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STUDY OF A FISSION-LIKE ENVIRONMENT IN REACTIONS WITH VERY HEAVY IONS*

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The dynamical aspects of the later stages of fission can be studied in the broader context of those reactions where the collective degrees of freedom play a dominant role. The interaction of large heavy ions with nuclei provides an ideal tool to sample the conditions prevailing in a scission-like environment. For this purpose a program has been started to study the reactions between ^{40}Ar and various targets. Energetic particles produced in these reactions are observed at various angles by means of a counter telescope. The analysis of the data provides the atomic number of the emitted particles, their angular distribution and their kinetic energy distribution. The reactions between ^{40}Ar and both a Cu and a Ag target at 288 MeV bombarding energy show an impressive emission of particles ranging in atomic number from 1 to 25 and above, matched in variety only by the fission process itself. The angular distributions

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are mostly peaked forward with the exception of the fragments with atomic number close to 18 in the case of the Cu target, for which a cross section increasing with angle is observed. The Z distribution at various angles suggests that the system is relaxing along the mass asymmetry coordinate. In the case of the Cu target the charge distribution seems to drift toward lower Z while in the case of the Ag target the drift is in the direction of larger Z. This is consistent with the potential energy of two spherical liquid drops in contact and rigidly rotating. The kinetic energy distributions are gaussian-like and peak at energies close to the Coulomb energies of two touching spheres. Both the charge distributions and the kinetic energy distributions suggest the picture of a very viscous dynamical evolution dominated by the potential energy. This evidence is consistent with the assumption of a viscous dynamical process in the latter stages of fission.

INTRODUCTION

Most of the progress which has occurred in understanding the fission process over the years is the result of improved knowledge of the potential energy of the system taken together with the applications of statistical mechanics in suitable critical stages of the reaction. The liquid drop model, corrected for shell effects by means of the Strutinski procedure, has provided an adequate understanding of the behavior of the nuclear potential energy as a function of deformation not only in the neighborhood of the ground state but also at the saddle point deformations. The use of statistical mechanics describing the random access to the saddle point has provided a quantitative understanding of the fission decay widths and of the fission fragment angular distributions. Finally the de-excitation of the excited fragments in flight is also well understood in terms of the standard statistical theory of evaporation. However this series of flattering successes is interrupted at a crucial stage of the fission process where the present theoretical understanding is unsatisfactory notwithstanding the detailed experimental evidence available. This stage is the descent from saddle to scission. In this region the lack of stationary points in the potential energy makes it necessary to perform dynamical calculations. Two new quantities are required to specify the dynamical evolution of a system: the viscosity tensor and the inertia tensor. Both quantities are very difficult to calculate from the nucleon-nucleon interaction or even empirically and very little experimental information is available. However there is hope that one might be able to decide whether the system behaves more like a viscous or like a non-viscous fluid. In the former case the system is prevented from achieving large velocities and the potential energy dominates the outcome of the reaction. In the latter case the system can achieve large velocities and the inertias dominate the course of the reaction. At first sight one might hope that a simple check on the fission fragment kinetic energies could provide direct information about the viscosity of the saddle to scission descent. In order to be able to draw any conclusion one must gain experimental information on how the total kinetic energy is divided into a pre-scission and a post-scission component. Unfortunately there is almost no experimental information on the subject. Calculations have been performed with various assumptions about the inertias and the viscosity [1-4]. However it appears that a definite answer about the viscosity of nuclear matter must depend on experimental data.

The fission kinetic energies provide ambiguous information regarding the viscosity associated with the collective degrees of freedom. However it is possible to visualize a suitable scission-like environment where the same collective degrees of freedom are called into play and where the initial kinetic energy injected into the system can be chosen at will. Such a scission-like environment can be easily obtained in the collision between nuclei and large heavy ions. The non-compound nucleus reactions occurring in these collisions are associated with the production of a large variety of particles and strongly suggest the involvement of collective degrees of freedom [5-7].

The two touching nuclei can evolve along many different collective coordinates, like the mass asymmetry, the charge asymmetry and various deformation parameters. This evolution may lead to the formation of the compound nucleus or to the direct re-emission of another fragment. The charges, masses, and the kinetic energies of these fragments emitted in a direct process contain information about the dynamical conditions prevailing in a scission-like environment. In particular one may gather information about the relaxation times associated with the various collective degrees of freedom and about macroscopic quantities such as friction coefficients and viscosity tensors.

In the present paper some preliminary results are presented about the charge distributions, kinetic energy distributions and angular distributions of the fragments emitted in the interaction between Cu and Ag targets with 288 MeV Ar ions.

DESCRIPTION OF THE EXPERIMENT

Two different targets, a 1.37 mg/cm^2 Cu target and a 0.9 mg/cm^2 Ag target, have been bombarded with a 288 MeV ^{40}Ar beam provided by the Berkeley Super-HILAC. The beam is collimated into a 3 mm diameter spot by means of a set of three carbon collimators. This beam, after passing through the target is collected using a Faraday cup and integrated in order to provide the total charge to which the target has been exposed. The particles emitted in the reaction are detected by means of two solid state counter telescopes. The first telescope was composed of a 9.6 μm ΔE detector and of a 380 μm E detector; the second telescope was composed of a 28 μm ΔE detector and of a 380 μm E detector. The thicker ΔE telescope was used to detect lighter particles, the thinner ΔE telescope was used to detect heavier particles. The two telescopes were mounted on movable arms and could be placed at various angles with respect to the beam. A schematic diagram of the electronic equipment is shown in Fig. 1. The pulses coming from the two telescopes are fed to a standard linear and logic circuitry and are finally digitized by an analog multiplexer and ADC system. The digitized information accompanied by identification markers is fed to the computer event by event, through a CAMAC system, packaged and recorded on magnetic tape. A "busy" signal fed back by the computer is used to turn off a scaler which counts the single events in one of the ΔE counters. At the same time another scaler counts the single events from the same ΔE counter without interruption. The counts from both scalers are used to correct for the dead time.

For monitoring purposes the signals from each telescope are fed to a Landis-Goulding particle identifier which produces a preliminary identification spectrum. The data recorded on magnetic tape are analyzed on a 7600 CDC computer. A E-ΔE map is generated and simultaneously a particle identification function (PI) of a standard type is calculated. The adequacy of the particle identification function is checked by means of a PI, E_{Total} map. The kinetic energy distributions associated with each atomic number are corrected for the target thickness and for the dead layers of the various counters. The integrated counting rate for each atomic number is transformed into cross section using the known detection efficiency of the telescopes, the total charge collected in the Faraday cup, the mean charge of Ar when entering the Faraday cup and the target thickness.

