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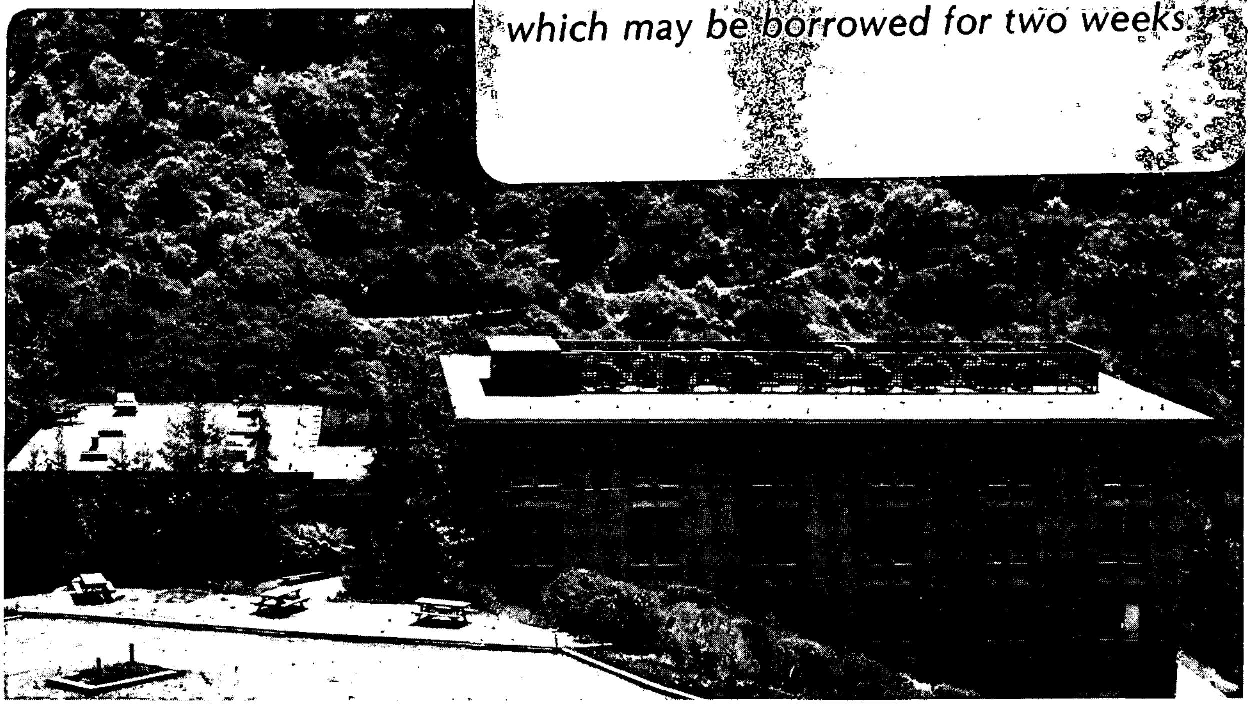

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CHARGE CHANGING CROSS SECTIONS OF RELATIVISTIC URANIUM

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We report equilibrium charge state distributions of uranium at energies of 962 MeV/nucleon, 437 MeV/nucleon and 200 MeV/nucleon in low Z and high Z targets and the cross sections for $U^{92+} \rightleftarrows U^{91+}$ and $U^{91+} \rightleftarrows U^{90+}$ at 962 MeV/nucleon and 437 MeV/nucleon. Equilibrium thickness Cu targets produce ≈ 5% bare U^{92+} at 200 MeV/nucleon and 85% U^{92+} at 962 MeV/nucleon.

