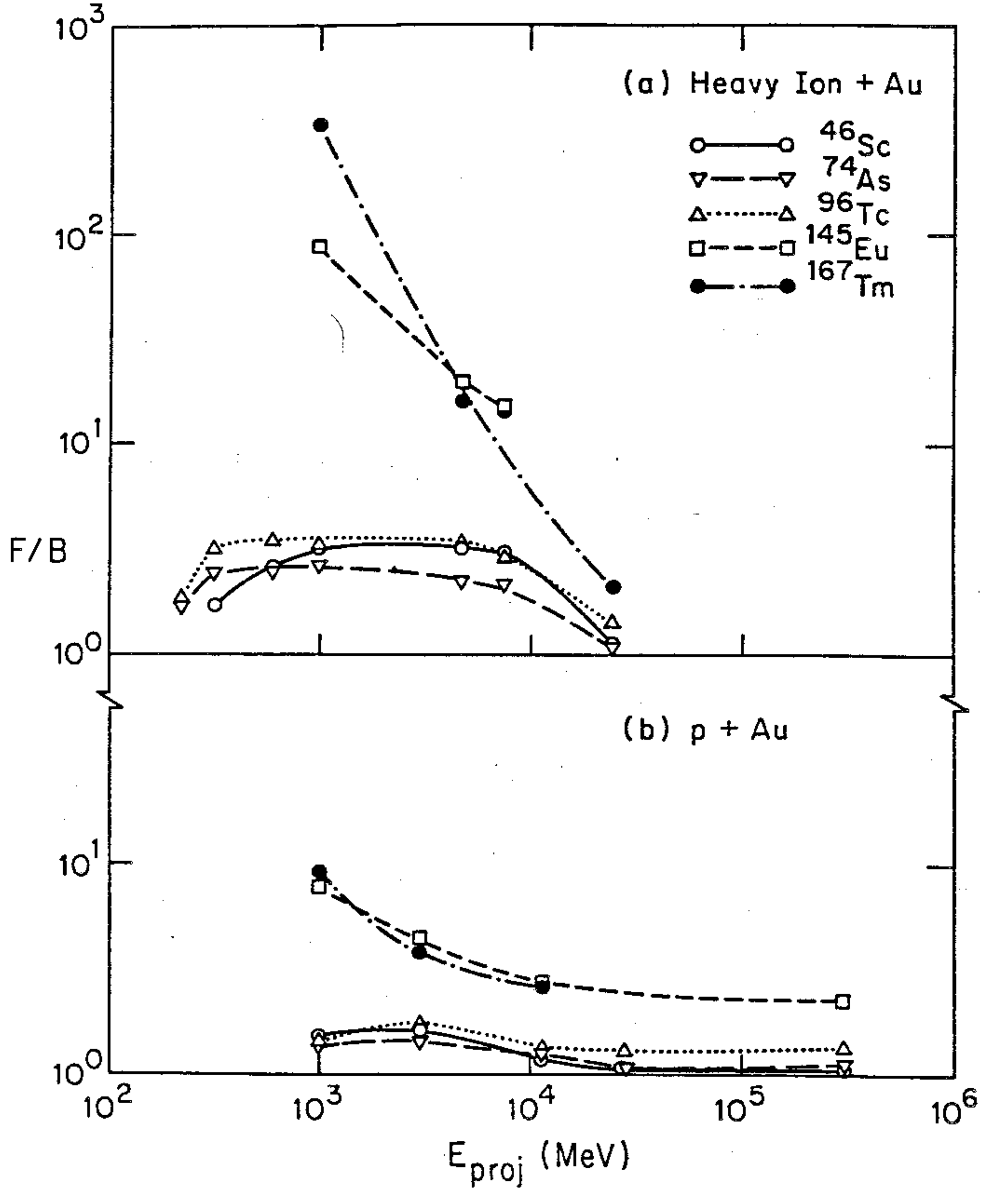
(a) Heavy Ion + Au
^{46}Sc
^{74}As
^{96}Tc
^{145}Eu
^{167}Tm
(b) p + Au
F/B
10^3
10^2
10^1
10^0
10^1
10^0
10^2
10^3
10^4
10^5
10^6
E$_{proj}$ (MeV)

Fig. 4.