The effects of possible contaminants (C, O) on the experimental results has been checked by bombarding a 50 $\mu g/cm^2$ C target and by collecting the fragments with the same equipment described above. The amount of C deposited on the targets during the various bombardments has been estimated by visually comparing the target beam spots with a series of targets on which different amounts of C were evaporated. In the case of the Cu targets the C contamination appeared to be < 3 μg/cm^2, in the case of the Ag targets the C contamination appeared to be < 2 μg/cm^2. Because of the rapid drop of the cross section for the C target with increasing Z, the contamination effects are more serious at low Z. At Z = 18 the C contamination contributes to the cross section less than 1% in the Cu bombardment and less than 10% in the Ag bombardment. At Z = 10 the contribution to the cross section due to contamination is less than 0.1% in Cu and less than ∿ 1% in Ag. At larger Z the corrections are completely negligible.

EXPERIMENTAL RESULTS

A very large variety of fragments is produced in the reactions of both targets which have been studied here. Portions of the particle identification spectra for Cu and Ag targets are shown in Fig. 2. More detailed information about the actual range in atomic numbers which has been investigated experimentally can be obtained from the following figures. In the case of Cu the Z range is from $Z = 5$ to $Z = 19$ while in the case of Ag the Z range is from $Z = 5$ to $Z = 25$. The boundaries of these ranges are purely instrumental. It has been ascertained that particles with $Z < 5$ are also abundantly produced and can be easily identified. Particles with $Z > 19$ for Cu and with $Z > 25$ for Ag are also produced. However their identification becomes more difficult and the kinetic energy spectra are substantially cut-off on the low energy side because of the thickness of the ΔE counter.

The cross sections for the production of fragments with various Z at each angle are displayed in Fig. 3. In the case of the Cu target a peak in the cross section is observed at $Z = 12$ for the 20° and 30° angles, while at 50° angle the cross sections increase with some alternation from $Z = 6$ to $Z = 18$.

In the case of the Ag target the cross sections tend to increase with increasing atomic number both at 30° and at 40°. At 50° angle the cross section peaks around $Z = 21$. Even-odd fluctuations can be discerned in some of the distributions. Quite remarkable is the yield of ${}_9F$ which is systematically low in all the distributions for both targets.

The angular distributions in the experimental angular range associated with the various atomic numbers are displayed in Fig. 4. For the Cu target the angular distributions are strongly peaked forward for the lower atomic numbers. The forward peaking decreases with increasing Z until, for $Z \simeq 15$ the cross section is approximately equal at all angles. Above $Z = 15$ the cross section appears to increase at larger angles. On the other hand, for the Ag target, the angular distributions are peaked forward for all the atomic numbers. The kinetic energy distributions, corrected for target thickness and for the detector dead layers appear as broad gaussian distributions. Some examples of such distributions are shown in Fig. 5. The most probable kinetic energies, are presented in Fig. 6. In both cases the most probable kinetic energies for each angle increase with atomic number. Such an increase becomes slower at the highest atomic numbers where in fact a slight decrease begins to appear. The widths of the kinetic energy spectra are very large. The FWHM ranges from ∿ 20 MeV at $Z = 5$ to ∿ 45 MeV for $Z = 25$ for the Ag target and from ∿ 30 MeV to ∿ 60 MeV for the Cu target.

DISCUSSION

Evidence of a Two Body Kinematics. The results of the present experiment may be related to the conditions prevailing in the scission of a fissioning nucleus only if the observed reaction is mainly a two body process. Only a coincidence experiment can give a definite answer to this question. However there are a few tests which may provide evidence for or against the binary nature of the process. Kinematic evidence can be obtained by transforming the observed laboratory kinetic energies to the center of mass system. If the kinetic energies observed at various laboratory angles transform to essentially the same kinetic energy in the center of mass it should be a good indication in favor of a binary disintegration. In order to perform such a transformation it is necessary to determine the masses of the fragments. In the present experiments only the charges and not the masses of the products are measured. Therefore one must make an assumption about the charge to mass ratio in order to obtain the necessary mass of the fragment. For lack of better knowledge two extreme choices have been made: in one case it is assumed that the charge to mass ratio of the observed fragment is the same as in ^{40}Ar, in the second case it is assumed that the charge to mass ratio is the same as in the combined system. For the Cu + Ar system the two choices are practically identical, for the Ag + Ar system the two choices differ only slightly. The transformations of the most probable kinetic energies to the center of mass sytems have been carried out and the results are shown in Fig. 7. It can be observed that the most probable kinetic energies for each given Z obtained at the various angles, once transformed to the center of mass system, agree remarkably well with each other, better in the case of the Ag target than in the case of the Cu target. In the same figures the kinetic energies which the fragments would obtain if just repelled by the Coulomb interaction are also shown. Such theoretical kinetic energies are strikingly close to the experimental values. The flattening out and bending down of the kinetic energy curve as a function of Z, due to the energy taken off by the recoiling partner is observed in the experimental data as well. This is further evidence of the validity of two body kinematics. This evidence does not rule out that some of the particles arise from the break-up of an Ar like excited particle obtained by the transfer of a limited number of nucleons [8]. However it seems that the great majority of the particles with $Z > 6$ are obtained by means of a large transfer of nucleons from the projectile. This is further supported by the identification of particles with Z as large as 25 and with unresolved Z larger than 25.

Thus the discussion will be continued under the assumption that the process is essentially binary.

The Fragment Kinetic Energies. The values of the kinetic energies of the emitted particles represent a most revealing observation. As mentioned above, the most probable values of the kinetic energies essentially coincide with the kinetic energies that the fragments would have as a result of the Coulomb repulsion. The initial kinetic energy brought in by the projectile seems to be completely dissipated in the short time interval during which projectile and target interact with each other. This relaxation phenomenon can be interpreted classically as due to a very large viscosity and friction associated with the relevant collective degrees of freedom in which the system is injected at the instant of collision. The behavior of a dynamical system can be characterized in terms of the potential energy, of the inertia tensor and of the viscosity tensor. When the components of the viscosity tensor are small the system becomes controlled by the inertia and by the potential energy. In such a case it is very difficult to discuss the properties of the system without relying on a full dynamical calculation. On the other hand, if the viscosity tensor is large, the effect of the inertias is inhibited so that the system in its behavior reflects mainly the potential energy. In the present case the latter condition seems to apply since the effect of the Coulomb potential is observed so clearly.