A knowledge of charge changing cross sections is essential for the design of accelerators and storage rings for relativistic very heavy ions and for heavy ion inertial fusion. For accelerator design the cross section for electron capture by bare nuclei sets the maximum allowable pressure for beam survival in a storage ring. While the electron capture and ionization cross sections determine the energy needed to strip to bare nuclei, as well as the appropriate target to achieve the maximum stripping with the minimum energy straggling. In heavy ion inertial fusion the rate of energy deposition in the target will depend very strongly upon the charge state of the heavy ion. The charge state, initially very low to allow focusing of the beam, will change continuously as the ion penetrates the target. The energy deposition profile can be calculated only if the charge state distribution is known at each point in the target. This is possible if the capture and loss cross sections are understood. Relativistic charge changing cross sections are also necessary to interpret cosmic ray data[1]. Here, particles are identified by their rate of energy loss in materials, which depends upon the cosmic-ray charge state. For very heavy cosmic rays, the nuclei are not always bare.

In our experiments, charge changing cross sections are determined by least squares fits of capture and loss cross sections to curves of charge state populations versus target thickness. The distributions are measured (Fig. 1) by magnetically analyzing the uranium ions after they pass through a target. After analysis the the separated charge states are detected by a position-sensitive proportional counter located about 10 meters downstream from the magnetic spectrometer. At the proportional counter, the separation between adjacent uranium charge states is about 1 cm and the convolution of the beam-width and the position-resolution of the proportional counter is about 0.2 cm full-width at half-maximum.

Relativistic U^{68+} ions are obtained from the Lawrence Berkeley Laboratory's Bevalac[2] - a heavy ion linear accelerator (Super-HILAC) and a synchrotron (Bevatron) operating in tandem. To reach these energies, the uranium ions are accelerated in five separate stages and stripped at the end of the second, third and fourth stages.

The equilibrium charge state distributions for 200 MeV/nucleon uranium (Fig. 2) were determined by substituting targets of increasing thickness until no change in the charge state distribution was observed. The equilibrium charge state distributions for 437 MeV/nucleon and 962 MeV/nucleon uranium (Fig. 3) were determined from the ratios of capture and ionization cross sections. This is a potentially more accurate method because it avoids the problem of the beam slowing down or scattering in thick targets and uses data from many targets. We estimate the uncertainty in determining the the equilibrium distributions, mostly due to statistics and a small background, to be less than 5 percent of the total counts. At each of the three energies we observed all of the intermediate charge states from U^{68+} to U^{92+} as the target thickness was increased.

The absolute cross sections for 437 MeV/nucleon and 962 MeV/nucleon uranium, shown in Figures 4 and 5, and first reported in Ref.3 have an estimated error of a factor of two. The error is relatively large because only a few targets were used to cover a large range of target thicknesses. Fig. 4 shows the experimental cross section for ionization of U^{90+} and U^{91+} at 437 MeV/nucleon and 962 MeV/nucleon as a function of target atomic number (Z_T). To compare with theory we make use of the Bethe theory[4] for energy loss in matter. At high energies, the projectile looses energy by exciting and ionizing the target electrons. For ionization of the projectile, we simply reverse the role of the target and projectile and consider only transitions to the continuum. The cross section (σ_i) for ionization of $U^{90+,91+}$ is:

$$\sigma_i = 4\pi a_0^2 (\alpha/\beta)^2 \frac{1}{B_K} (Z_T^2 + Z_T) f_K \left\{ \ln \frac{(2\beta\gamma/\alpha)^2}{(.048\ B_K)} - \beta^2 \right\} \tag{1}$$

where a_0 is the Bohr radius of hydrogen, α is the fine structure constant, B_K is is the K-shell binding energy in units of Rydbergs, Z_T is the target atomic number and f_K is a constant times the oscillator strength for transitions from the K shell to the continuum: f_K = 0.29 and 0.58 for U^{91+} and U^{90+} respectively. The theory predicts a Z_T^2 dependence of the cross section which is consistent with the experimental data in Fig. 4. Absolute values are also in agreement with experiment as our present level of accuracy.

