Title

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ABSTRACT

The angular distributions of target fragments from relativistic heavy ion reactions have been measured for the first time. Eight nuclides from a ^{197}Au target and seven nuclides from a ^{238}U target with a 3.0 GeV ^{12}C projectile, and six nuclides from a ^{197}Au target and six nuclides from a ^{238}U target with 12.0 GeV ^{12}C projectile were observed and their angular distributions were obtained. From ^{197}Au, all the fragments observed in this work showed forward peaked angular distributions; from ^{238}U, the fragments of typical fission-product nuclides showed isotropic distributions in the laboratory system and the rest of the fragments showed forward peaked distributions similar to those from ^{197}Au. The observed angular distributions were consistent with the values of F/B ratios measured previously.

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KEY WORDS

Relativistic heavy ion reaction, target fragment angular distribution for 3.0 GeV, 12.0 GeV ^{12}C + ^{197}Au, ^{238}U; two step vector model.

1. INTRODUCTION

Despite extensive studies of high energy heavy ion reactions, no clear understanding of the reaction mechanisms exists. This description is especially applicable to target fragmentation reactions, i.e., reactions in which the initial projectile-target interaction produces relatively large fragments of the original target nuclei, ranging in mass from $A \cong 24$ up to almost the target mass. Numerous theoretical models for the interactions have been proposed[1,2,3] and have been compared to experimental data[4,5,6] characterizing target fragmentation. Modest success is achieved in predicting the yields of fragments of differing Z and A, but the recoil energy and spatial distribution of the fragments are poorly described. Because of the importance of the fragment angular distributions in defining the operating reaction mechanisms, and because previous experimental studies of heavy ion-induced target fragmentation[5,7] have only involved measurements of F/B, a crude range-weighted measure of the extent of forward peaking of the angular distributions, we thought it

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to be of interest to directly measure the target fragment angular distributions for relativistic heavy ion reactions. In this paper, we report the first such measurements for relativistic nucleus-nucleus collisions.

The results were obtained from the interactions of a "sub-relativistic" heavy ion, 3.0 GeV ^{12}C and a relativistic heavy ion, 12.0 GeV ^{12}C, with a very fissionable target nuclide, ^{238}U, and a much less fissionable heavy nuclide, ^{197}Au. Because of the extremely low intensity of the projectile beams (< ~10^{10} particles/minute) from the LBL Bevalac where this study was carried out, we were able to measure only crude four-point angular distributions for eight product nuclides from the interaction of 3.0 GeV ^{12}C + ^{197}Au, seven from 3.0 GeV ^{12}C + ^{238}U, six from 12.0 GeV ^{12}C + ^{197}Au and six from 12.0 GeV ^{12}C + ^{238}U. Nonetheless, certain interesting physical insights can be obtained from examining the results of these measurements.

2. EXPERIMENTAL

The major barrier to the measurement of target fragment angular distributions at the LBL Bevalac is the relatively low beam intensities. For the measurements described herein, ^{238}U and ^{197}Au target assemblies were placed behind one another in an evacuated beam tube (P ~ 3×10^{-2} Torr). The attenuation and scattering of the beam in passing through the thin targets and catcher assemblies were negligible. No corrections were made for the effect of secondary particle induced reactions. The total particle fluence for the 3.0 GeV ^{12}C bombardment was 8.39×10^{13} particles delivered over a time of 1605 minutes, while the fluence for the 12.0 GeV ^{12}C bombardment was 9.07×10^{12} particles over a time of 687 minutes. The Bevalac beam diameter during these irradiations varied from 1.6 - 2.8 cm and the spot positions on the target changed. This resulted in a uniform exposure of the entire target area. To overcome the problem of low beam intensity, special target-catcher assemblies were employed as shown in Fig. 1. Each assembly consisted of 17 identical target foils, each surrounded by a conical catcher foil assembly in which the fragments recoiling from the target were stopped. Each ^{238}U target foil consisted of a 12.8 mg/cm^2 Al foil onto which a circular spot (1.59 cm diameter) of UF_4 of thickness 1.25 mg/cm^2 had been evaporated. Each ^{197}Au target foil consisted of 34.4 mg/cm^2 Mylar foil with a similar circular spot of evaporated Au of thickness 1.00 mg/cm^2. Each catcher was a cone of height 0.84 cm and with a radius of the base of 3.86 cm. The catcher assemblies were constructed of Mylar of thickness 7.32 mg/cm^2; like the target backing foils, these catchers should have been sufficiently thick to stop the recoiling target fragments.[5,8,9] After irradiation, each conical catcher foil was cut into four pieces, corresponding to angular ranges of 0° - 30°, 30° - 50°, 50° - 70°, and 70° -90°, with respect to the center of the evaporated target. Catcher foils corresponding to the same angular range from each of the 17 targets were combined and counted as a single sample by a Ge(Li) detector. Gamma-ray spectroscopic techniques that have been generally described elsewhere[10] were used to assay the relative amounts of different radionuclides present in each foil.

