Presented at the Nobel Symposium on
Superheavy Elements, Ronneby Brunn,
Sweden, June 11-15, 1974.

LBL-2940
c.2

MACROSCOPIC ASPECTS OF HEAVY ION REACTIONS

S. G. Thompson, L. G. Moretto, R. C. Jared,
R. P. Babinet, J. Galin, M. M. Fowler,
R. C. Gatti and J. B. Hunter

RECEIVED
LAWRENCE
RADIATION LABORATORY

JUL 16 1974

LIBRARY AND
DOCUMENTS SECTION

June 1974

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY

LBL-2940
c.2

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-2940

MACROSCOPIC ASPECTS OF HEAVY ION REACTIONS

S. G. Thompson, L. G. Moretto, R. C. Jared, R. P. Babinet

J. Galin, M. M. Fowler, R. C. Gatti and J. B. Hunter

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
Physica Scripta (Sweden)

ABSTRACT

Heavy ion beams of ^{40}Ar (288 MeV) and ^{84}Kr (~600 MeV) from Hilac acceleration and ^{14}N (100, 160, 250, MeV) and ^{20}Ne (250 MeV) from the 88" cyclotron have been used to bombard natural silver targets. Formation cross sections, angular distributions and kinetic energy distributions for reaction products in the range Z = 6 - 20 have been measured using gas ΔE - E telescopes. Kinetic energy distributions generally agree well with coulomb repulsion energies for binary division. Angular distributions are discussed in terms of relaxation time for the mass asymmetry mode compared to rotational periods.

1. Introduction

During recent years there has been increased interest in reaction studies with heavy ions. On one hand spectroscopic studies have been performed for reactions in which few nucleons are transferred. On the other hand compound nucleus reactions have been studied in which large amounts of excitation energy and angular momentum are introduced by the heavy ions. In performing these studies some reactions have been unveiled that have characteristics between the two extremes. These reactions are similar to compound nucleus reactions in that a high degree of inelasticity is associated with them but they are also similar to direct reactions in that there appears to be some coupling between entrance and exit channels. It is this latter class of reactions that will be emphasized in the present discussion of some of the experimental work done by our group at Berkeley. In order to have a guideline for the presentation of our work certain remarks should be made concerning the expected properties of the intermediate systems. As shown by Nix [1] collective degrees of freedom are likely to control the fusion of the two nuclei. Furthermore, calculations show that the decay times, for example for neutron emission and for other modes are of the same order of magnitude as the periods of rotation and vibration of the nucleus itself. Thus a compound nucleus with the traditional characteristics may not be formed. Indeed one may expect partial relaxation of some modes but perhaps not of others. With these facts in mind we plan to present the data according to the following scheme:

1) The dissipation of the translational kinetic energy into internal energy will be determined by studying the kinetic energies of some of the products formed.

2) With regard to the relaxation of the mass asymmetry mode, it is of interest to examine the cross sections as a function of atomic number Z.

3) One may attempt to study the decay time of the intermediate system relative to rotational periods by observing the angular distributions.

2. Experimental

In our experiments we use ΔE-E counter telescopes to identify the atomic numbers and kinetic energies of the particles. Gas proportional counters [2] were used in the early work but improvements have resulted recently from the use of ionization ΔE counters which have given atomic number separations up to Z = 30. The counter telescopes can be moved to different angles to obtain angular distributions and in certain cases one telescope has been used in coincidence with an E detector.

We have bombarded natural silver targets with $^{14}_{7}N$ at several energies and with $^{20}_{10}Ne$ (250 MeV) at the 88" cyclotron. It is useful to compare these data with those obtained at the Hilac, where natural silver was bombarded with full energy $^{40}_{18}Ar$ (288 MeV) [3]. A small amount of data were obtained by bombarding silver with full energy $^{84}_{36}Kr$ (~600 MeV).

3. Results

3.1 Kinetic Energy Distributions for Ag + ^{40}Ar (288 MeV)

A map of total energy vs. ΔE at angle 30° is shown in fig. 1. One should note the large diversity of products formed with atomic numbers from z = 6 to Z = 20. Lower Z products are observed but they are not plotted here. Of course, we also have the large quasi-elastic argon peak.

For products near the projectile, e.g. Z = 16, 17 we have two components in the kinetic energy distributions. The higher energy peak we call the quasi-elastic peak. It has an energy close to that of the elastic scattered particles. The lower energy peak we call the relaxed peak. It has an energy very close to the coulomb energy of two touching fragments in a binary division. Thus, it appears that one observes a complete relaxation of the translational kinetic energy into the intrinsic degrees of freedom.

In fig. 2 we show the kinetic energy distributions in the center of mass system for atomic numbers close to that of the projectile. These data are shown for three different angles. The critical angle is 28°. At angle 25° the quasi-elastic peak dominates. At 30°, a relaxed peak appears, and at 40° the relaxed peak is dominant.

For atomic numbers further away from the projectile, e.g. Z = 12, 13, 14, the center of mass spectra measured at angles 25° and 40° coincide very well (fig. 3). The centroid energies, as before, correspond to the coulomb energies of fragments in contact in a binary division.

3.2 Kinetic Energy Distributions for Ag + ^{14}N

These spectra obtained from 88" cyclotron experiments are shown for purposes of comparison with those obtained at the Hilac with argon. In this case, ^{14}N ions at three different energies were used; 100, 160, and 250 MeV.

As before we observed a wide diversity of products with separated elements up to Z = 20 and greater. In fig. 4, kinetic energy spectra for Z = 9 and Z = 14 are shown at various angles. One notes a large difference in energy for Z = 9 at lab angles 70° and 150° and for Z = 14 at angles

35°, 70° and 150°. However, in the center of mass, all the spectra overlap except for Z = 9 at 35°. Thus a part of this latter spectrum does not seem to be completely relaxed.

3.3 Summary of Kinetic Energy Distributions

In fig. 5, a summary is given of the most probable kinetic energies for the relaxed peak vs. Z in the lab system for the reaction Ag + Ar (288 MeV). A large spread in energy at the various angles is observed. Figure 6 shows the result of transferring these data to the center of mass, where the results fall in a rather narrow band for all products and angles. The upper line is the coulomb repulsion energy of two touching spheres and the lower one represents the coulomb energy of two touching spheroids which are allowed to achieve their equilibrium deformation.

In fig. 7, we show the same data for Ag + N (160 MeV). In this case the experimental points also agree well with the coulomb repulsion energy of two touching spheres.

Thus there seems to be a reasonably good understanding of the kinetic energy distributions which over a large angular range are relaxed and behave as if the reactions occurred through a compound nucleus. In other words, in most cases a complete thermalization of the energy has occurred.

The shapes of these distributions are roughly Gaussian and can be reproduced quantitatively on the basis of a purely statistical model [4].

3.4. Cross Sections

The cross sections as a function of Z can provide information on the degree of relaxation associated with the mass asymmetry degree of freedom.