Fig. 5 shows the experimental cross sections for capture of an electron by U^{92+} and U^{91+} at energies of 962 MeV/nucleon and 437 MeV/nucleon for different targets. Relativistic uranium captures electrons by radiative electron capture (REC) and by charge exchange. REC is the inverse process of photoionization and in the the limit of high energy the ratio of the REC cross section to the photo-ionization cross section approaches one. At 200 MeV/nucleon the ratio is 0.46. The energy of the emitted photon is equal to the (K shell) binding energy plus the kinetic energy of an electron seen in the rest frame of the uranium. For 962 MeV/nucleon and 437 MeV/nucleon this corresponds to photons of 0.66 MeV and 0.37 MeV respectively. The photoionization cross sections for uranium at these energies are ≈ 25 b and 90 b respectively[5]. Multiplying by the number of electrons in the target atom, we obtain values of σ_{REC} for U^{92+} shown in Fig. 4. σ_{REC} for U^{91+} is about half as large.

The second process for electron capture is nonradiative charge exchange[6]. Relativistic cross sections for capture of an electron by a bare nuclei from a multi electron target have not yet been calculated. Calculations[6] for hydrogenlike targets however show that compared with REC, the cross sections for charge exchange decrease more rapidly with increasing energy and decreasing target Z.

The data in Fig. 5 are consistent with REC being the dominant capture mechanism for low Z_T targets. At low Z_T the data is fit by the calculated REC cross sections and is in agreement with the uranium K shell REC cross sections measured at 422 MeV/nucleon by Anholt *et al*[7]. For high Z_T, the experimental cross sections are in excess of the REC cross section. The excess is larger at the lower energy and we attribute it to the contribution from charge exchange which scales as a high powers of Z_T. The ionization cross section (Eq. 1) scales as $\approx Z_T^2$, and the REC cross section scales only as Z_T.

The consequence of these scalings is that in the high energy region, where charge exchange is small and REC dominates, higher average charge states will be observed for high Z_T targets because the ionization cross section grows faster with Z_T than does the REC cross section. At low energies, where charge exchange dominates, the charge exchange cross section grows faster with Z_T than the ionization cross section and higher average charge states are produced from low Z_T targets. At intermediate energies the highest average charge states would then come from targets of intermediate Z_T.

This behavior is observed in the charge state distributions in Fig.'s 2,3. At 962 MeV/nucleon, Ta ($Z_T = 73$) gives a slightly higher average charge state than Cu ($Z_T = 29$) and a much higher average charge state than mylar. At 437 MeV/nucleon Cu gives the highest average charge state - substantially higher than mylar or Ta. At 200 MeV/nucleon, however, mylar is almost as effective a stripper as Cu and Al ($Z_T = 13$) is a slightly better stripper.

Our measurements show that bare uranium can be produced at energies of from as low as 200 MeV/nucleon (5% yield), and with a yield of 50% at 400 MeV/nucleon and 85% at 1 GeV/nucleon. Beams with ≈ 40% hydrogenlike U^{91+} or 60% heliumlike U^{90+} can be produced. This makes it possible to perform spectroscopic measurements to test quantum electrodynamics using U^{90+} and U^{91+}. At very high Z the higher order terms in the self energy are the dominant QED contribution to the energy levels.

The REC cross sections measured here indicate that at an energy of 1 GeV/nucleon, the mean time for electron capture by bare U^{92+} in a storage ring with a vacuum of 10^{-10} Torr N_2 is over 1/2 day. The mean survival time for U^{90+} at this pressure would be several hours.

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FOOTNOTES

(1.) See for example, P.H. Fowler, V.M. Clapham, V.G. Cowen, J.M. Kidd, and R.T. Moses, Proc. Roy. Soc. (London) A318 (1970) 1.

(2.) See, for example, J.R. Alonso *et al.*, Science 217 (1982) 1135.

(3) H. Gould, D. Greiner, P. Lindstrom, T.J.M. Symons, and H. Crawford, Phys. Rev. Lett. 52, (1984) 180; Errata- Phys. Rev. Lett. 52 (1984) 1654.