The disappearance of such a large amount of kinetic energy suggests that a strong thermalization process takes place, in which the kinetic energy becomes shared among the internal degrees of freedom of the system. There are indications that the overall system is characterized by a rather large temperature in the width of the kinetic energy distributions. Such widths are much larger than any expected temperature; however it is known that thermal fluctuations in the shape of the system can be strongly amplified by the Coulomb field producing very large fluctuations in the kinetic energy of the fragments at infinity.

A further evidence of a large temperature is related to the fact that the two body kinematics is more apparent in the case of the Ag target than in the case of the Cu target. For the same emitted fragment the partner is heavier for a Ag target than for a Cu target. The heavier the partner, the more its share of excitation energy and the lesser the excitation energy of the primary light fragment. Therefore, for a Ag target, the small fragment may have less chance to decay and the main features of the two body kinematics remain distinctly observable.

The Charge and Mass Distribution. As a system removed from equilibrium evolves, the degrees of freedom with highest natural frequency are expected to achieve thermal equilibrium faster than the degrees of freedom with lower frequency. This rule should be obeyed if the viscous damping is the same for all the degrees of freedom. It seems that the experiment indicates a nearly complete relaxation of the single particle degrees of freedom whose phonon energy is approximately $\hbar\omega_o = 41\ A^{-1/3}$. Similarly there is evidence for the relaxation of the charge asymmetry mode (dipole giant resonance) whose phonon energy is of the order of 10 to 15 MeV. On the other hand the mass asymmetry degree of freedom is expected to have a small phonon energy ($\sim$ 1 MeV) and does not seem to have achieved equilibrium. The experimental evidence of such a condition is visible in the experimental charge distribution which is expected to follow closely the mass distribution. In order to better appreciate the potential energy experienced by the system in its motion along the mass asymmetry coordinate, the potential energies of two touching liquid drop spheres, rigidly rotating with different amounts of angular momentum are plotted in Fig. 8 as a function of the asymmetry parameter $A_1/(A_1 + A_2)$ for the composite systems Cu + Ar and Ag + Ar. In the case of Cu + Ar at zero angular momentum the potential energy has a maximum at symmetry and decreases as the system becomes more asymmetric. This reflects the instability in the mass asymmetry mode of the fission saddle point below the Businaro-Gallone point ($x = 0.396$). A system experiencing such a potential tends to slide down towards larger and larger asymmetries.

As the angular momentum increases, the maximum in potential energy becomes flatter until a depression is generated and a minimum appears in correspondence to the symmetric saddle point. In other words the angular momentum tends to stabilize the mass asymmetry mode.

The Ag + Ar system exhibits a minimum in the potential energy at symmetry even without angular momentum. If the initial asymmetry is small, the system tends to become more symmetric. If the initial asymmetry is large, the system, like in the Cu + Ar case, tends to drift towards larger and larger asymmetries. As the angular momentum increases, the symmetric minimum becomes deeper and the maximum is displaced towards larger and larger asymmetries.

Many values of the angular momentum can be involved in the two reactions. The Cu + Ar system is characterized by a maximum classical angular momentum $I_{max} = 106\ \hbar$. The corresponding average angular momentum $\sqrt{\overline{I^2}}$ is $75\ \hbar$. In the case of the Ag + Ar system $I_{max} = 166\ \hbar$ and $\sqrt{\overline{I^2}} = 118\ \hbar$. Without taking such calculations too quantitatively one may be led to conclude that in the case of Cu + Ar there should be a tendency in the system to move towards larger asymmetries while in the case of Ag + Ar the system should move towards lesser asymmetries.

An inspection of the Cu + Ar charge distributions shows that at 50° angle the yields peak at Ar (it may be at higher Z but no data are available). At smaller angles the main yields move downward in Z, peaking at $Z \sim 12$ and showing a dramatic depletion in the Ar region.

The charge yields in the Ag + Ar system show a broad peak at 50° angle between $Z = 18$ and $Z = 22$. At smaller angles the yield distribution becomes broader and flatter while the peak moves up to $Z \sim 25$. This behavior can be interpreted qualitatively if one assumes that the distributions at the various angles correspond to a time sequence. Such an assumption can be jusitifed in the following general discussion on the angular distributions.

The Angular Distributions. Under the condition of strong friction between target and projectile, the idea of a nearly unperturbed Coulomb trajectory associated with the extreme impact parameters becomes useless. Similarly the critical angle θ_{cr} should not appear as a significant quantity in the angular distributions. If a large friction is experienced by a particle on a grazing trajectory, the particle will lose the greatest part of its tangential velocity, aside from the amount necessary for angular momentum conservation. If the particle is instantaneously re-emitted it is expected to move away radially at a well defined angle θ_R. If the target nucleus is assumed to have infinite mass and moment of inertia, such an angle is

$$\theta_R = \frac{\theta_c + \pi}{2} ,$$

which is in most cases much larger than θ_c. For a finite target nucleus mass the angle θ_R is different but large nontheless.

If the two particles remain attached to one another for a certain time, the system rotates rigidly with an angular velocity defined by the total angular momentum and by the moment of inertia. If the characteristic splitting time is very small as compared to the rotation period, then the emitted particle should peak at angles close to θ_R. For a splitting time comparable but smaller than the rotation period the angular distribution should be forward peaked, while for a splitting time much larger than the rotation period the angular distribution should be symmetric about 90°. The experimental lack of symmetry about 90° suggests that the splitting time is smaller than the rotation period. Therefore the observation of the particles at various angle does indeed correspond approximately to different times, longer for the smaller angles.

In conclusion the change in charge distribution observed in going from larger to smaller angles can indeed be interpreted as a time evolution of the system under the effect of the potential illustrated in the previous subsection.

CONCLUSION

The results discussed in the previous section seem to indicate that short relaxation times and consequently large viscosities are associated with the collective degrees of freedom involved in heavy ion collisions. These conclusions may be relevant to systems in the neighborhood of the scission point. The inability of the collective degrees of freedom to bear any substantial amount of kinetic energy suggests that the descent from saddle to scission should be very slow. Under these conditions one should not expect any relevant amount of pre-scission kinetic energy. Furthermore such an extreme viscous limit suggests that the dynamical evolution of the system is controlled by the slowest mode (perhaps the neck constriction mode) while all the other faster modes, collective and intrinsic, remain constantly in thermal equilibrium.