In fig. 8, we show plots of cross section in mb/sr as a function of Z at various angles for the reaction Ag + Ar (288 MeV). One observes an increase in cross sections as Z increases. An even-odd fluctuation also can be observed which seems to be commonplace in reactions which have undergone extensive relaxation.

Figure 9 shows similar data for the reaction Ag + N (160 MeV). These cross sections show dramatic peaks in the region of Z = 6, 7 and 8 which is close to the projectile. These peaks decrease in magnitude at higher angles and at higher Z values where the cross section becomes roughly constant above Z = 12. It appears that the large peaks are associated with coupling between the entrance and exit channels. A further feature of the spectra is again the even-odd fluctuation.

Similar effects are observed for the case of Ag + N (250 MeV) and for the same reaction at 100 MeV. However, in the case of Z's well away from the projectile the cross sections for the 250 MeV data are about 3 to 4 times larger than for the 160 MeV case and at 100 MeV they are about a factor of ten lower than at 160 MeV. Thus, for high Z products the cross sections are increasing with energy in a way which reminds us of the excitation functions associated with compound nucleus formation.

3.5 Angular Distribution

The angular distributions obtained from our data are especially significant. In fig. 10 both the laboratory and center of mass angular distributions for the reaction Ag + Ar (288 MeV) are shown. All the angular distributions associated with the various atomic numbers are strongly forward peaked. There is a suggestion of a slight rise of the

cross section in the backward direction. It should be kept in mind that the cross sections for reactions induced in this way are modulated by the geometrical factor $\frac{1}{\sin\Theta}$ because of the orientation of the angular momenta in a plane perpendicular to the beam direction. Thus, if a long-lived compound nucleus were formed, the angular distributions would follow a $\frac{1}{\sin\Theta}$ dependence. However, if the decay occurs in a time comparable to the time of rotation the forward angles will be populated with greater probability than the backward angles.

In fig. 11 we show the angular distributions obtained in the reaction Ag + N (160 MeV). Here one observes a strong peaking in the forward direction and distinct peaking is also seen in the backward directions. The forward peaking is extremely large, perhaps of the order 10-100 for fragments close to the projectile such as Z = 5, 6, 7, 8, and 9. The angular distributions become increasingly flatter for heavier fragments such as Z = 10 to 14 and here the deviation from a $\frac{1}{\sin\Theta}$ distribution is perhaps only a factor of two in the forward direction while the agreement seems quite good in the backward direction.

One conclusion that may be reached is that the forward backward asymmetry suggest some general ideas about the time scale for the processes which appear to occur. The time scale is comparable with the period of rotation of the system. The time scale for the decay of fragments close to the projectiles is shorter than it is for the decay of particles removed from the projectile. This result may have a simple explanation. If only a few nucleons are transferred the decay takes place early. Otherwise, more particles would be transferred. In this case the angular

distributions should be more pronounced in the forward direction than in the backward direction. If on the other hand many particles are transferred, the decay time is long and the system will have more time to rotate thus making the angular distribution more symmetric about 90°.

In conclusion, there is some evidence that these angular distributions may provide a possible means for studying relaxation phenomena which occur in a time scale shorter than previously investigated, perhaps as short as 10^{-20} or 10^{-21} seconds.

References

1. J. R. Nix, Washington APS Meeting. (April 1974).

2. K. D. Hildenbrand, H. H. Gutbrod, W. V. Oertzen and R. Bock, Nucl. Phys. A157 (1970) 297.

3. L. G. Moretto, D. Heunemann, R. C. Jared, R. C. Gatti and S. G. Thompson, Third Symposium on the Physics and Chemistry of Fission, Rochester, New York, (August 1973).

4. L. G. Moretto, Phys. Letters 40B2 (1972) 185.

Figure Captions

Fig. 1. Typical contour map Δ E-E obtained with proportional counter.

Fig. 2. Energy spectra for different elements detected in the ^{40}Ar (288 MeV) induced reaction on natural Ag.

Fig. 3. Same as Fig. 2.

Fig. 4. Energy spectra measured at different angles.

Fig. 5. Most probable kinetic energies as a function of atomic number of the fragments at various angles.

Fig. 6. Most probable kinetic energies as a function of atomic number of the fragment in the center of mass system. The upper line corresponds to the coulomb energies of two touching spheres. The lower line corresponds to the coulomb energies of two touching spheroids at equilibrium deformation.

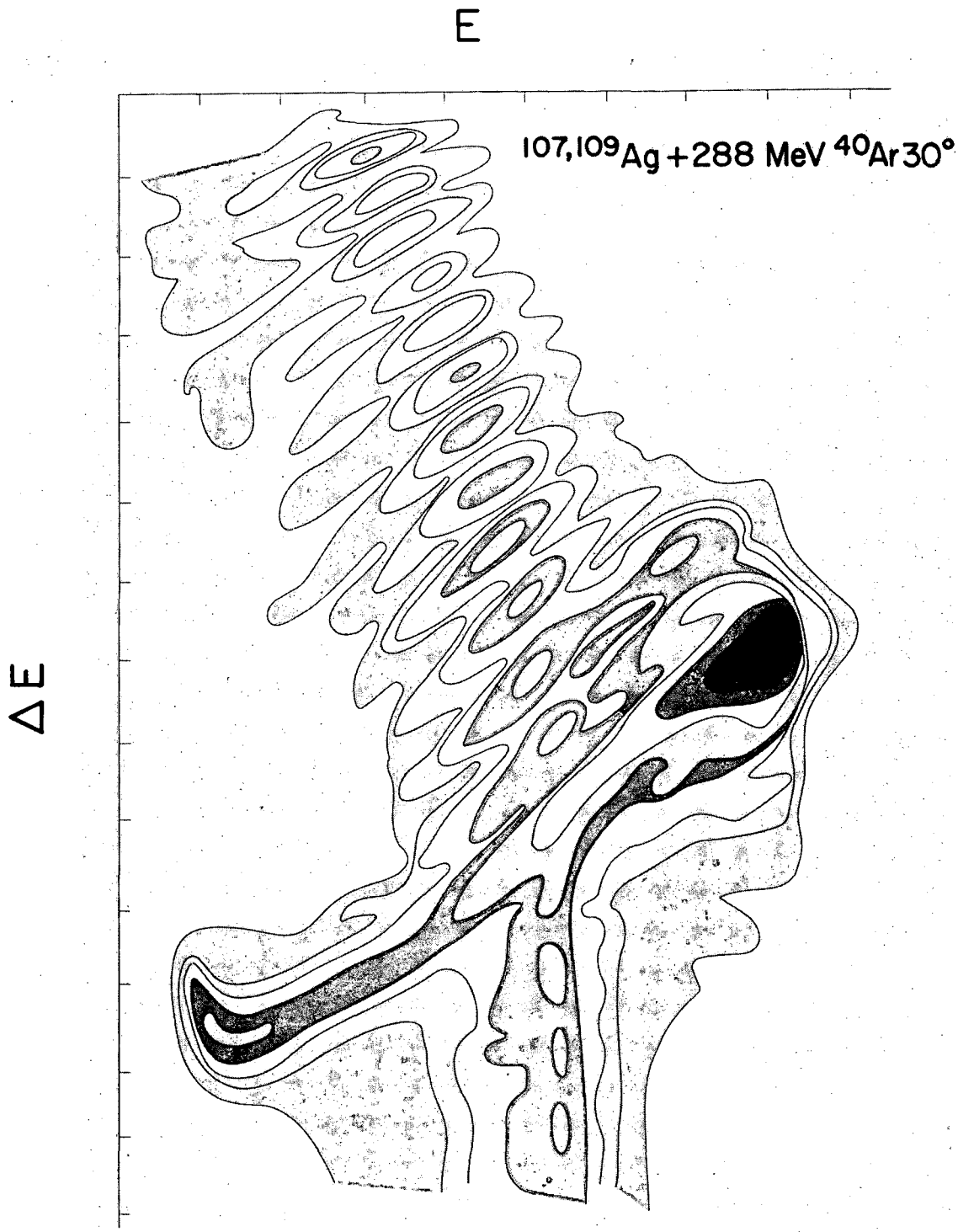
Fig. 7. Most probable energies as a function of atomic number in the center of mass system. The line corresponds to the coulomb energy of two touching spheres.