(4.) H.A. Bethe, Ann. Phys. (Leipzig) 5 (1930) 325; C. Moller, Ann. Phys. (Leipzig) 14 (1932) 531.

(5.) Cross sections were interpolated from values given in W.H. McMaster, N. Kerr Del Grande, J.H. Mallett and J.H. Hubbell, *Compilation of X-Ray Cross Sections*, Lawrence Livermore Laboratory Report No. UCRL-50174 Sec. II Rev. 1 (pub. National Technical Information Service, U.S. Dept. Commerce, Springfield VA 22151, 1969) p. 344.

(6.) R. Shakeshaft, Phys. Rev. A20 (1979) 779; B.L. Moiseiwitsch, and S.G. Stockman, J. Phys. B13 (1980) 2975; B13 (1980) 4031; D.H. Jakubaßa-Amundsen, and P.A. Amundsen, Z. Physik A298 (1980) 13.

(7.) R. Anholt, S.A. Andriamonje, E. Morenzoni, Ch. Stoller, J.D. Molitoris, W.E. Meyerhof, H. Bowman, J.-S. Xu, Z.-Z. Xu, J.O. Rasmussen and D.H.H. Hoffmann, Phys. Rev. Lett. 53 (1984) 234.

FIGURES

Figure 1. Schematic diagram of the apparatus

Figure 2. - Charge state distributions of uranium at 200 MeV/nucleon for equilibrium thicknesses targets of mylar ($Z_T \approx 6.6$), Al ($Z_T = 13$), Cu ($Z_T = 29$), and Ag ($Z_T = 47$).

Figure 3. - Charge state distributions of uranium at energies of 962 MeV/nucleon and 437 MeV/nucleon for equilibrium thicknesses targets of mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$).

Figure 4. - Cross sections for ionization of U^{91+} and U^{90+} at energies of 962 MeV/nucleon and 437 MeV/nucleon as a function of Z_T. Experimental points are for mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). The continuous curves are the ionization cross sections calculated from Eq(1) for U^{91+} (upper curve) and U^{90+} (lower curve).

Figure 5. - Cross sections for capture of an electron by U^{92+} and U^{91+} at energies of 962 MeV/nucleon and 437 MeV/nucleon as a function of Z_T. Experimental points are for mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). σ_{REC} for U^{92+}, from theory, is shown as the continuous curve.