The tentative conclusions reached here should be valid in general. However there might be some exception associated with very low energy or spontaneous fission, where the system could retain its superfluidity from saddle to scission. The present results may be relevant also to the formation of superheavy nuclei in heavy ion bombardments. The quick dissipation of kinetic energy along the collective coordinates may prevent the system from achieving the near spherical configuration necessary for the shell effects to operate.

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of the data collection system.

Fig. 2. Examples of particle identification spectra for both Cu and Ag targets at various angles. The ΔE counter thickness is 9.6 μ and the E counter thickness is 380 μ.

Fig. 3. Cross sections for the production of the identified elements at various angles.

Fig. 4. Angular distributions for the various elements.

Fig. 5. Examples of kinetic energy distributions in the laboratory system.

Fig. 6. Most probable kinetic energies as a function of atomic number of the fragments at various angles.

Fig. 7. Most probable kinetic energies as a function of atomic number of the fragment in the center of mass system. The upper lines correspond to the Coulomb energies of two touching spheres. The lower lines correspond to the Coulomb energies of two touching spheroids at equilibrium deformation.

Data Collection System

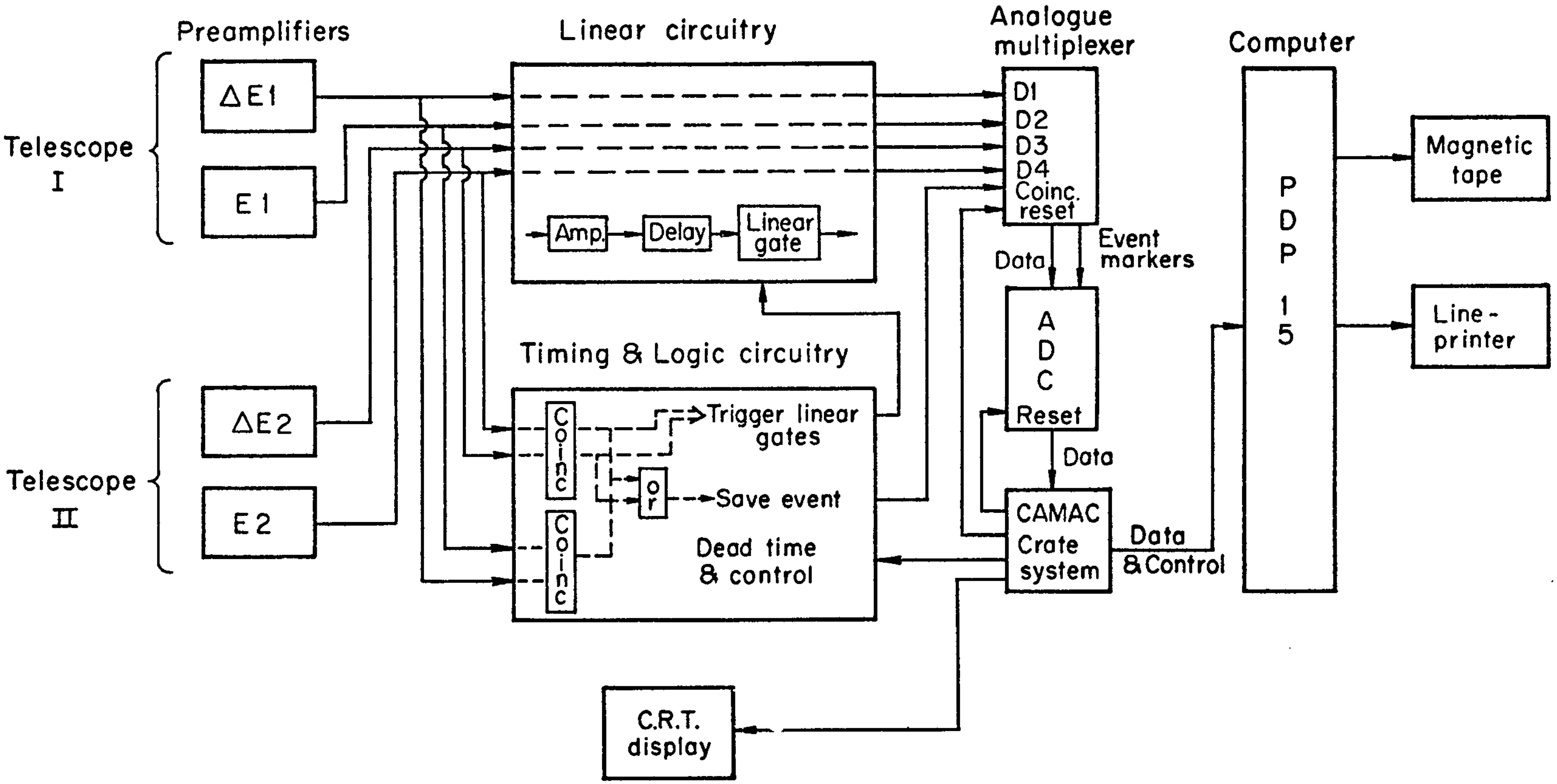

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Fig. 1

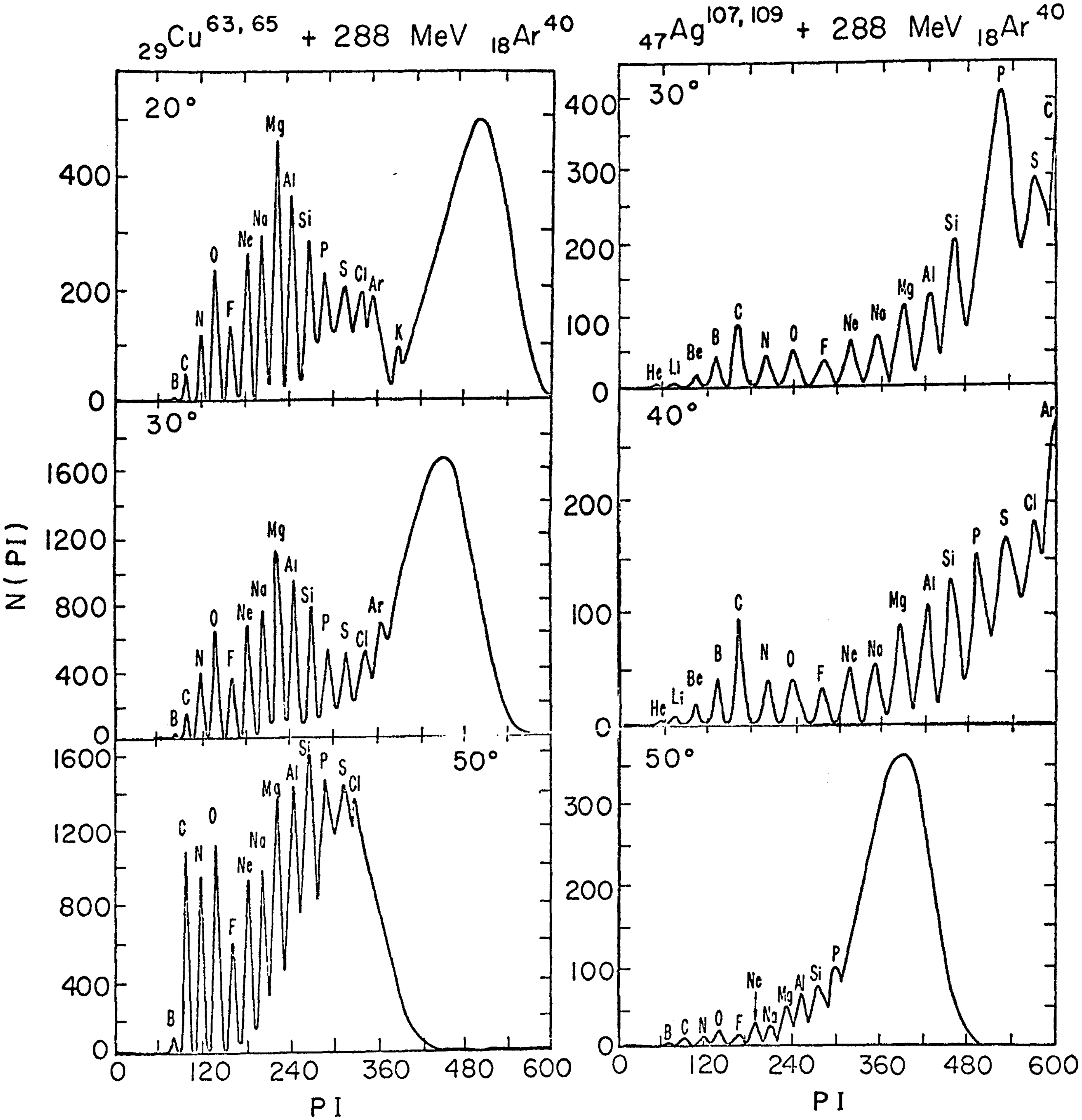

Fig. 2

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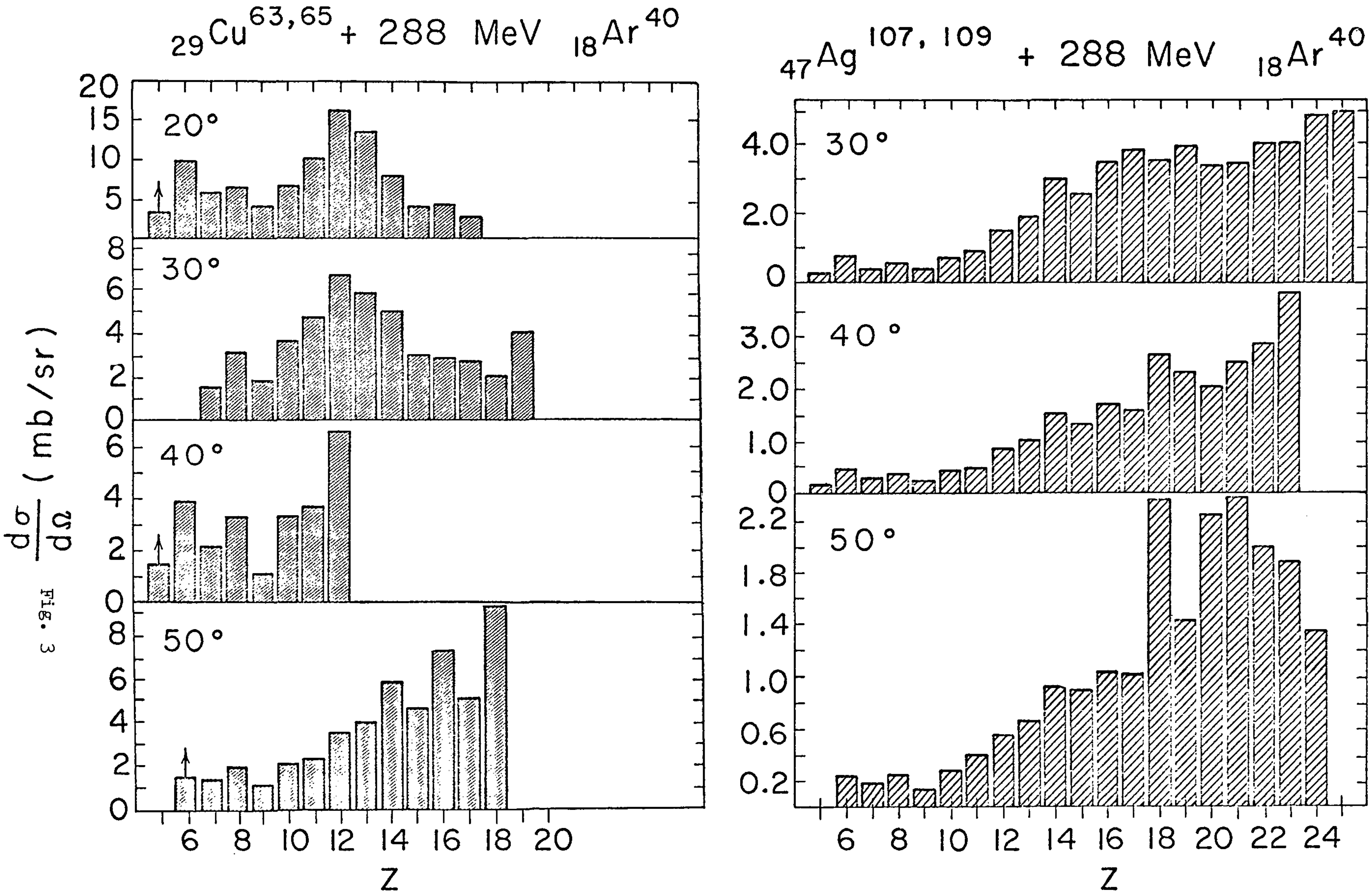