The determination of the effective solid angle subtended by each catcher foil, the correction for fragment absorption and scattering in the relatively thick targets, and the correction for widely differing counting efficiencies for the geometry between the Ge(Li) crystal and the extended counting sources produced in this work were complex matters. First, the relative solid angles subtended by the various catcher conic sections with respect to the extended area circular targets were numerically evaluated. As part of this procedure, the average recoil angles of the fragments stopped in the different catcher foil sections were evaluated. The average angles corresponding to the four pieces of the conical catcher were 22.7°, 33.1°, 44.3°, and 73.8°.

The next step involved the use of a single $^{238}UF_4$ target-catcher assembly to measure the fission fragment angular distribution from the 43 MeV α-particle-induced fission of ^{238}U. During this bombardment, the α-particle beam from the LBL 88-inch cyclotron was defocused to uniformly irradiate the entire 1.6 cm diameter ^{238}U target, thus simulating the conditions present in the Bevalac experiments. The relative activities of typical fission products in the four pieces of the conical catcher assembly were assayed using the same counting geometry and techniques as employed in the Bevalac experiments. Relative values of the differential cross sections, $d\sigma/d\Omega\ (\theta)$, were calculated for each fission radionuclide using the measured activities and the numerically calculated solid angles. The values of $d\sigma/d\Omega\ (\theta)$ for the different nuclides were then averaged and compared to the known gross fission fragment angular distribution[11] for this reaction. This comparison was used to generate a set of correction factors for the effects of extended counting sources and fission fragment absorption in the target material.

Strictly speaking, this calibration procedure should be only valid for fragments from the α-induced ^{238}U fission. However, since many non-fission products (with $50 \leq A \leq 140$) from relativistic heavy ion (RHI) reactions with ^{197}Au and ^{238}U have ranges similar to the fission fragments, the errors involved in such a procedure are of little importance The lightest fragments ($A \leq 50$) from RHI reactions have ranges[5,8] in matter that exceed fission fragment ranges by factors of up to 4 or 5. No attempt was made to correct for this difference between the light fragments and the fission fragments. The problem of how to evaluate the absorption and scattering of the heavy fragments ($A \geq 140$) produced in RHI reactions is more serious. For example, fragments with $A > 165$ produced in these reactions were estimated to have ranges[5,8] in the target material of $\lesssim$2 mg/cm , meaning that a significant number of fragments with large recoil angles were stopped in the target. Therefore, while it was possible to measure angular distributions for such fragments, the fission fragment calibration procedures are grossly inadequate for such fragments. We will only consider the angular distributions of fragments with $A \leq 150$ whose ranges in matter are at least twice the target thickness. We will report the result for the heavy fragment angular distributions after further investigation.

RESULTS AND DISCUSSION

The measured fragment angular distributions for the reaction of 3.0 GeV ^{12}C with ^{197}Au and ^{238}U and the reaction of 12.0 GeV ^{12}C with ^{197}Au and ^{238}U are shown in Figures 2, 3, 4, and 5, respectively. The results are also tabulated in Tables 1, 2, 3, and 4. Despite the measures used to overcome the problems of low beam intensity, an appreciable uncertainty is present in some of the data. Nonetheless, there are many interesting trends apparent in the results. In general, one observes roughly isotropic angular distributions for neutron-rich ^{238}U fission products, such as ^{97}Zr, ^{99}Mo, and ^{133}I (Figures 3 and 5), in good agreement with previous determinations that the low excitation energy fission of ^{238}U were induced by RHI from peripheral collisions with low momentum transfer. In the case of ^{238}U, the fragments other than those associated with ^{238}U fission products showed forward-peaked distributions with the greatest degree of forward-peaking being observed in the ^{149}Gd angular distribution. This is in qualitative agreement with the trends of the F/B ratios.[5] For the interactions of RHI with ^{197}Au, all the observed distributions were forward-peaked with the large degree of forward peaking observed for fragments with $145 \leq A \leq 155$, in agreement with general trends previously observed[8] in the F/B ratio.