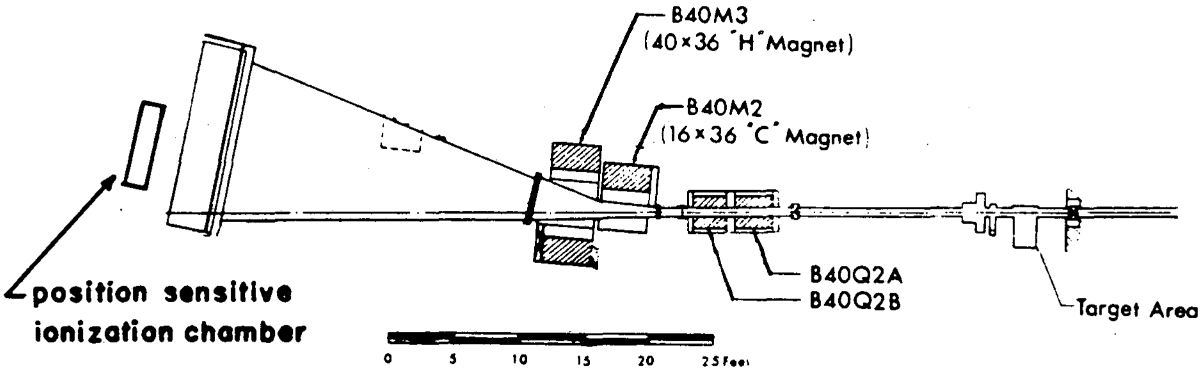

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Figure 1

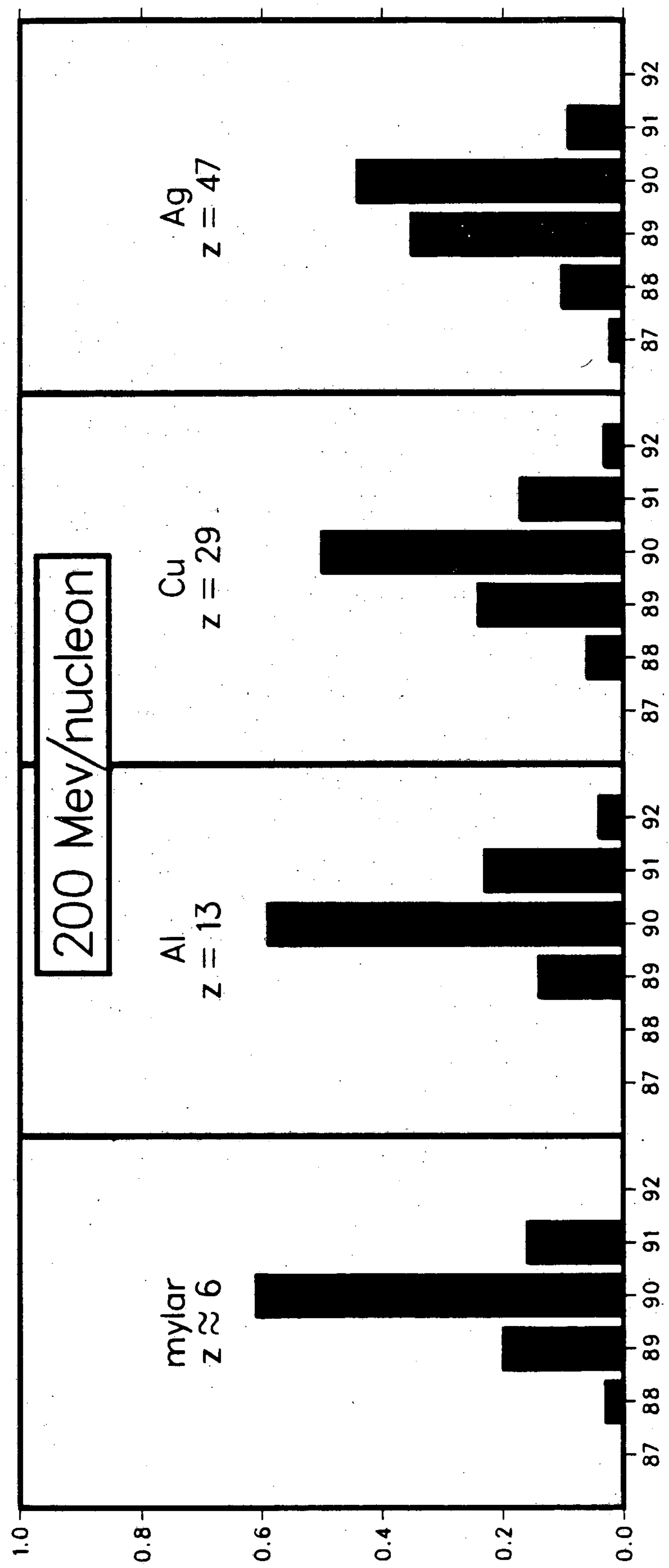
200 Mev/nucleon
mylar
z ≈ 6
Al
z = 13
Cu
z = 29
Ag
z = 47
1.0
0.8
0.6
0.4
0.2
0.0
87
88
89
90
91
92