Fig. 3

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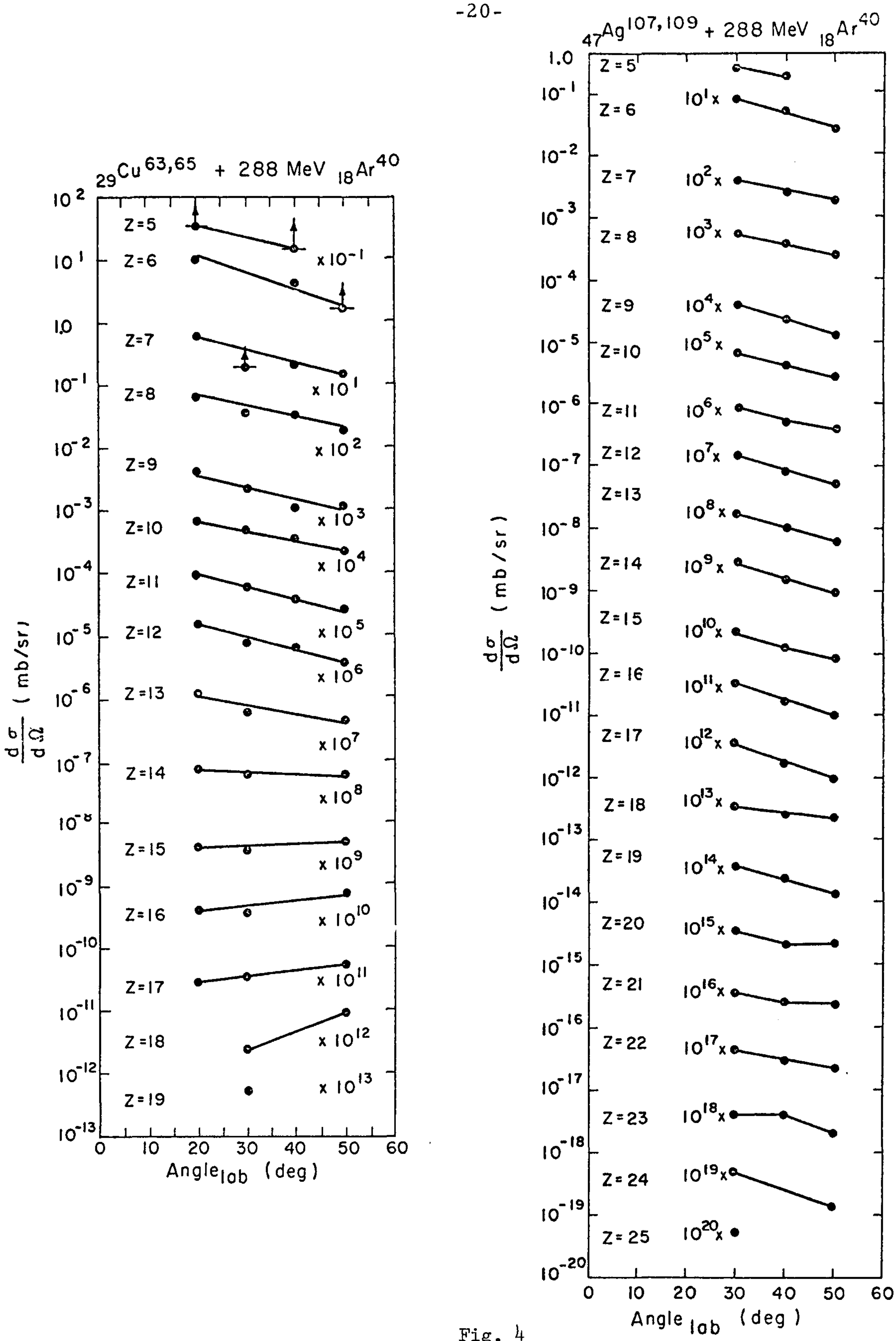

Fig. 4

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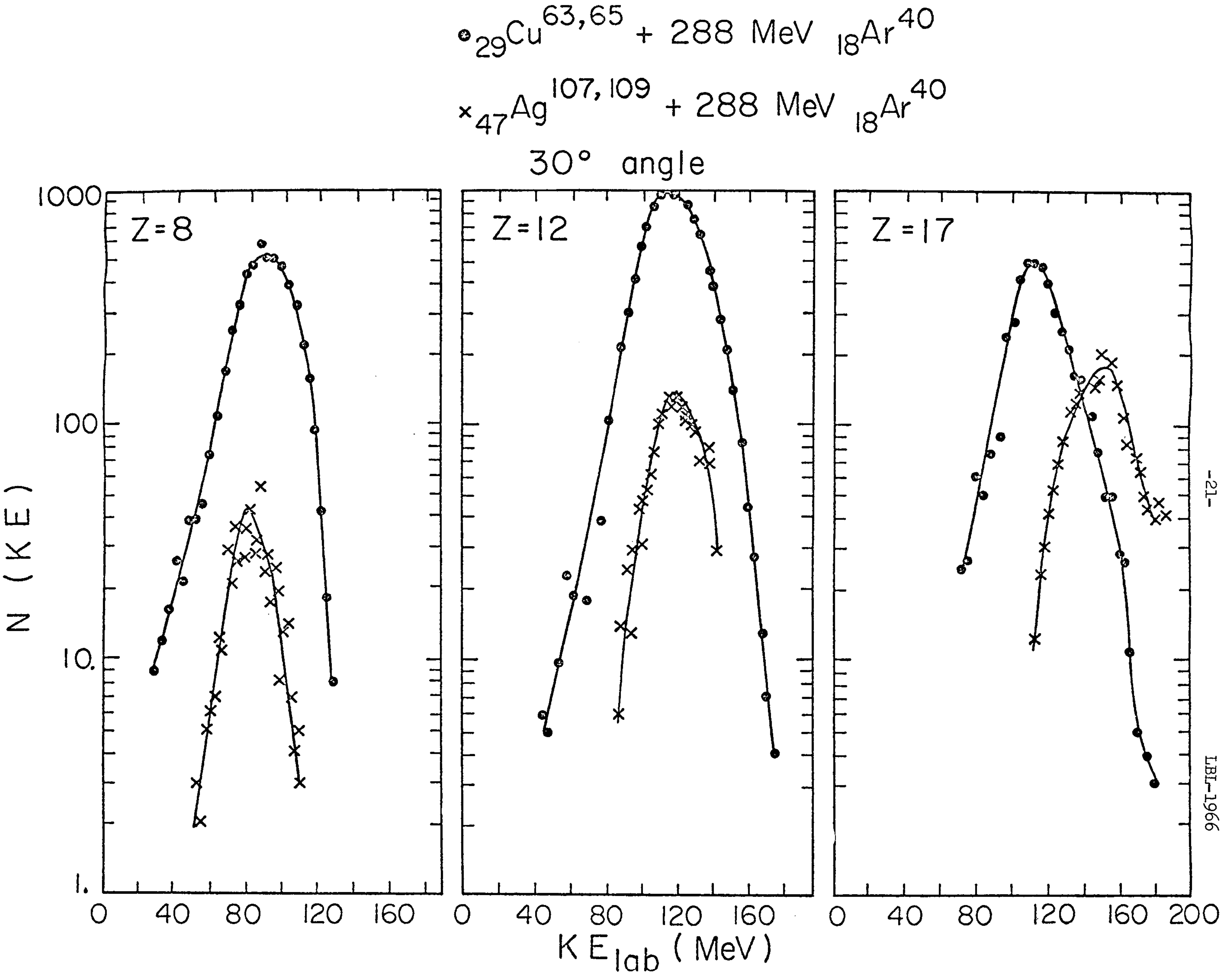

