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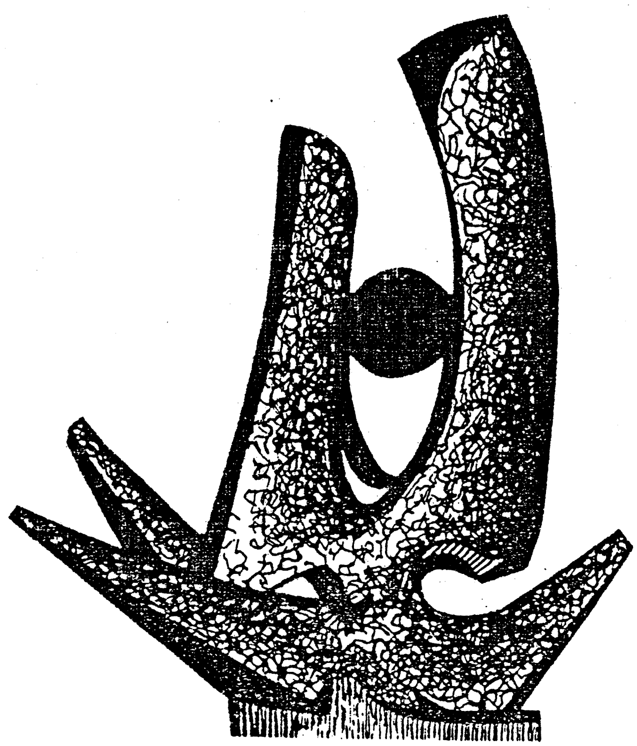

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ABSTRACT

Cross sections for low energy intermediate mass fragments were measured for ^{12}C induced reactions on Ag and Au. For reactions on Au, these cross sections increase by more than one order of magnitude between the incident energies of 15 and 30 MeV per nucleon. For reactions on Ag at E/A=30 MeV, the element yields exhibit a characteristic power law dependence, $Y(Z) \approx Z^{-2.6}$, similar to recent observations in relativistic nuclear reactions. Simple statistical calculations reproduce the qualitative trends of the element yields.

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Light particle evaporation and fission are recognized as the dominant decay modes for highly excited nuclear systems. The emission of low energy intermediate mass fragments, as a process distinct from light particle evaporation or fission[1-10], is generally associated with the most violent collisions in intermediate and high energy nuclear reactions (E/A>200MeV). Theoretical models used for the interpretation of these reactions range from direct splitting or fragmentation of the target nucleus by high energy projectiles[11] to statistical models based on the assumption of thermodynamic equilibrium[12,13].

Statistical calculations[12,13] have predicted that the emission of low energy intermediate mass fragments is favored at moderate temperatures of about 5 MeV and should, therefore, be observable in low energy nucleus - nucleus collisions. In order to test this prediction we have measured elemental yields of intermediate mass fragments (Z= 3 - 25) in ^{12}C induced reactions on Au and Ag at the incident energies of 15 and 30 MeV per nucleon. At these two bombarding energies the nuclear temperatures of the equilibrated composite systems are 3.4 and 4.9 MeV for the ^{12}C+Au reaction and 4.6 and 6.6 MeV for the ^{12}C+Ag reaction, assuming an ideal Fermi gas at normal nuclear density.

The experiment was performed with the K=500 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University. Self supporting Au and Ag targets of 0.6 mg/cm^2 thickness were irradiated with ^{12}C ions of 15 and 30 MeV per nucleon energy. Low energy intermediate mass fragments were identified by a dE-dE-E telescope subtending a solid angle of 5 msr and consisting of a Frisch - grid ion chamber[14] and two 0.4 mm thick surface barrier detectors . Elements up to Z = 25 were clearly resolved at all scattering angles. Absolute cross-sections for the production of intermediate mass fragments have an estimated uncertainty of less than 20% .

In order to eliminate contributions from peripheral reactions, the measurements were performed at angles significantly backward of the scattering angles for grazing Coulomb trajectories (11 and 25 degrees for ^{12}C+Au,and 7 and 16 degrees for ^{12}C+Ag, at E/A=3Ø and 15 MeV, respectively).At these angles intermediate mass fragments are emitted with kinetic energies close to the exit channel Coulomb barrier as extrapolated from the systematics of ref.15. The detailed shapes of these energy spectra will be discussed in a separate paper. In this letter we discuss the main characteristics of the element cross sections.