Figure 2

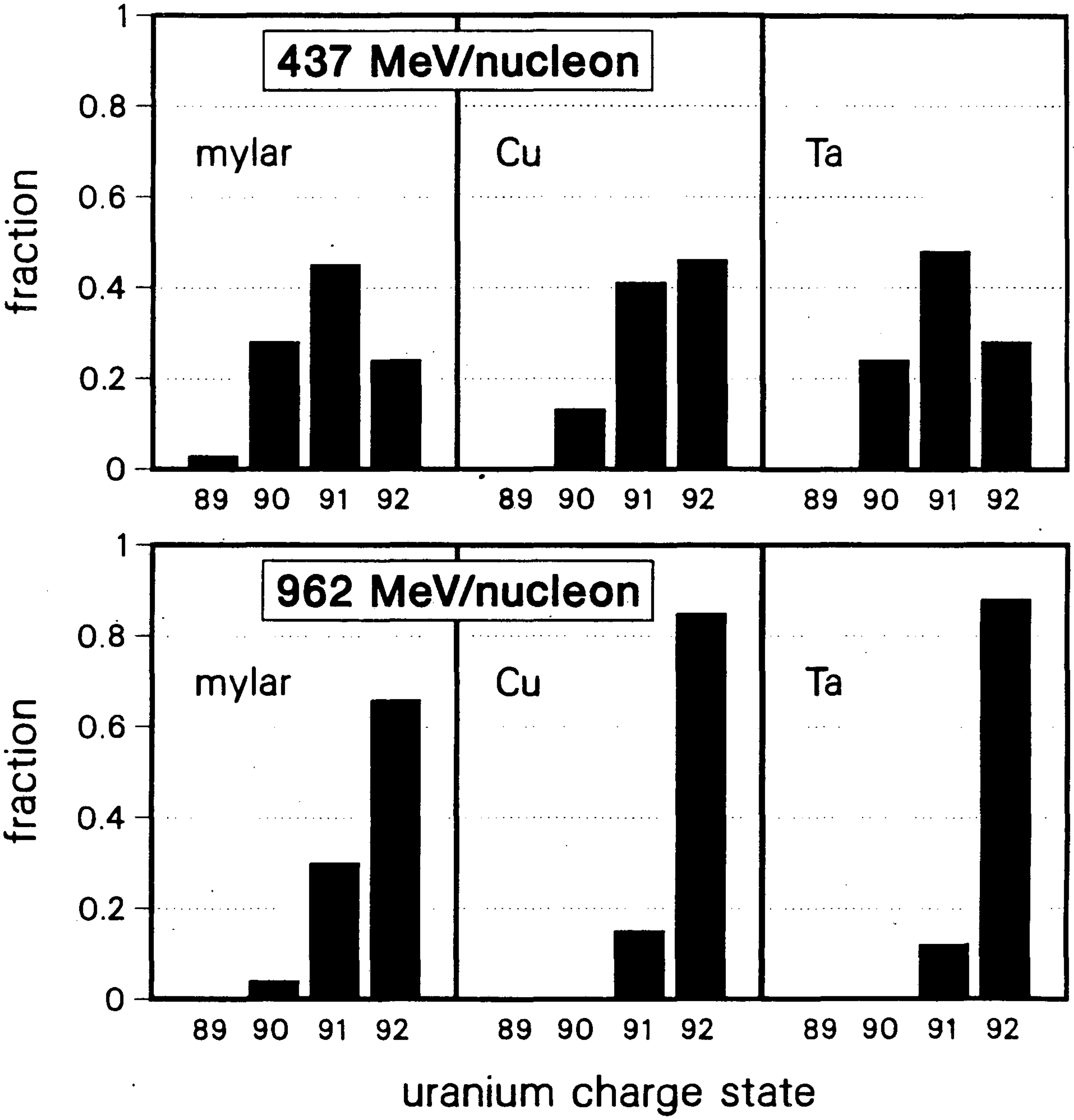

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Figure 3