Fig. 8. Cross sections for the formation of the identified elements at various angles.

Fig. 9. Same as Fig. 8.

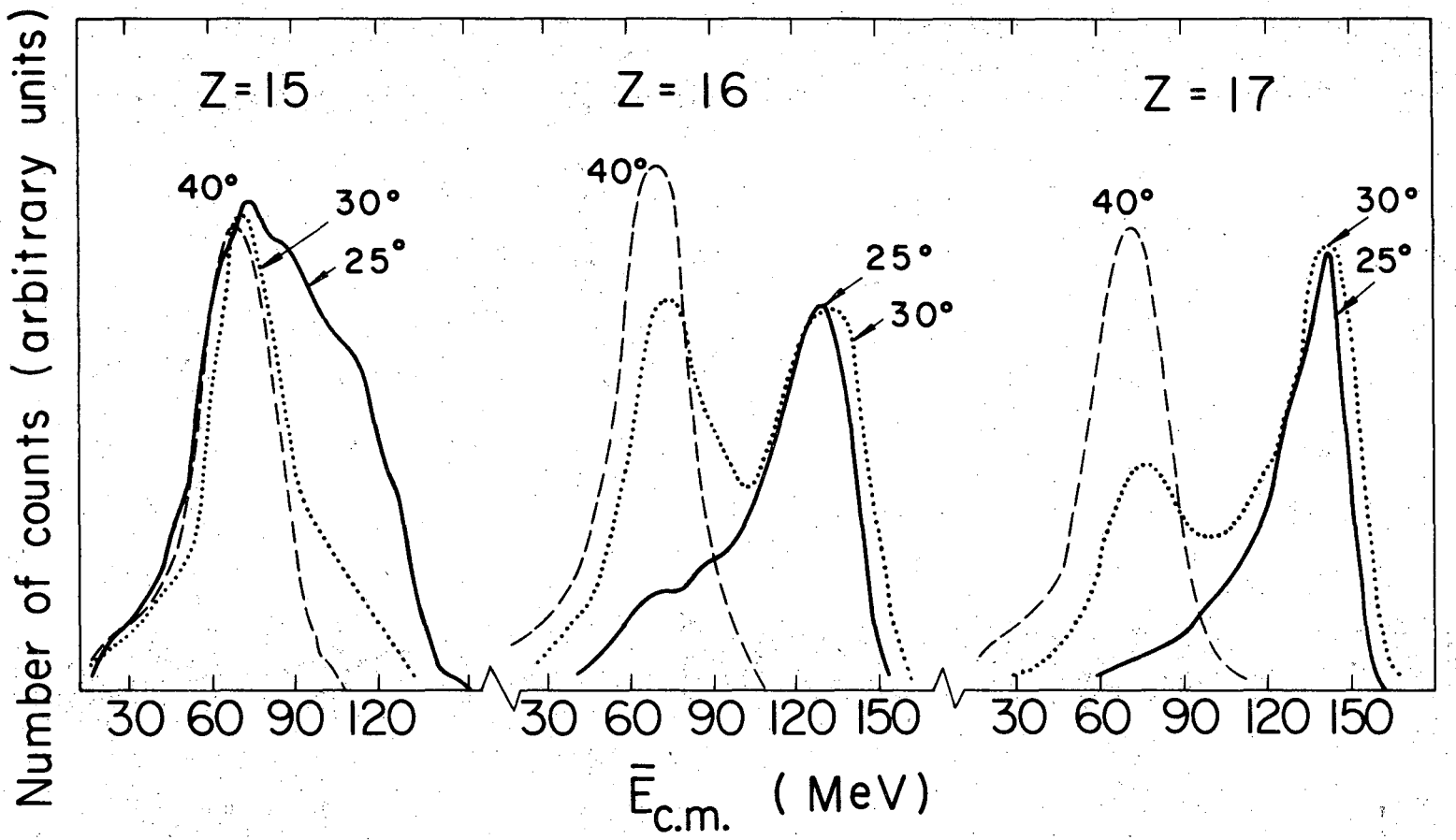
Fig.10. Angular distributions for the various elements.

Fig.11. Same as Fig. 10.