It is interesting to compare the fragment angular distributions measured in this work with similar data for the interaction of the high energy protons with ^{238}U. Fortney and Porile[12] have measured the angular distribution of ^{48}Sc fragments in the interactions of the 3.0 and 11.5 GeV protons with ^{238}U. A representation of these results is shown in Figures 3a and 5a, along with the distributions obtained in this work for ^{43}K. Although the uncertainties in the angular distributions from the RHI reactions are large, there is no evidence for the side-wise peak in our measurement as seen in the proton-induced reactions.

One important reason for directly measuring the fission fragment angular distributions is to study the reaction kinematics in a model-independent way unlike the use of the thick target - thick catcher recoil technique whose results are dependent upon the validity of the two step vector model.[13,14,15] In Figures 2, 3, and 5, we compare, for selected fragments, the angular distributions measured in this work with those deduced from the two step vector model analysis of thick target - thick catcher recoil data for the reactions of 3.0 GeV and 12.0 GeV ^{12}C with ^{197}Au and ^{238}U targets by applying a Maxwell distribution to the secondary recoil energy distribution. The experimental and computed angular distributions show roughly the same trends, giving a measure of the applicability of the two step vector model.

CONCLUSION

From the results, we can extract the following conclusions.

From ^{197}Au targets, we observed forward peaked angular distributions for all the nuclides identified in this work. The 3.0 GeV and 11.5 GeV proton experiments did not produce the same distribution trends as those reported in this work, so our results can be attributed to phenomena arising from the relativistic nucleus-nucleus reactions. Also, our fragment distributions were observed to have a larger degree of forward peaking with an increase of the product mass number. The light mass products may not have been produced by the primary reaction process alone, but the heavier mass products may have been more directly produced by the fast, primary reaction process which can be related to the impact parameters between the projectile and target nucleus.

The angular distributions of ^{97}Zr, ^{99}Mo, and ^{133}I from ^{238}U targets were isotropic. Noting that they are typical fission product nuclides, it is reasonable to say that the major contribution to the production of these fragments was the fission process, although some other types of reaction processes may also have contributed to produce these fragments. The observed isotropic distribution in the laboratory system implies the primary momentum transfer from the projectile nucleus to the target is small in comparison with the momentum imparted by the fission process. The distributions for the rest of the observed nuclides from ^{238}U had forward peaks similar to those from ^{197}Au. The contribution of the fast, primary reaction of the RHI to produce these fragments was much larger than the fission contribution.

The results in this work are consistent with the F/B values measured before.[5,9] The fragments whose angular distributions have a larger degree of forward peaking give larger values of F/B and the fragments with isotropic distributions have F/B values of approximately unity.

Finally, we did not observe any significant change in the fragment angular distributions between the two projectile energies, to the accuracy of our experiments.

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TABLE 1

$d\sigma/d\Omega\ (\theta)$ From the Reaction of 3.0 GeV ^{12}C + ^{197}Au, Normalized at the Average Angle 74°.

	Average Angle $\langle\theta\rangle$			
Nuclide	23°	33°	44°	74°
^{89}Zr	2.25±0.27	1.31±0.09	1.06±0.05	1.±0.04
^{90}Nb	2.49±0.18	1.77±0.09	1.55±0.05	1.±0.03
^{97}Ru	3.13±0.20	1.53±0.13	2.08±0.06	1.±0.05
^{123}I	4.04±0.16	2.27±0.07	2.24±0.03	1.±0.02
^{145}Eu	6.26±0.37	5.19±0.26	3.19±0.15	1.±0.07
^{149}Gd	6.17±0.21	4.06±0.11	3.48±0.05	1.±0.05
^{152}Tb	4.28±0.31	3.68±0.16	2.80±0.08	1.±0.05
^{155}Dy	7.00±0.28	5.82±0.19	4.14±0.09	1.±0.05

TABLE 2

dσ/dΩ (θ) From the Reaction of 3.0 GeV ^{12}C + ^{238}U, Normalized at the Average Angle 74°