Examples of angular distributions, $d\sigma/d\theta=2\pi \sin\theta \, d\sigma/d\Omega$, measured for ^{12}C+Au at E/A = 30 MeV, are shown in Figure 1. For elements heavier than neon, the angular distributions are consistent with $d\sigma/d\theta$ = const. For lighter elements, on the other hand, the angular distributions become increasingly forward peaked, indicating that the time scale for emission of these lighter elements is shorter than the rotational period of the emitting system and the time scale for reaching global equilibrium for the entire composite system. (The time scale for emission of lighter elements such as carbon from the compound nucleus is estimated[13] to be of the order (1-3) x $1Ø^{-21}$ s, which is not large compared to the rotational period of the compound nucleus, $\tau_{rot} \gtrsim 5\times1Ø^{-21}$ s.) The angular distributions measured in the present experiment are qualitatively similar to the forward peaked angular distributions for proton induced reactions on Ag at inermediate energies[6].

Element yields for intermediate mass fragments at the two energies, E/A=15 and 3Ø MeV, are compared in Figures 2 and 3. In order to reduce the effects of angular distibutions these yields are averaged over a finite angular interval at angles significantly larger than the angles for grazing Coulomb trajectories. The corresponding laboratory angular intervals are given in the figures. For reactions induced on Au, the rapid rise of the cross sections observed for heavier fragments, Z>15, is most likely due to the tails of the element distribution resulting from fission (Figure 2). Between the two energies, a dramatic increase by more than one order of magnitude is observed for the cross sections of intermediate mass fragments with Z<15. For reactions induced on Ag, the cross sections increase by more than a factor of four (Figure 3).

At the higher incident energy of E/A=3Ø MeV, the element cross sections measured for the ^{12}C+Ag reaction are rather well described in terms of a simple power law, $Y(Z) = Z^{-2.6}$, as is shown by the dashed line in Figure 3. Such a power law dependence was recently observed[8-1Ø] for nuclear reactions at relativistic energies and was suggested to be a possible signature for the occurrence of statistical clustering near a critical point. Current theoretical calculations predict the onset of critical phenomena to occur at temperatures of 2Ø MeV in infinite nuclear matter and at about 12 MeV in finite nuclei[16-18]. In the present experiment, such high temperatures can only be achieved for a small subset of nucleons at the early stages of the reaction. In order to assess an upper bound for the temperatures that may be achieved in the present reaction we assume a locally heated region of nuclear matter at normal nuclear density that is composed of equal numbers of projectile and target nucleons. At the incident energy of E/A=3Ø MeV, the ideal Fermi gas temperature of such a subset of nucleons is T=12 MeV. This upper bound is consistent with the systematic trends of the temperature parameters deduced from the energy spectra of hydrogen and helium isotopes measured for ^{16}O and ^{2Ø}Ne induced reactions over wide range of energies[19,2Ø]. Within a thermal model, however, the emitting source must be larger than the detected fragment. Heavier fragments are, therefore, more likely emitted from larger thermal ensembles for which the temperatures will be smaller than 12 MeV.

It is instructive to compare the measured cross sections to statistical model calculations for the idealized case of emission from the completely equilibrated composite system[13]. Since important quantities such as nuclear temperatures, Coulomb barriers, and separation energies should impose similar phase space constraints for completely and partially equilibriated systems these calculations may provide rough estimates of the qualitative trends expected for the statistical emission of intermediate mass fragments. Because of increasing uncertainties about the level densities of particle stable states for heavier fragments, the emission of fragments heavier than neon has not yet been incorporated into the computer program. In our calculations, isotropic particle emission was assumed, angular momentum and deformation effects were neglected, and the level density was assumed to correspond to an ideal Fermi gas at normal nuclear density. The results of these calculations are shown by the solid histograms in Figures 2 and 3. The absolute normalizations of the calculations correspond to fusion cross sections of 310 and 500 mb for reactions on Ag and Au, respectively. In light of the rather considerable uncertainties that have to be associated with these schematic model calculations the agreement with experiment is quite remarkable. The calculations reproduce both the qualitative trends of the element yields as well as the energy dependence of the cross sections.

The emission of low energy intermediate mass fragments was also observed[21-23] for ^{14}N and ^{20}Ne induced reactions at incident energies below E/A=15 MeV. At these low energies, the strongly forward peaked angular distributions were interpreted in terms of a diffusion process along the mass asymmetry degree of freedom in which projectile and target retain their identity to a large extent. However, diffusion model calculations have not yet been able to reproduce the shapes of the angular distributions and the elemental cross sections , particularly for elements heavier than the projectile[23].