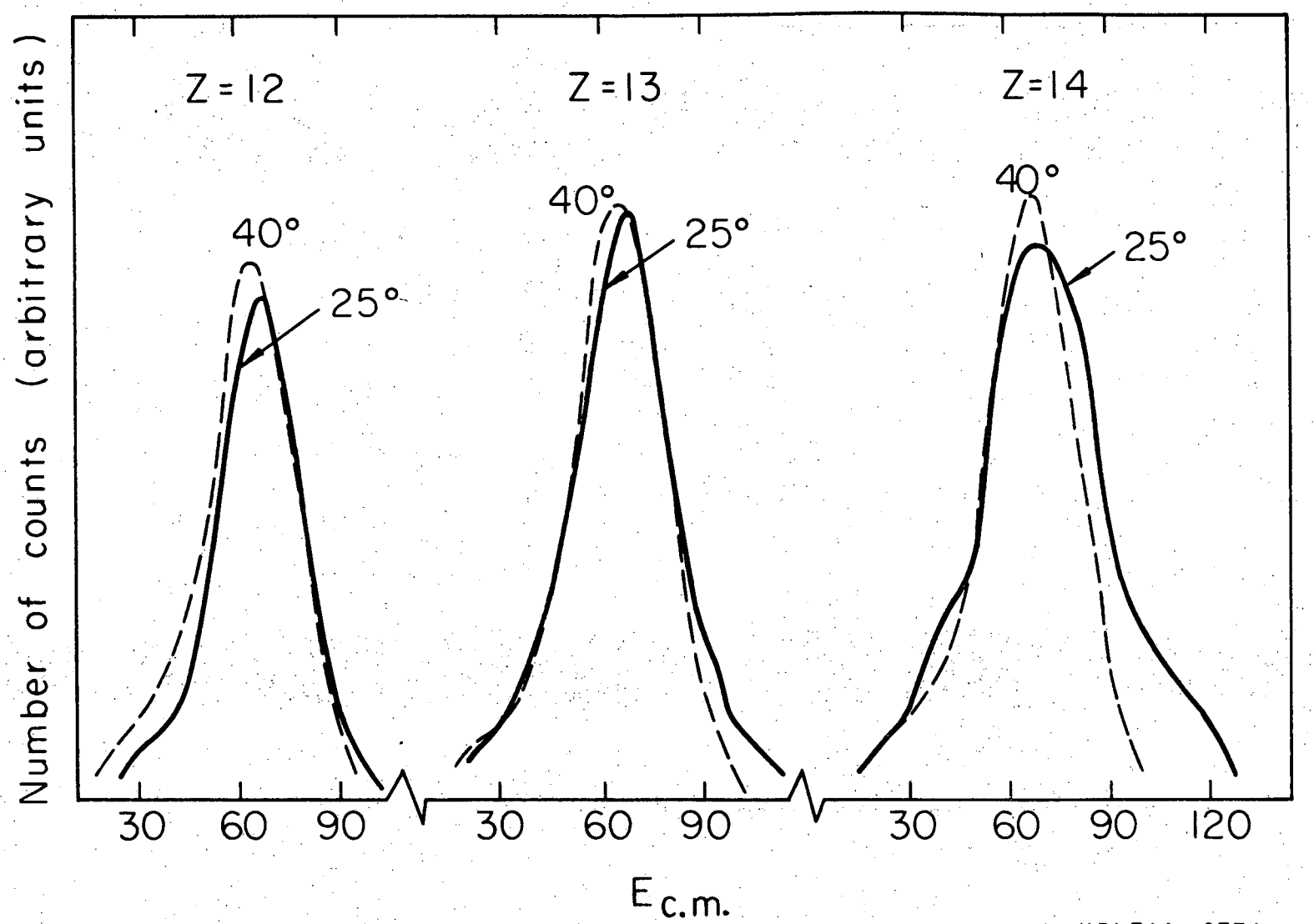
CBB 744-2278

Fig. 1.



XBL744-2775

Fig. 2.



XBL744 - 2774

Fig. 3.

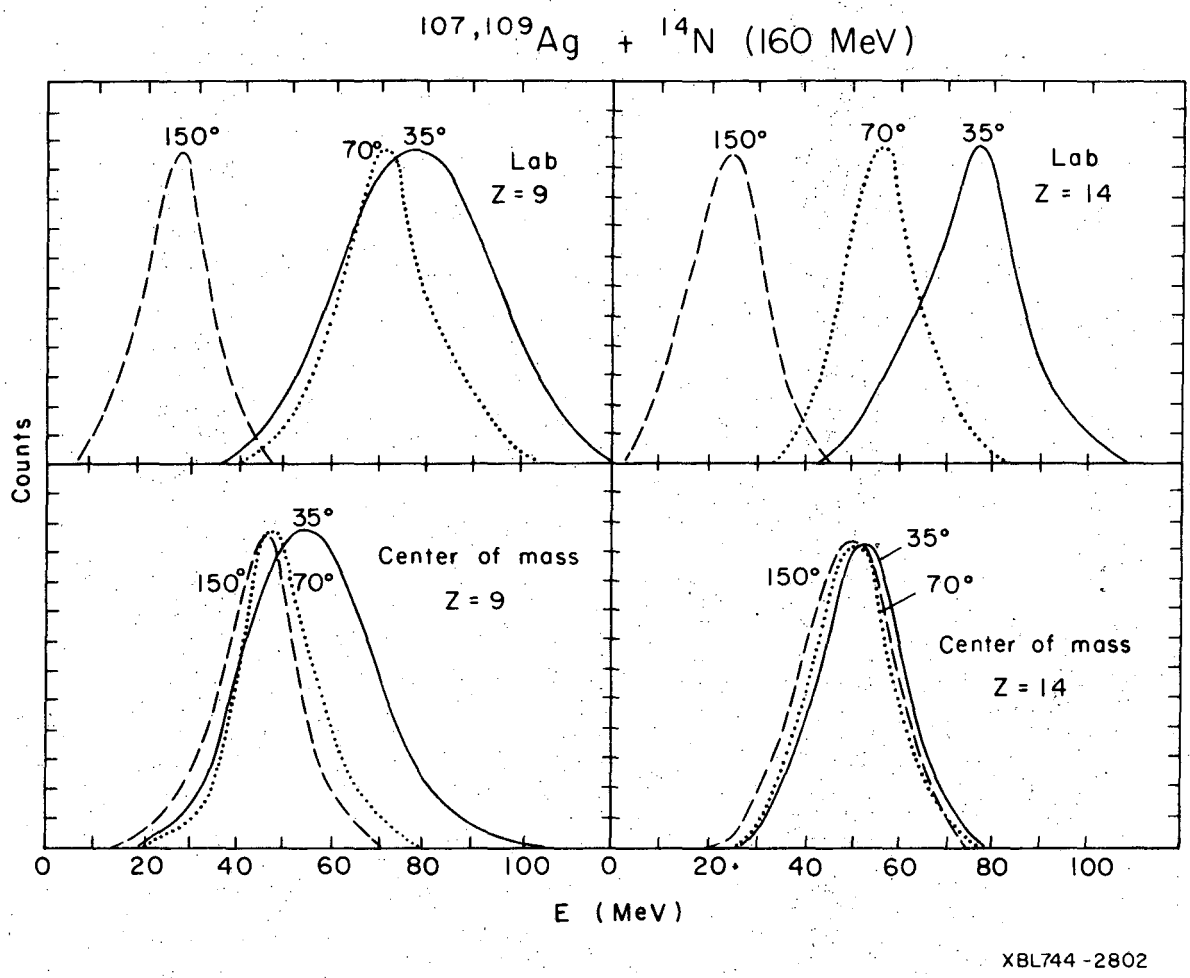
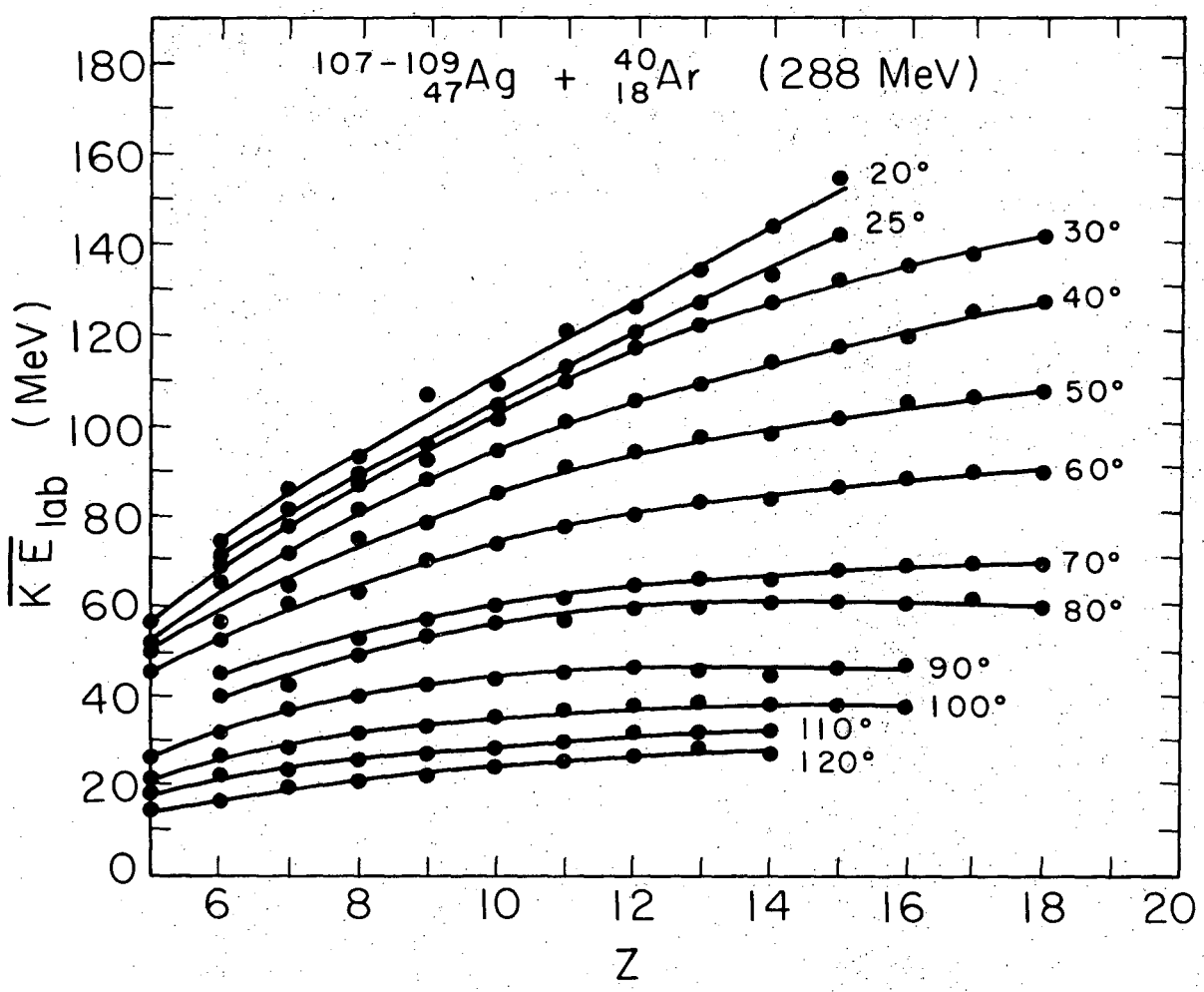