	Average Angle ⟨θ⟩			
Nuclide	23°	33°	44°	74°
^{43}K	1.15±0.11	0.94±0.05	1.08±0.03	1.±0.03
^{72}As	1.13±0.20	0.89±0.09	1.01±0.08	1.±0.09
^{89}Zr	0.80±0.17	0.66±0.07	0.77±0.05	1.±0.05
^{97}Zr	0.84±0.10	0.80±0.04	0.96±0.03	1.±0.04
^{99}Mo	1.05±0.02	0.88±0.01	1.04±0.01	1.±0.01
^{133}I	1.13±0.12	0.89±0.01	1.04±0.04	1.±0.05
^{149}Gd	2.34±0.28	1.73±0.13	1.68±0.07	1.±0.08

TABLE 3

$d\sigma/d\Omega\ (\theta)$ From the Reaction of 12.0 GeV ^{12}C + ^{197}Au, Normalized at the Average Angle 74°

Average Angle $\langle\theta\rangle$

Nuclide	23°	33°	44°	74°
^{89}Zr	2.78±0.72	2.78±0.50	0.67±0.17	1.±0.22
^{90}Nb	3.21±0.50	3.03±0.35	1.54±0.15	1.±0.14
^{97}Ru	2.15±0.53	1.29±0.21	1.26±0.11	1.±0.13
^{145}Eu	4.29±1.14	2.29±0.43	1.14±0.29	1.±0.14
^{149}Gd	9.33±1.58	3.00±0.58	1.67±0.25	1.±0.33
^{155}Dy	9.60±2.26	5.15±0.58	2.77±0.31	1.±0.27

TABLE 4

$d\sigma/d\Omega\ (\theta)$ From the Reaction of 12.0 GeV ^{12}C + ^{238}U, Normalized at the Average Angle 74°

	Average Angle $\langle\theta\rangle$			
Nuclide	23°	33°	44°	74°
^{43}K	1.97±0.31	0.85±0.13	1.02±0.07	1.±0.10
^{72}As	2.80±0.78	0.71±0.16	0.75±0.14	1.±0.16
^{97}Zr	1.86±0.30	0.81±0.14	1.18±0.09	1.±0.10
^{99}Mo	1.12±0.12	0.96±0.05	1.15±0.03	1.±0.02
^{133}I	1.16±0.27	0.68±0.14	0.61±0.08	1.±0.13
^{149}Gd	5.67±1.56	4.78±1.22	1.22±0.22	1.±0.33

FIGURE CAPTIONS

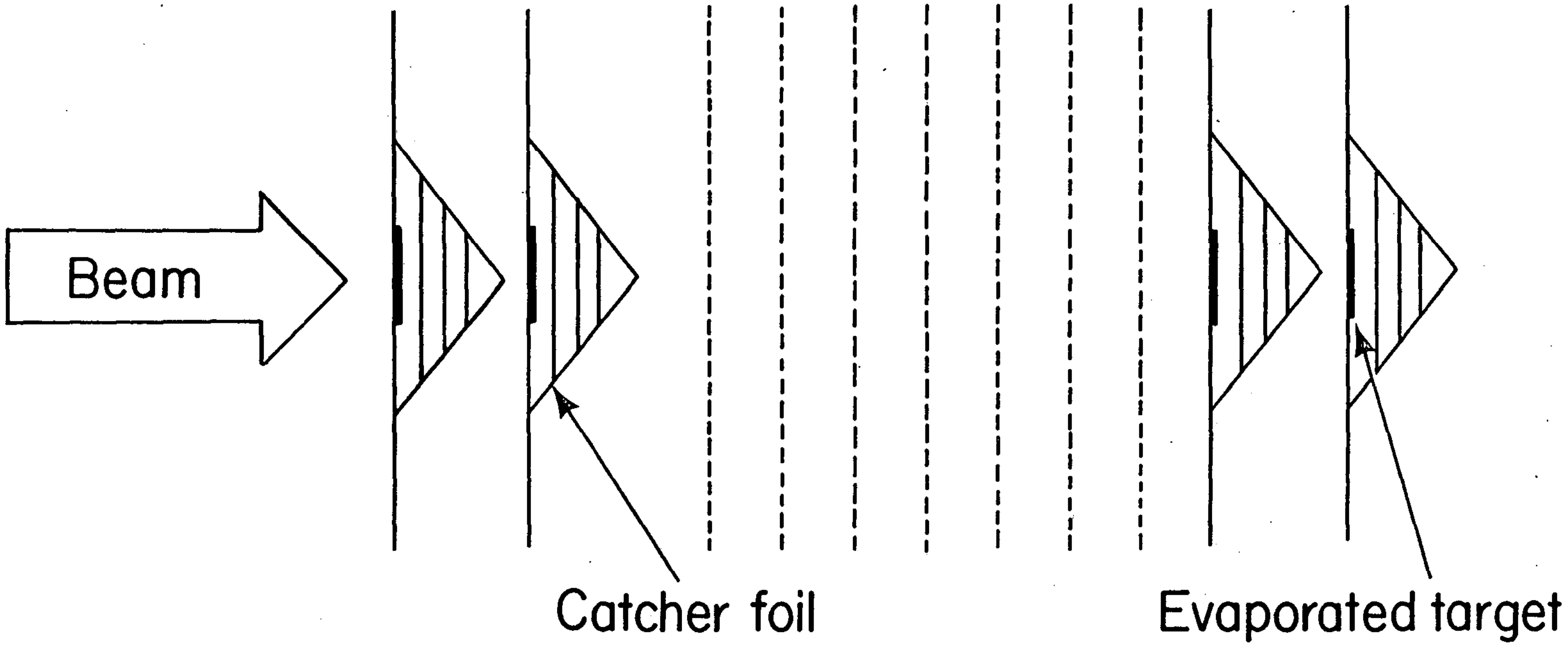
Figure 1. Schematic drawing of target assembly showing use of multiple target - conical catcher foil assemblies. XBL 8110-1479