● $_{29}Cu^{63,65}$ + 288 MeV $_{18}Ar^{40}$
× $_{47}Ag^{107,109}$ + 288 MeV $_{18}Ar^{40}$
30° angle
Z=8
Z=12
Z=17
N (KE)
1000
100
10.
1.
0
40
80
120
160
200
KE$_{lab}$ (MeV)

Fig. 5

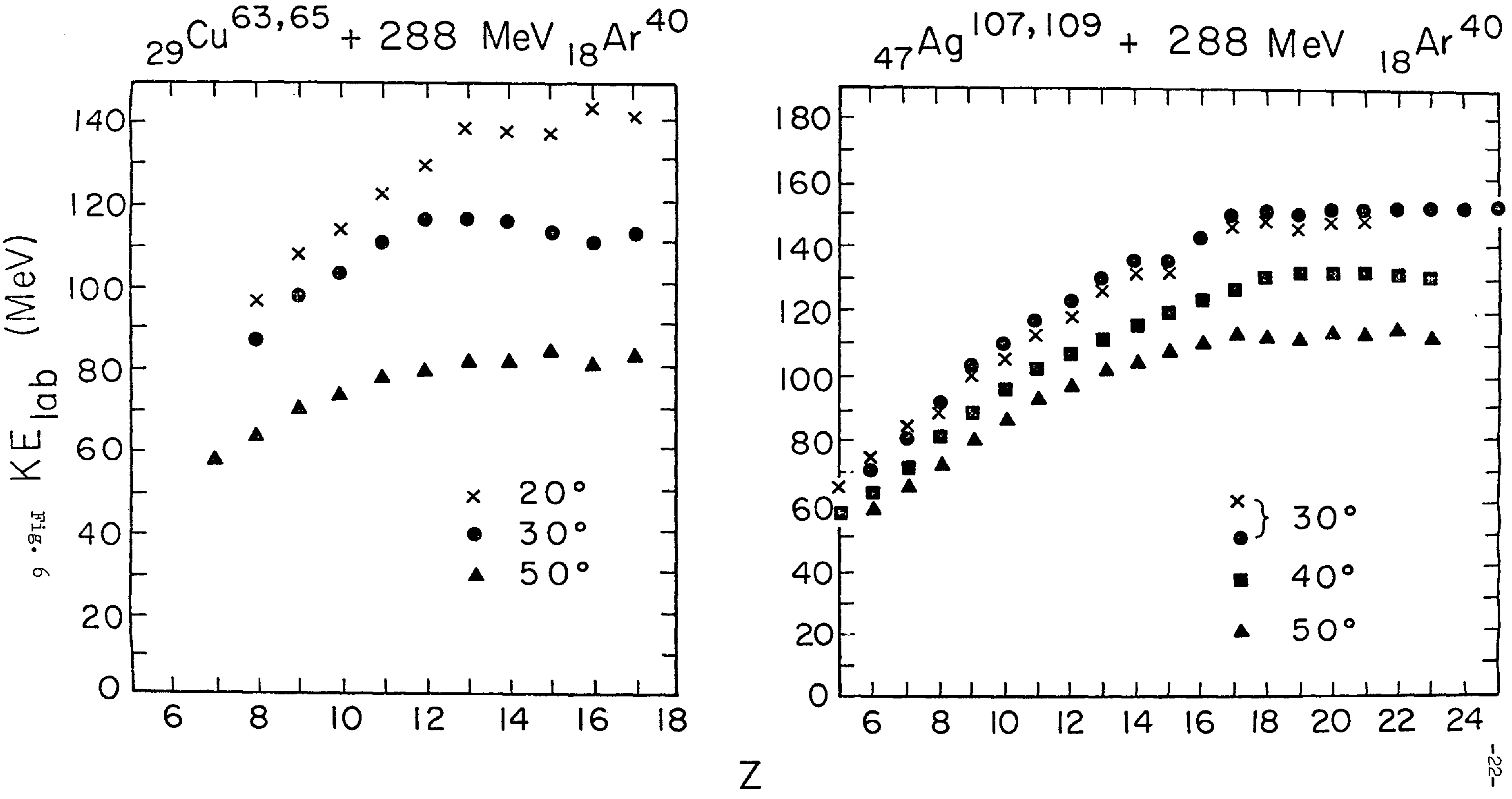

Fig. 6