In conclusion, the cross sections for the emission of low energy intermediate mass fragments increase by more than one order of magnitude between the incident energies of E/A=15 and 30 MeV for ^{12}C induced reactions on Au. The surprising success of statistical calculations in reproducing the qualitative trends of the elemental yields suggests that the emission of intermediate mass fragments is characteristic of the statistical decay of highly excited nuclear systems and that it is not limited to intermediate or high energy nuclear reactions. For reactions induced on Ag, a characteristic power law was observed for the element yields at E/A=30 MeV, but not at the lower energy. If this power law dependence should be interpreted in terms of statistical clustering close to a critical point, the corresponding critical temperature is most likely smaller than 12 MeV. Future theoretical work will be necessary to account for particle emission prior to the attainment of global equilibrium, which is indicated by the forward peaked angular distributions of lighter elements.

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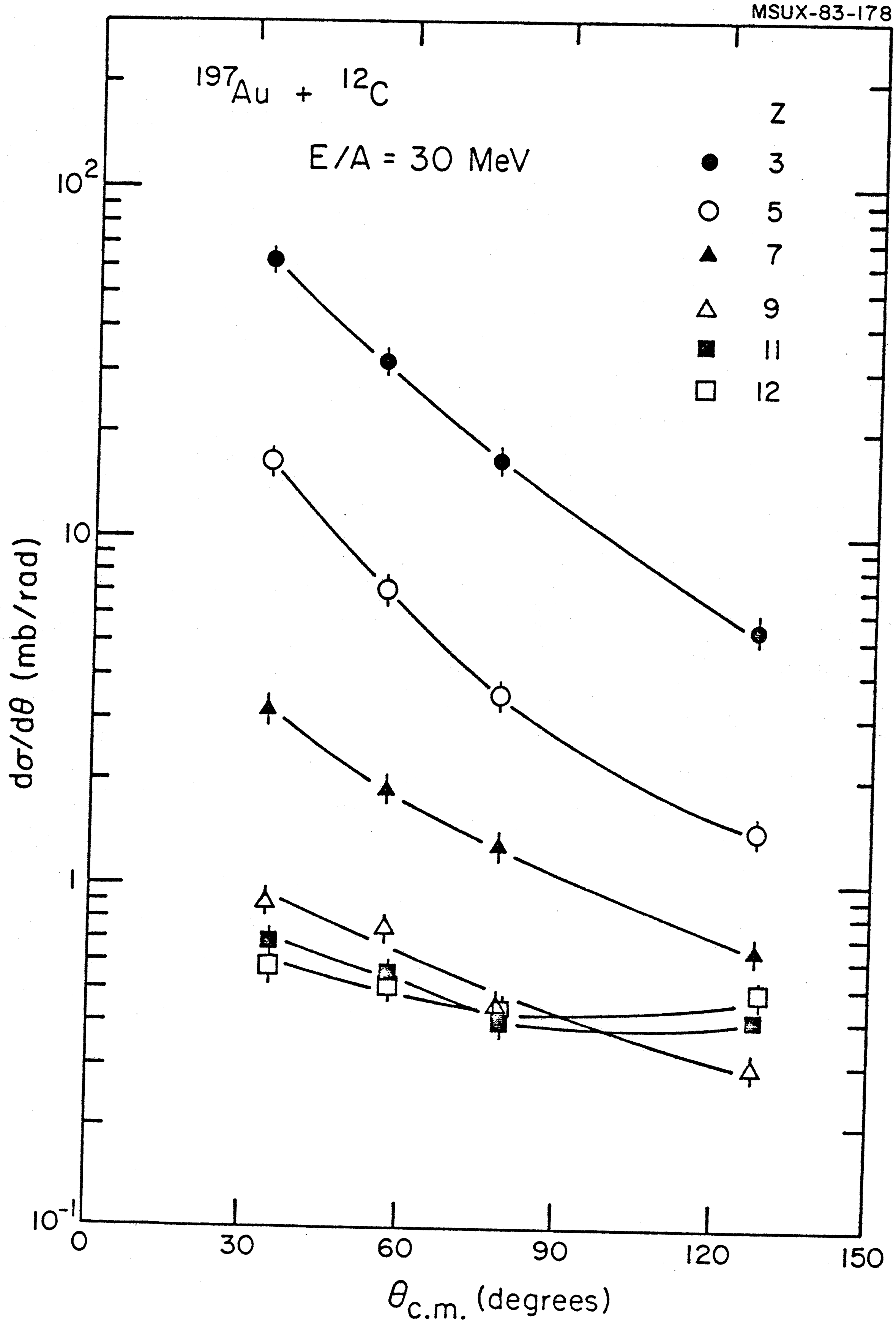
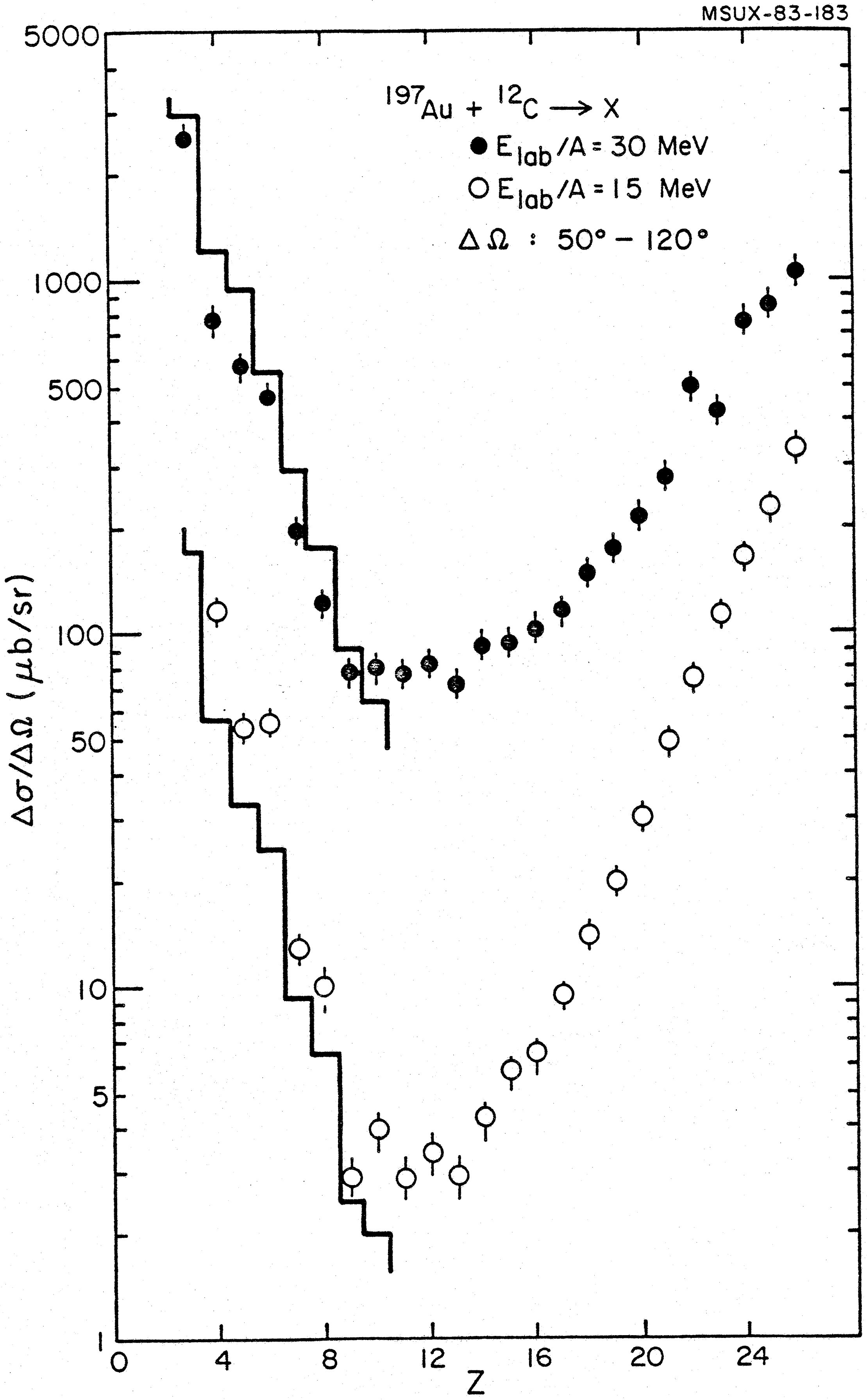
Figure Captions