Figure 2. Target fragment angular distributions normalized at the largest angle from the reaction of 3.0 GeV ^{12}C + ^{197}Au. The dotted curves are the computation results from the two step vector model. XBL 8110-1480

Figure 3. Target fragment angular distribution normalized at the largest angle from the reaction of 3.0 GeV ^{12}C + ^{238}U with a comparison of the ^{48}Sc angular distribution from Ref. 12. The dotted curves are the computation results from the two step vector model. XBL 8110-1481

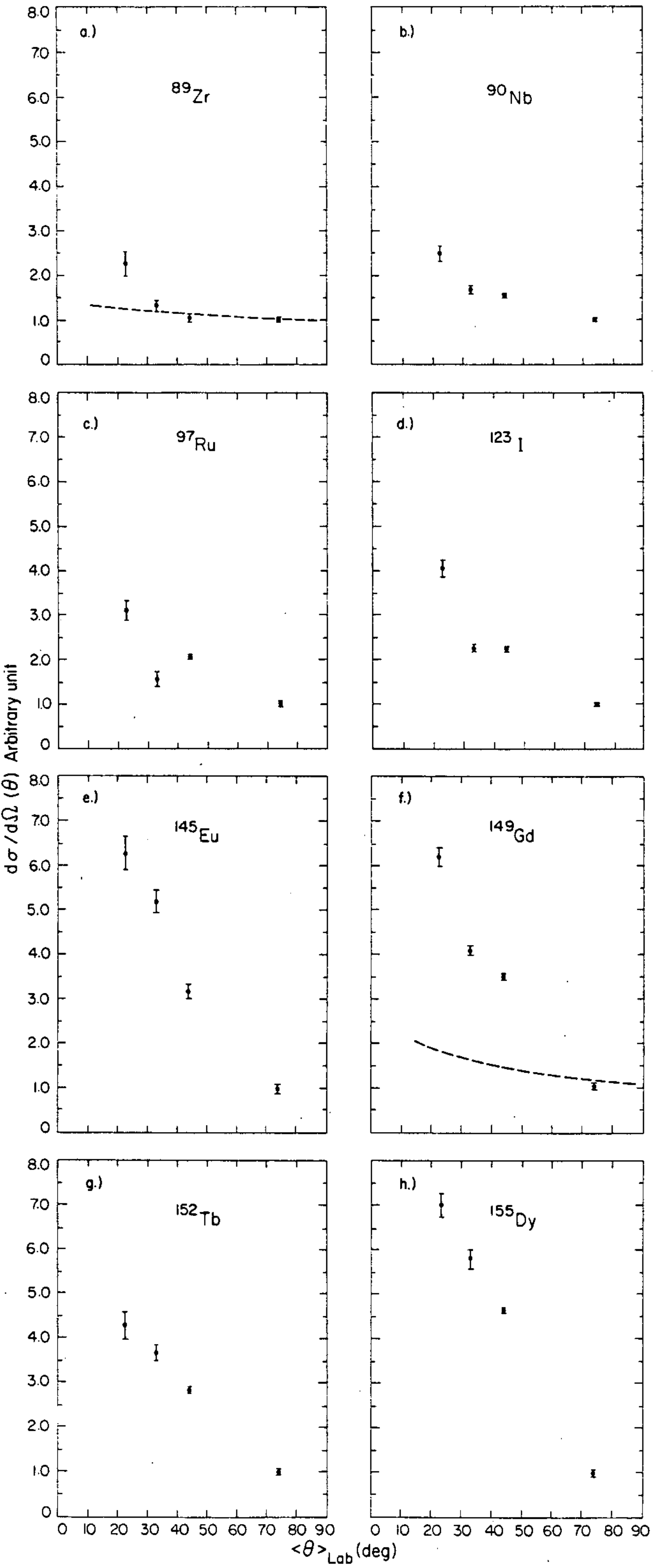
Figure 4. Target fragment angular distributions normalized at the largest angle from the reaction of 12.0 GeV ^{12}C + ^{197}Au. [illegible]
XBL 8110-1482