$^{107,109}Ag + {}^{14}N$ (160 MeV)
150°
70°
35°
Lab
Z = 9
150°
70°
35°
Lab
Z = 14
Counts
35°
150°
70°
Center of mass
Z = 9
35°
150°
70°
Center of mass
Z = 14
0
20
40
60
80
100
0
20
40
60
80
100
E (MeV)
XBL744-2802

Fig. 4.



XBL744-2803

Fig. 5.

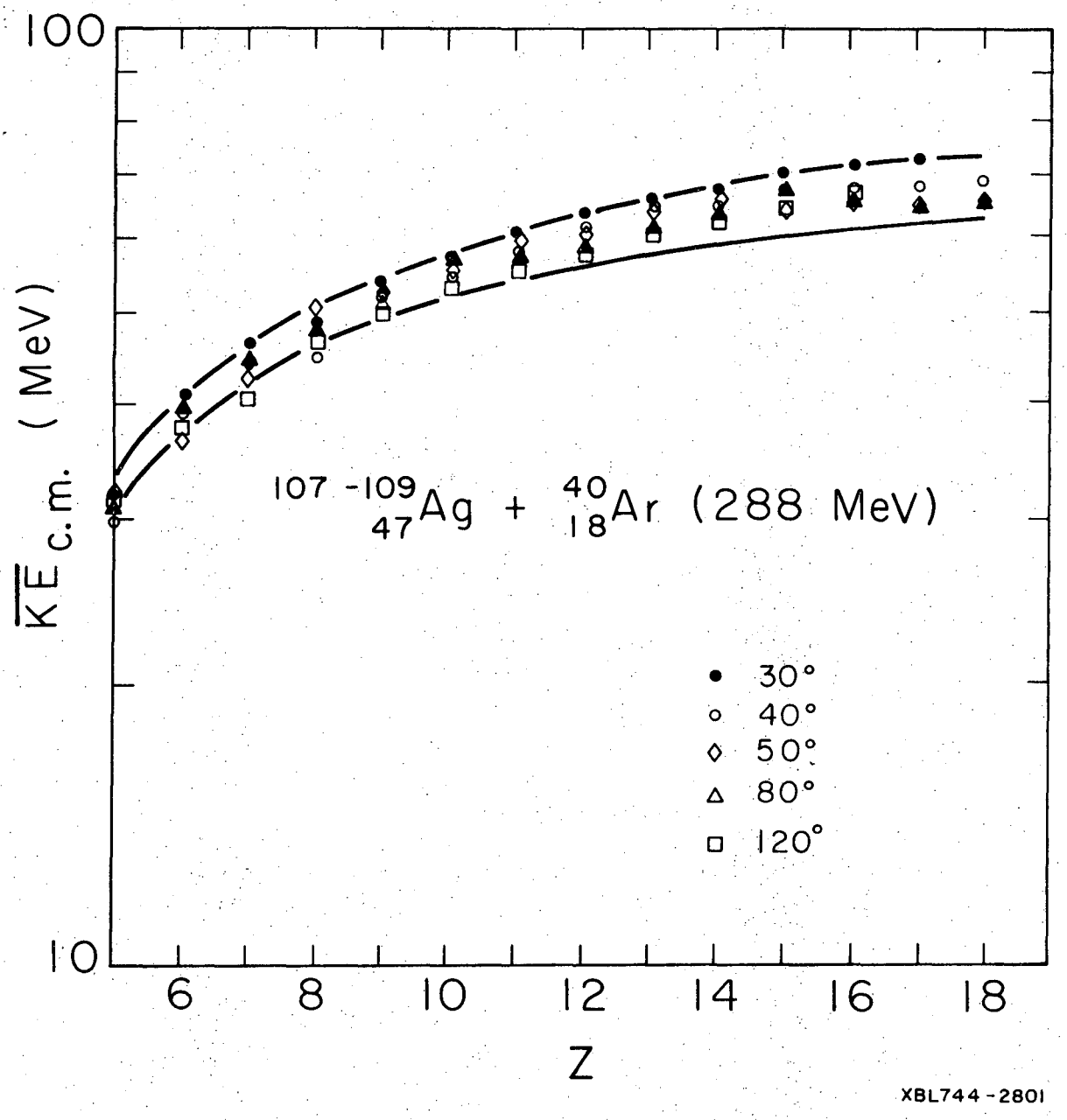
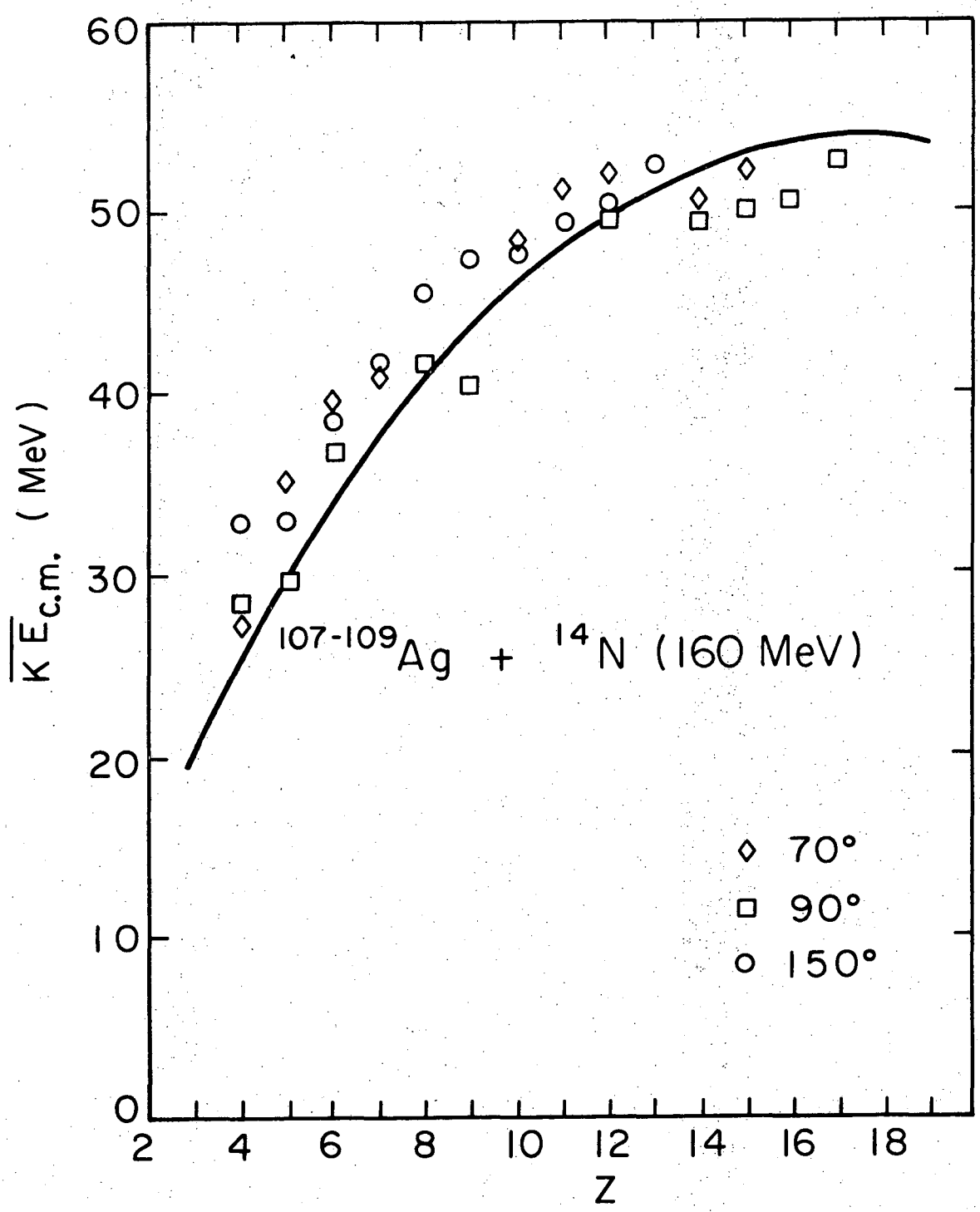
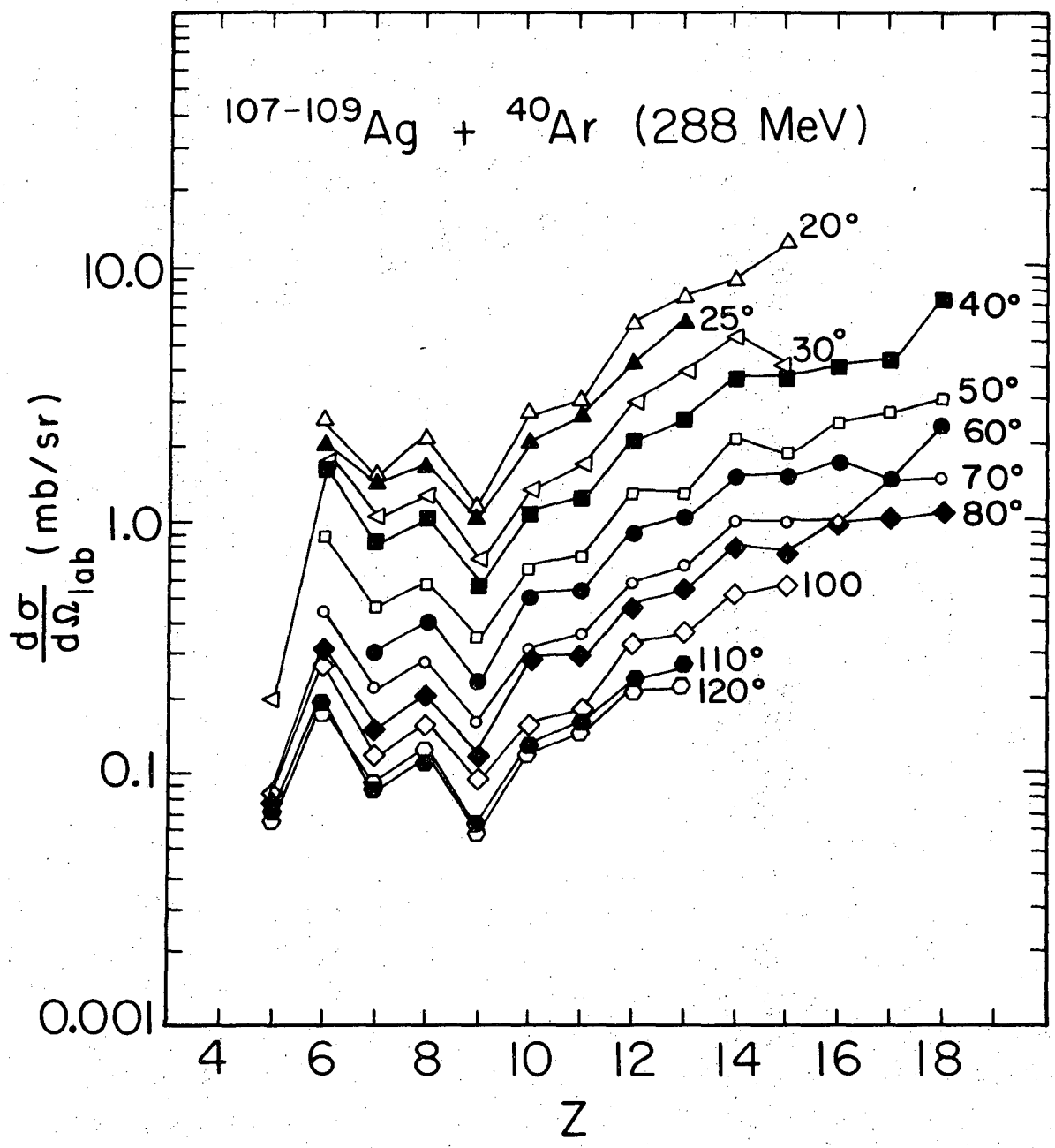