Figure 1. Angular distributions of low energy intermediate mass fragments measured for ^{12}C induced reactions on Au at E/A=30 MeV.

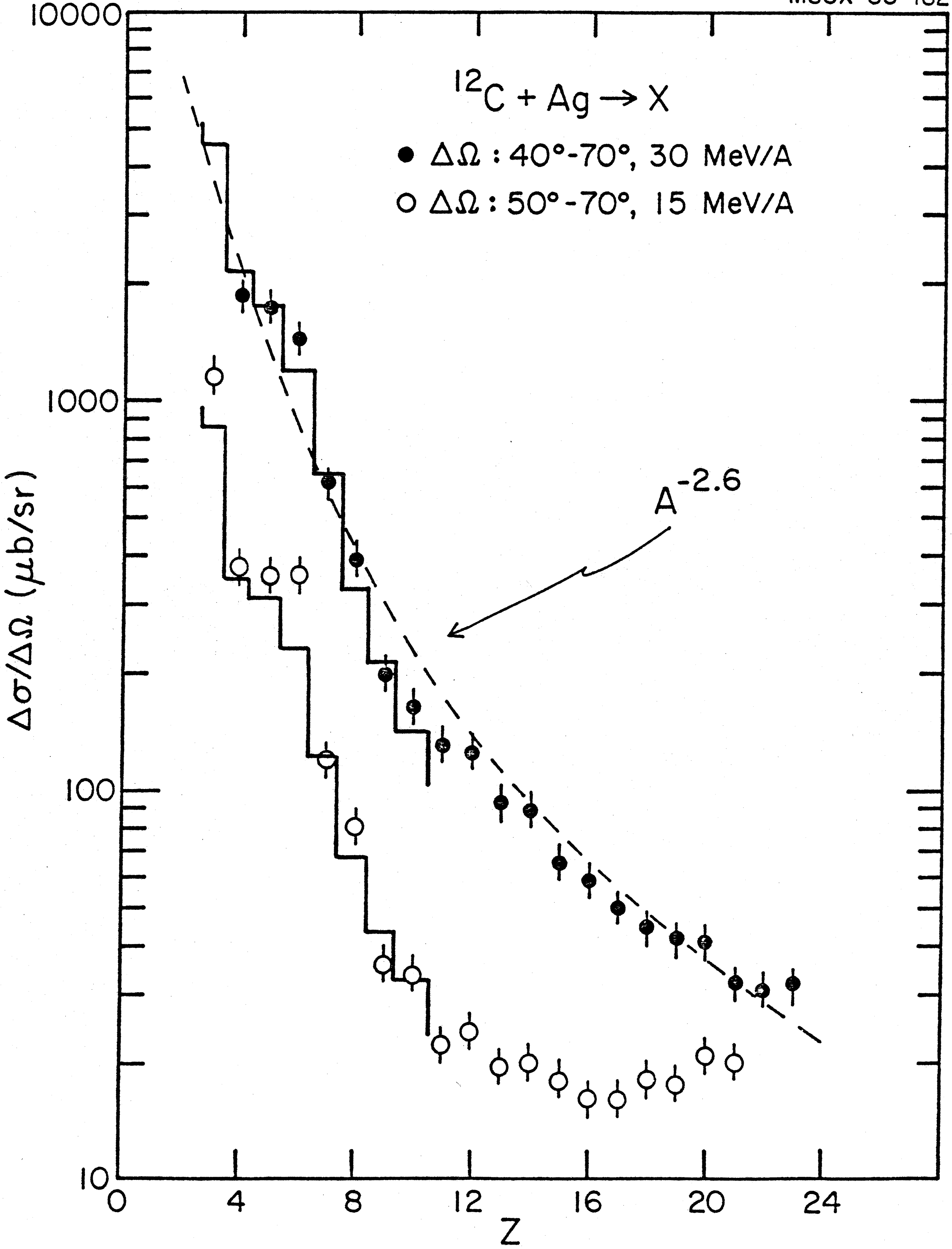
Figure 2. Angle averaged element cross sections for ^{12}C induced reactions on Au at E/A=15 and 30 MeV. The histograms show the result of the simple statistical calculations described in the text.

Figure 3. Angle averaged element cross sections for ^{12}C induced reactions on Ag at E/A=15 and 30 MeV. The histograms show the result of the simple statistical calculations described in the text.


MSUX-83-178
$^{197}Au + ^{12}C$
E/A = 30 MeV
Z
3
5
7
9
11
12
10^2
10
1
10^{-1}
$d\sigma/d\theta$ (mb/rad)
0
30
60
90
120
150
$\theta_{c.m.}$ (degrees)


MSUX-83-183
$^{197}Au + ^{12}C \rightarrow X$
● $E_{lab}/A = 30$ MeV
○ $E_{lab}/A = 15$ MeV
$\Delta\Omega$: 50° – 120°
$\Delta\sigma/\Delta\Omega$ (μb/sr)
5000
1000
500
100
50
10
5
1
0
4
8
12
16
20
24
Z

MSUX-83-182



$^{12}C + Ag \rightarrow X$
● ΔΩ : 40°-70°, 30 MeV/A
○ ΔΩ : 50°-70°, 15 MeV/A
$A^{-2.6}$
Δσ/ΔΩ (μb/sr)
10000
1000
100
10
0
4
8
12
16
20
24
Z