Figure 5. Target fragment angular distributions normalized at the largest angle from the reaction of 12.0 GeV ^{12}C + ^{238}U with a comparison of the ^{48}Sc angular distribution from Ref. 12. The dotted curves are the computation results from the two step vector model. XBL 8110-1483



XBL 8110-1479

Fig. 1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^{89}Zr
b.)
^{90}Nb
c.)
^{97}Ru
d.)
^{123}I
e.)
^{145}Eu
f.)
^{149}Gd
g.)
^{152}Tb
h.)
^{155}Dy
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
dσ/dΩ (θ) Arbitrary unit
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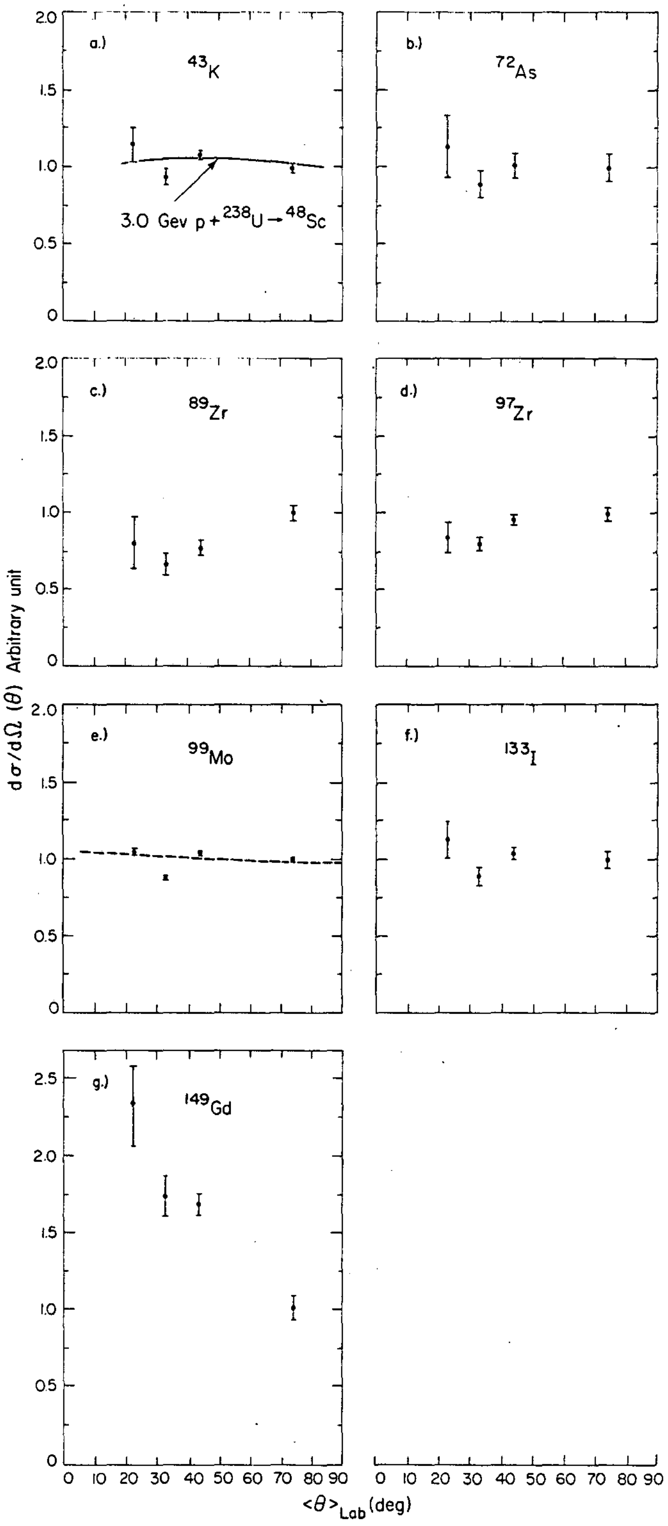
<θ>Lab (deg)
XBL 8110 1480