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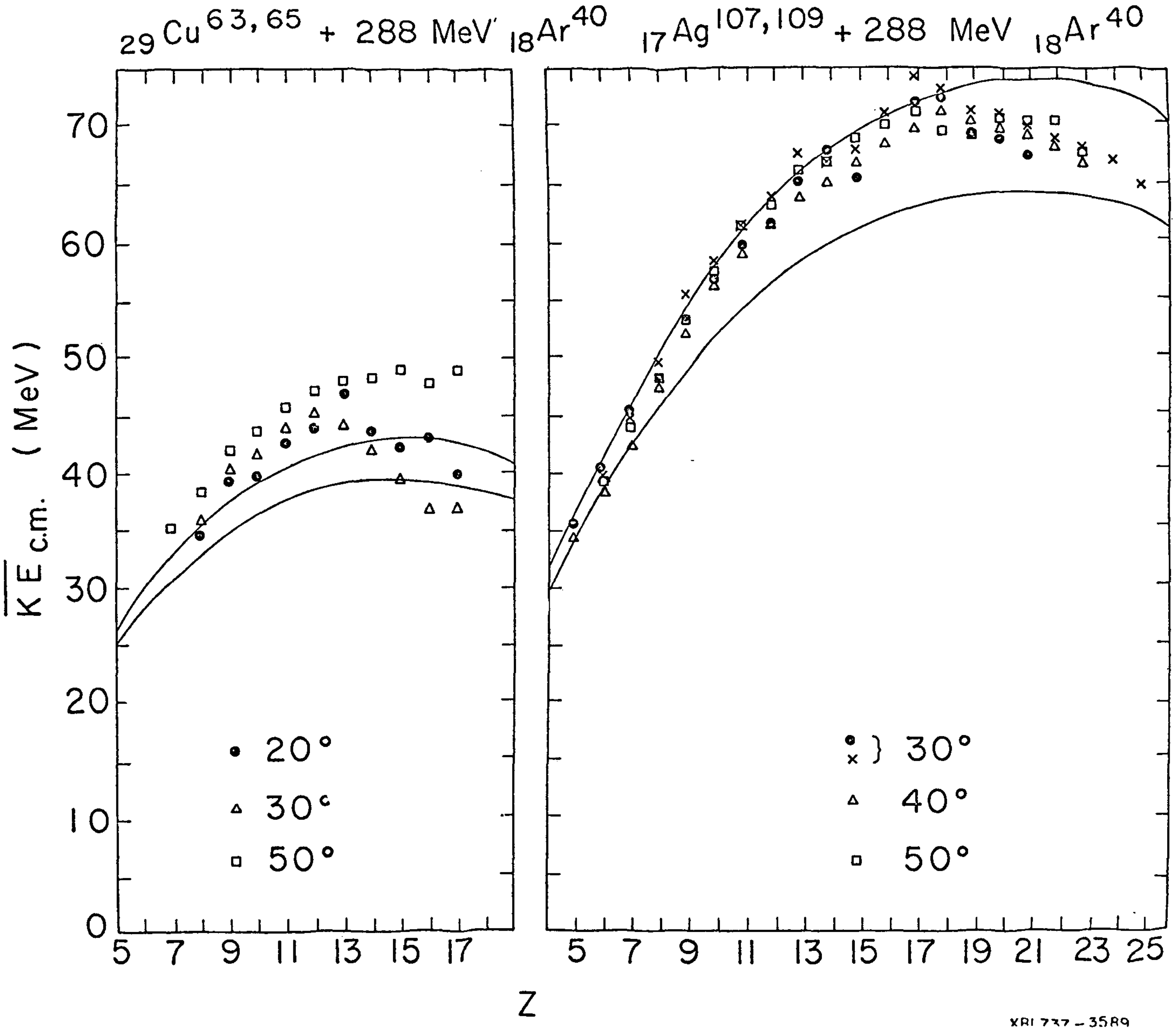

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Fig. 7

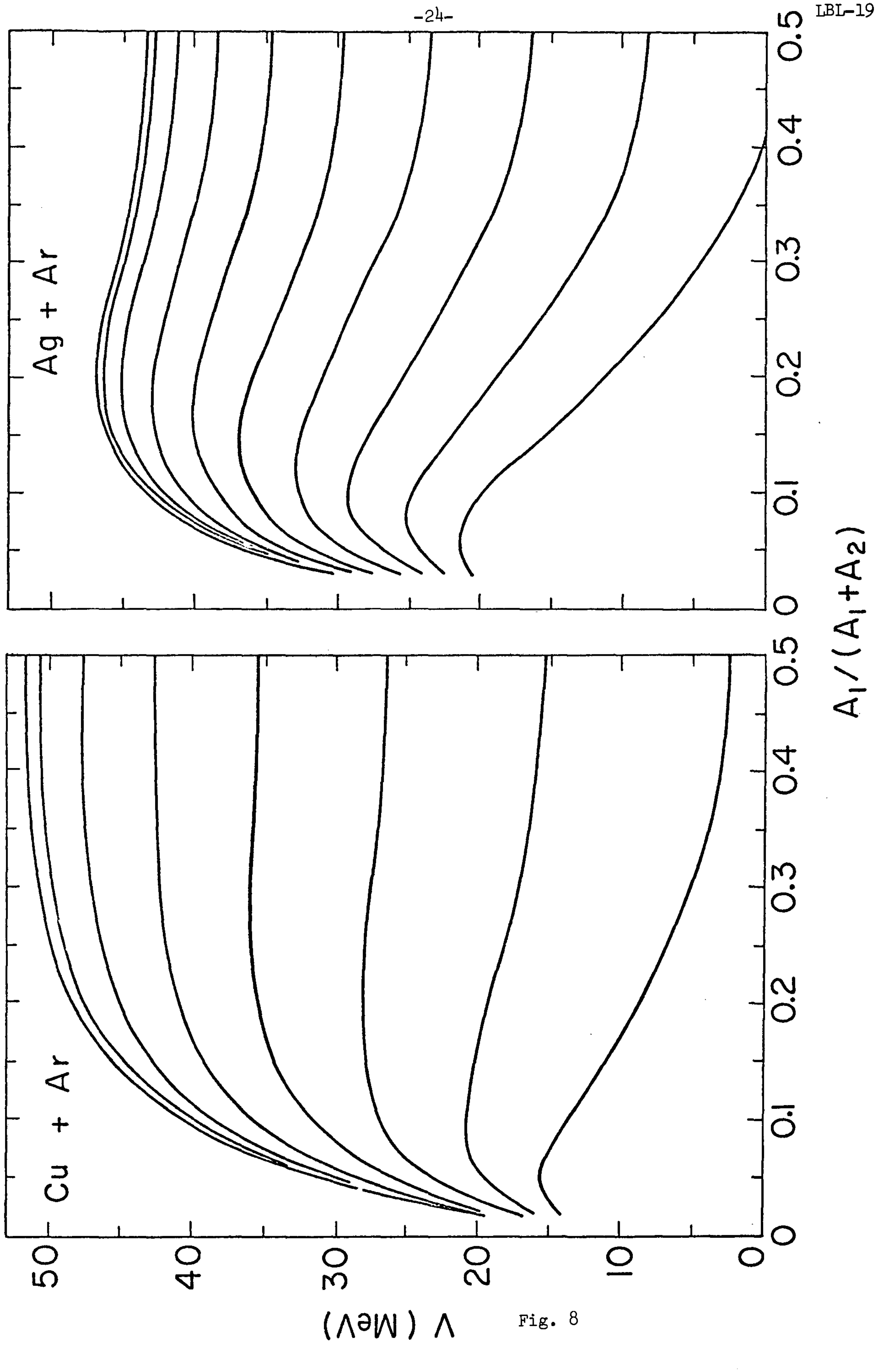

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Fig. 8

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