100
10
6
8
10
12
14
16
18
Z
$\overline{KE}_{c.m.}$ (MeV)
$^{107-109}_{47}Ag + ^{40}_{18}Ar$ (288 MeV)
30°
40°
50°
80°
120°
XBL744-2801

Fig. 6.



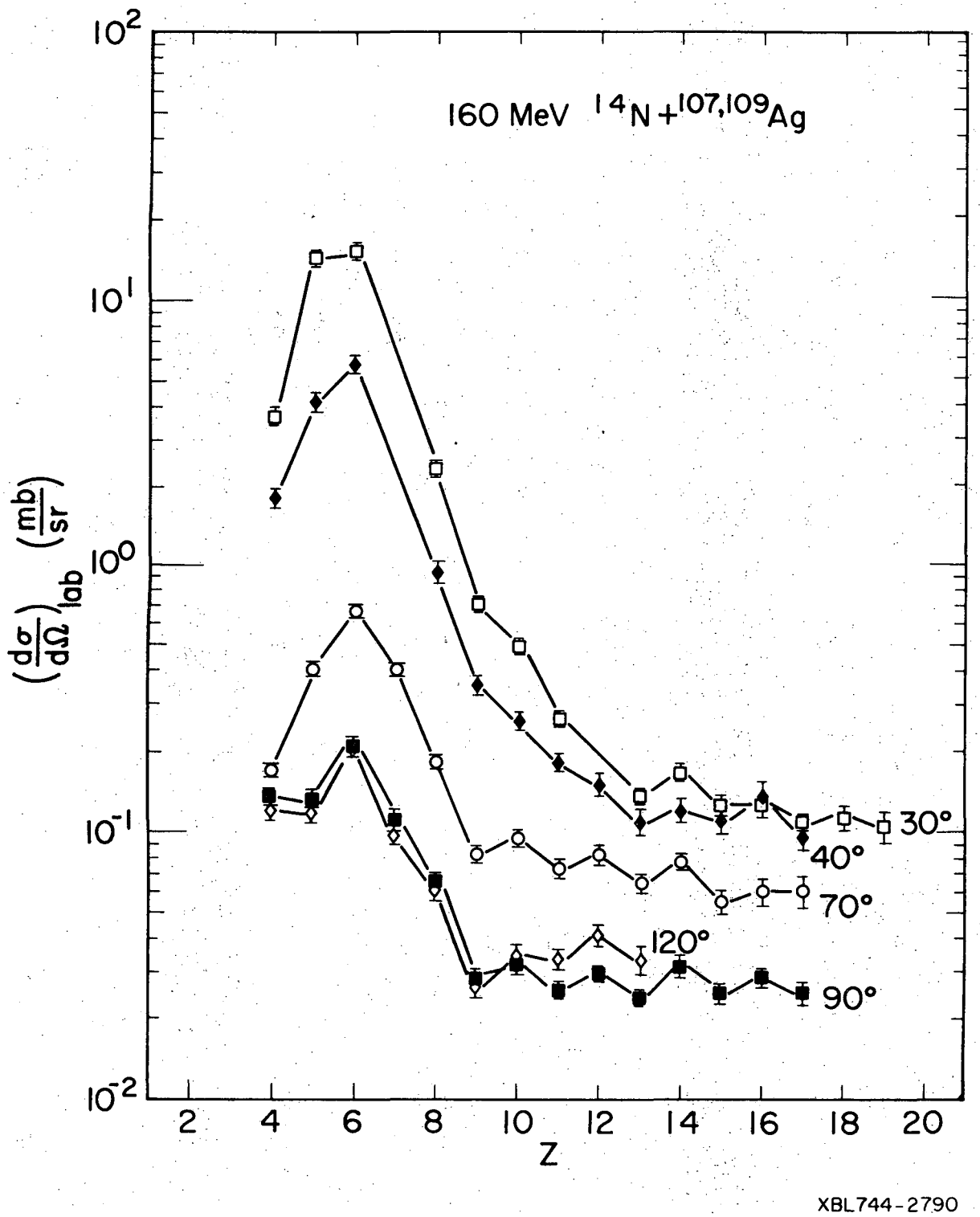
XBL744-2804

Fig. 7.



XBL744-2800

Fig. 8.



XBL744-2790

Fig. 9.