Fig. 2



XBL 8110-1481

Fig. 3

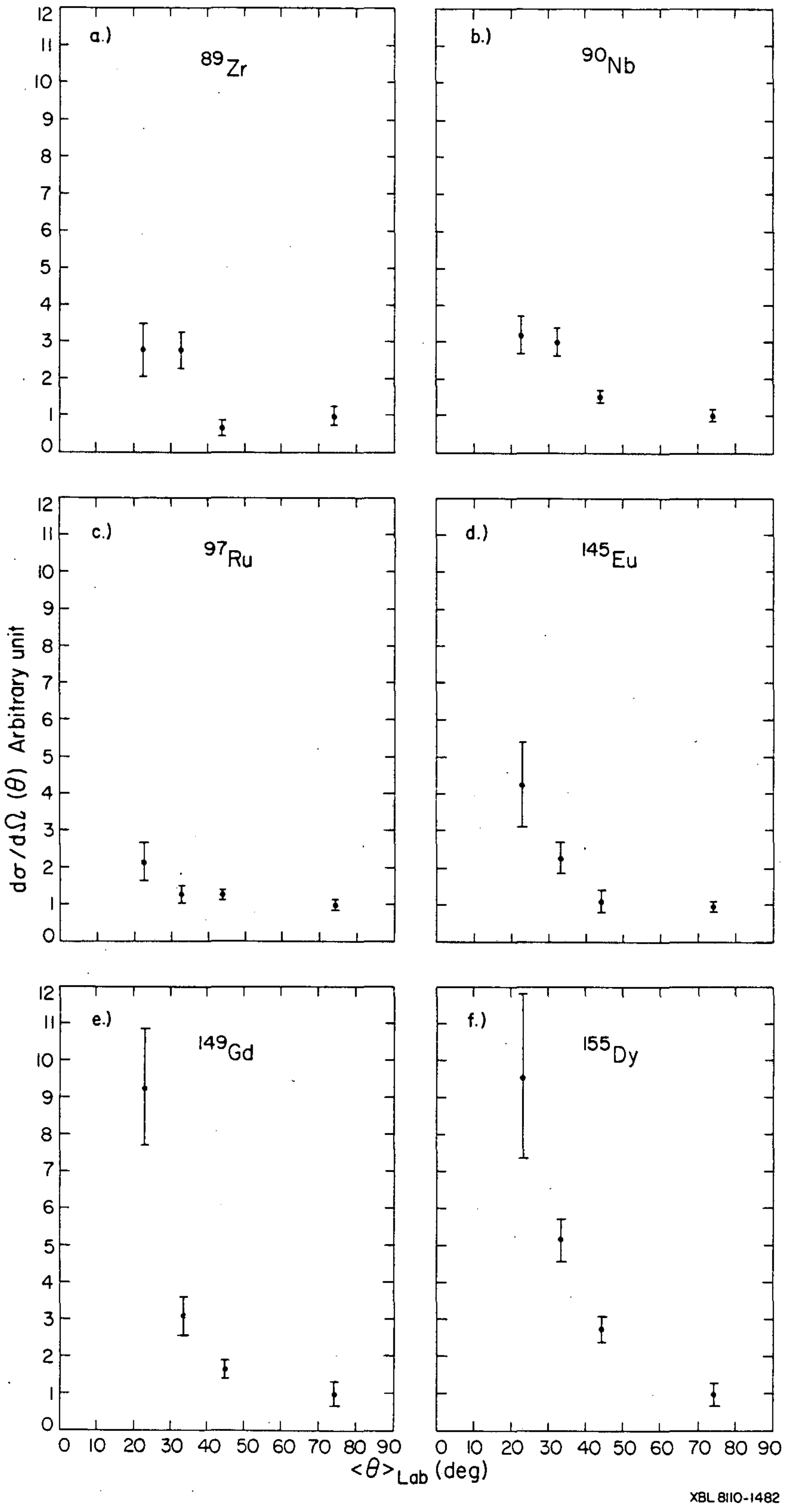
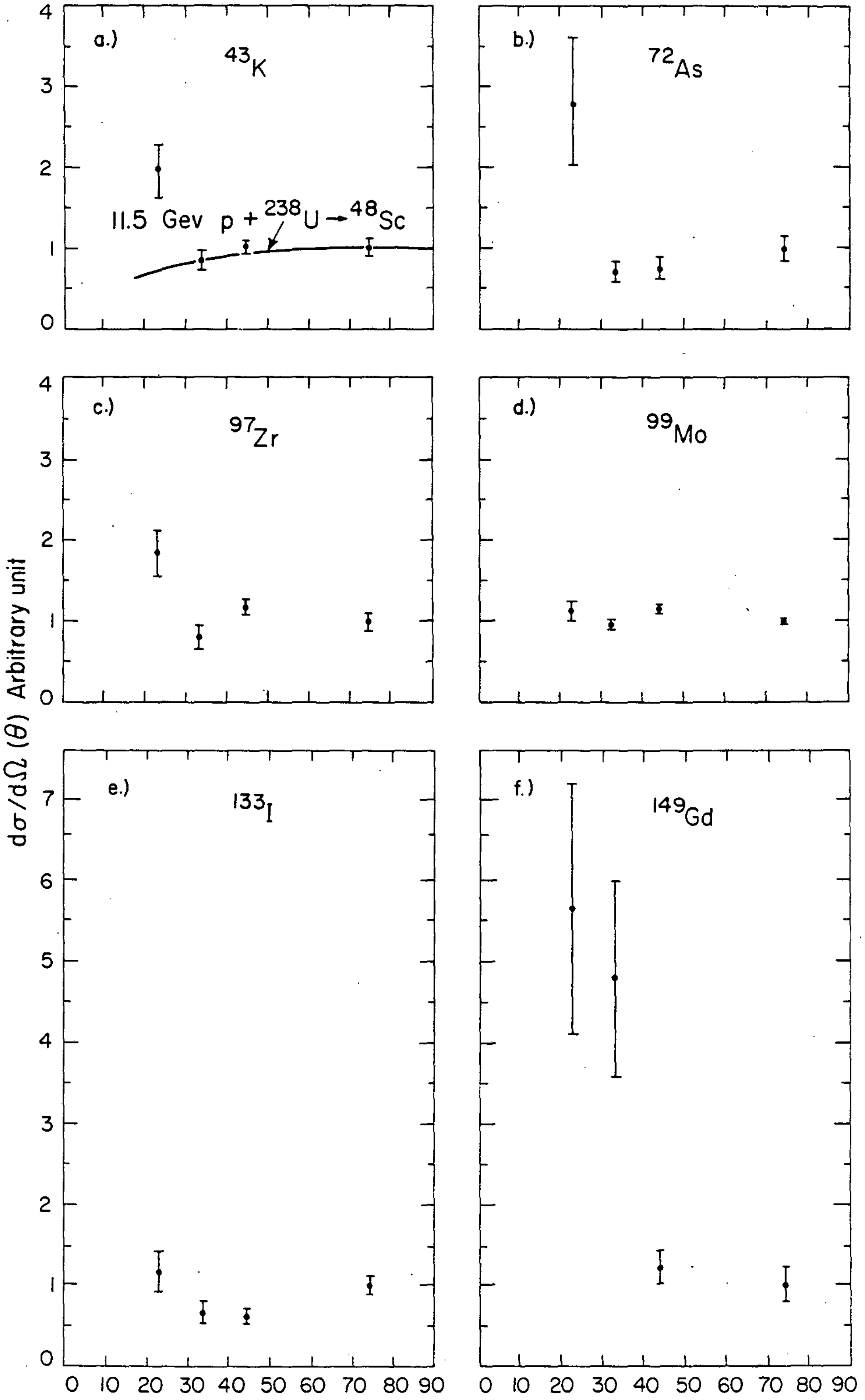

a.)
^{89}Zr
b.)
^{90}Nb
c.)
^{97}Ru
d.)
^{145}Eu
e.)
^{149}Gd
f.)
^{155}Dy
dσ/dΩ (θ) Arbitrary unit
0
1
2
3
4
5
6
7
8
9
10
11
12
0 10 20 30 40 50 60 70 80 90
<θ>$_{Lab}$ (deg)
XBL 8110-1482

Fig. 4



XBL 8110-1483

Fig. 5

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