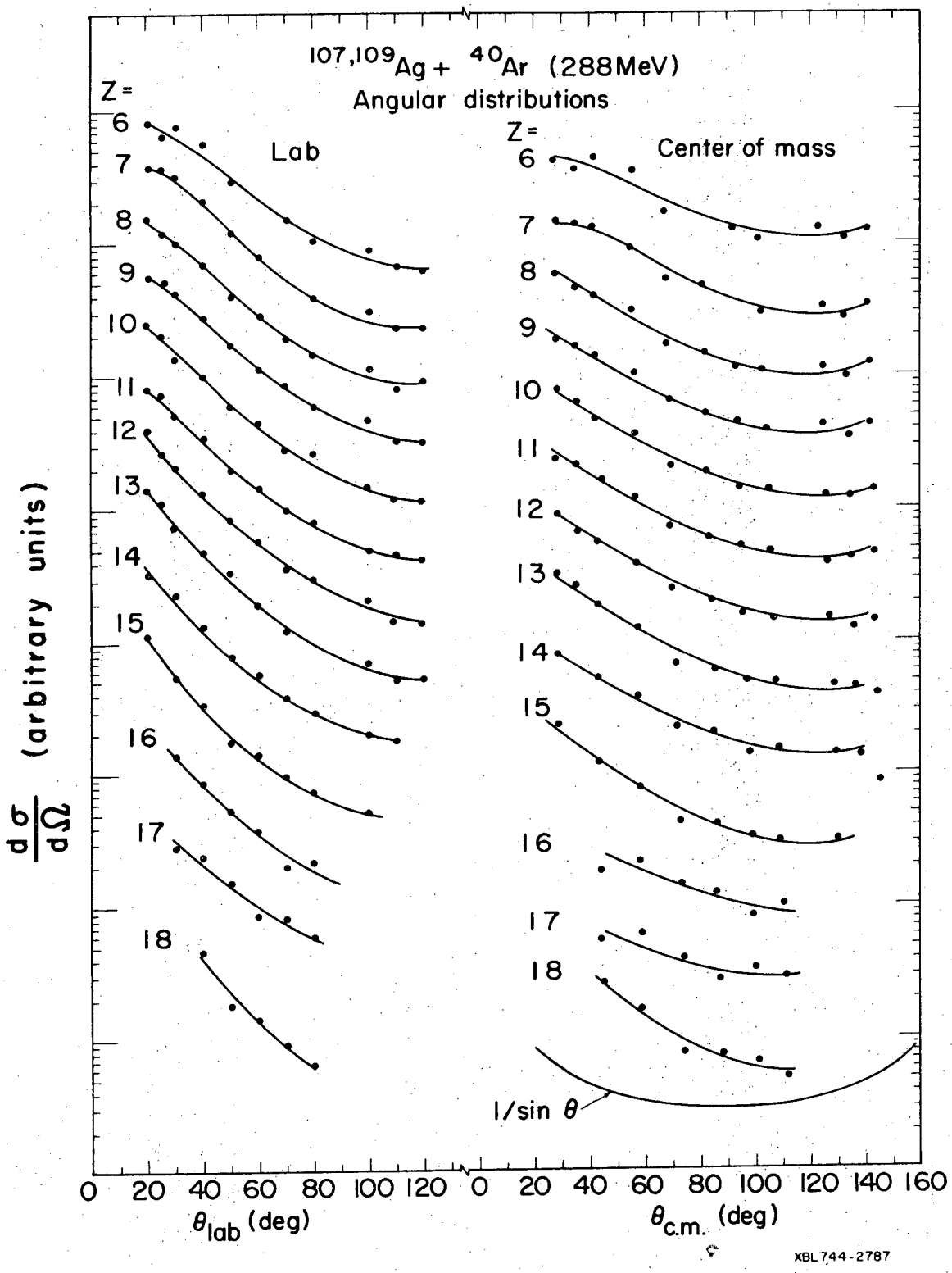

107,109Ag + 40Ar (288MeV)
Angular distributions
Lab
Center of mass
Z=
6
7
8
9
10
11
12
13
14
15
16
17
18
1/sin θ
dσ/dΩ (arbitrary units)
0 20 40 60 80 100 120
θlab (deg)
0 20 40 60 80 100 120 140 160
θc.m. (deg)
XBL744-2787

Fig. 10.

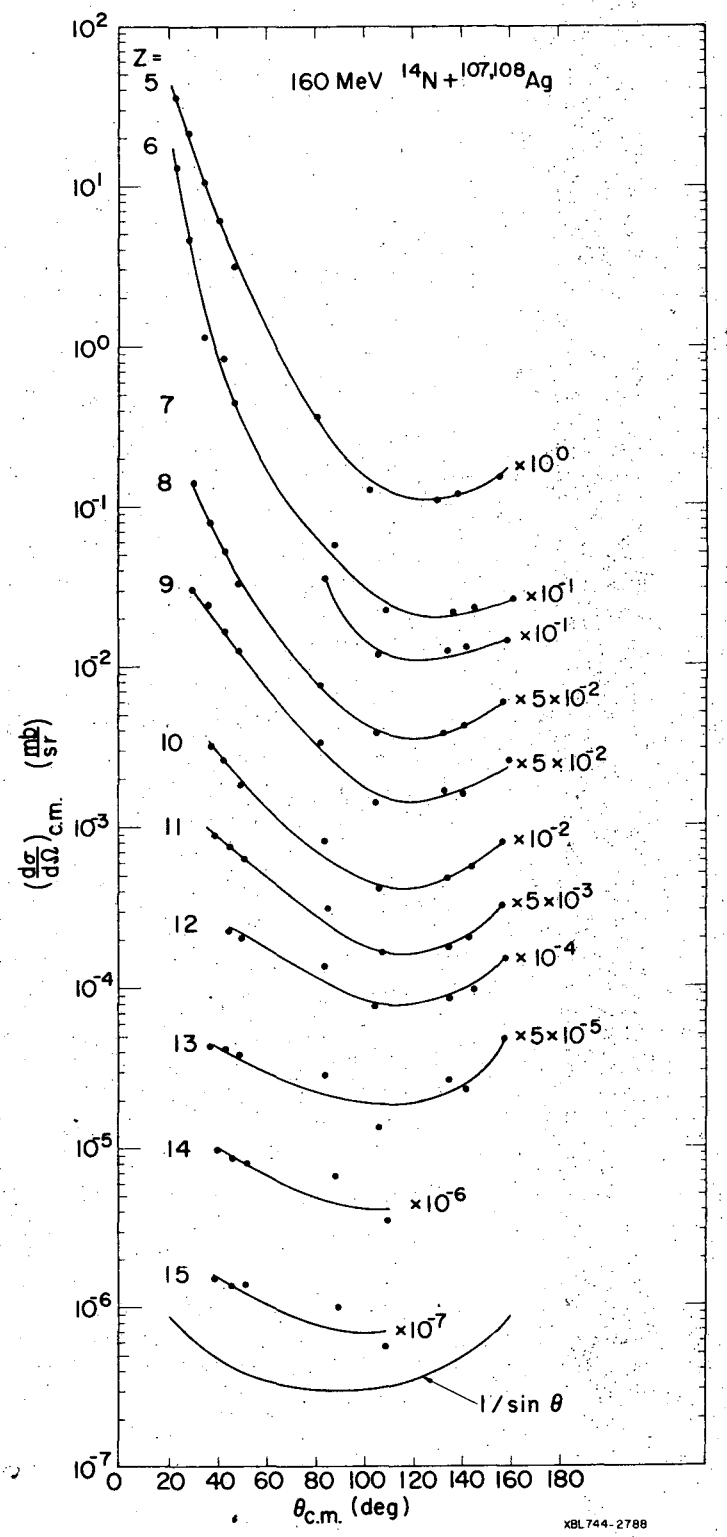

Z =
5
6
7
8
9
10
11
12
13
14
15
160 MeV $^{14}N + ^{107,108}Ag$
$\times 10^{0}$
$\times 10^{-1}$
$\times 10^{-1}$
$\times 5\times 10^{-2}$
$\times 5\times 10^{-2}$
$\times 10^{-2}$
$\times 5\times 10^{-3}$
$\times 10^{-4}$
$\times 5\times 10^{-5}$
$\times 10^{-6}$
$\times 10^{-7}$
1/sin θ
$(\frac{d\sigma}{d\Omega})_{c.m.}$ $(\frac{mb}{sr})$
$\theta_{c.m.}$ (deg)
XBL744-2788

Fig. 11.

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720