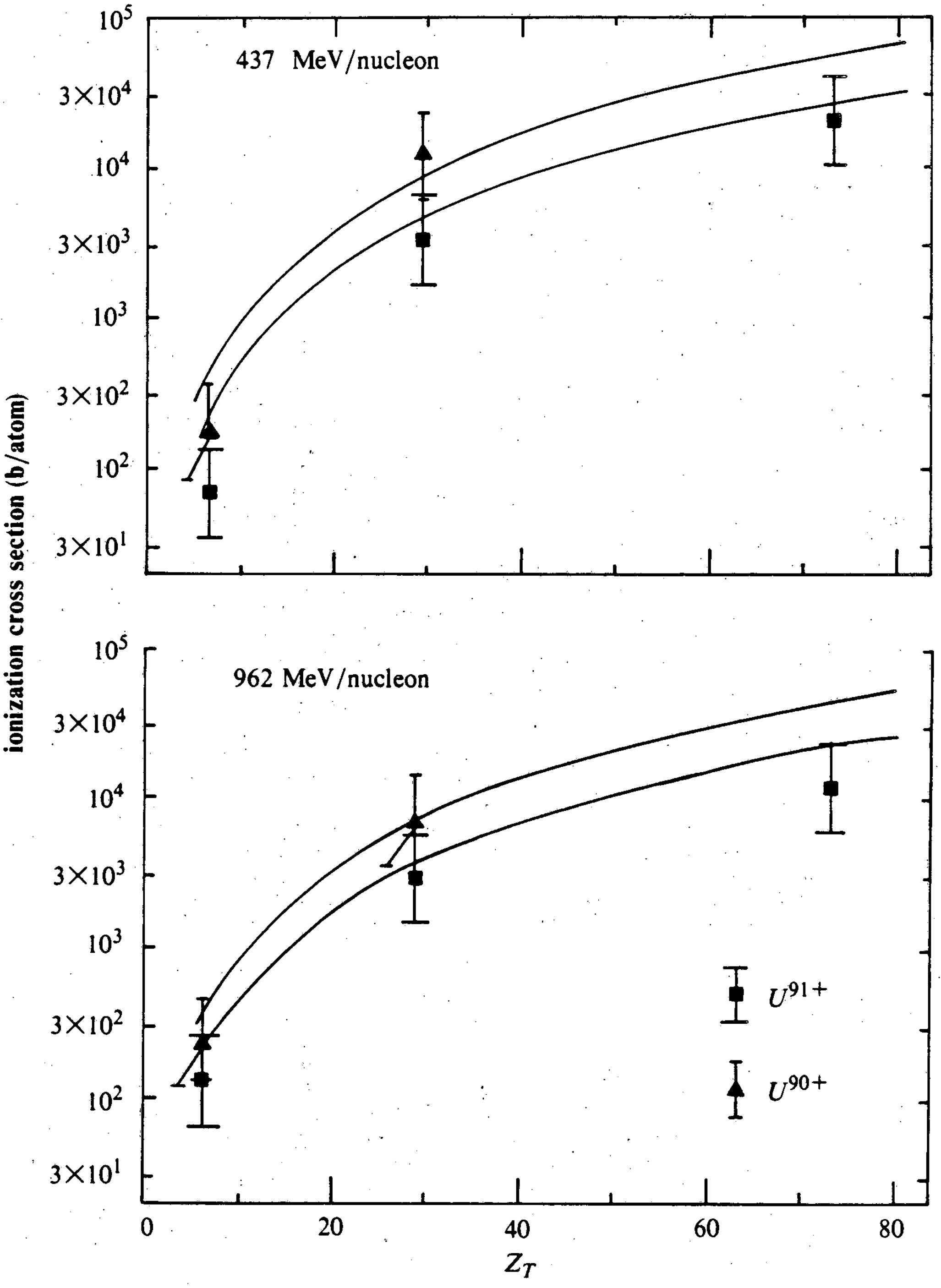

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Figure 4

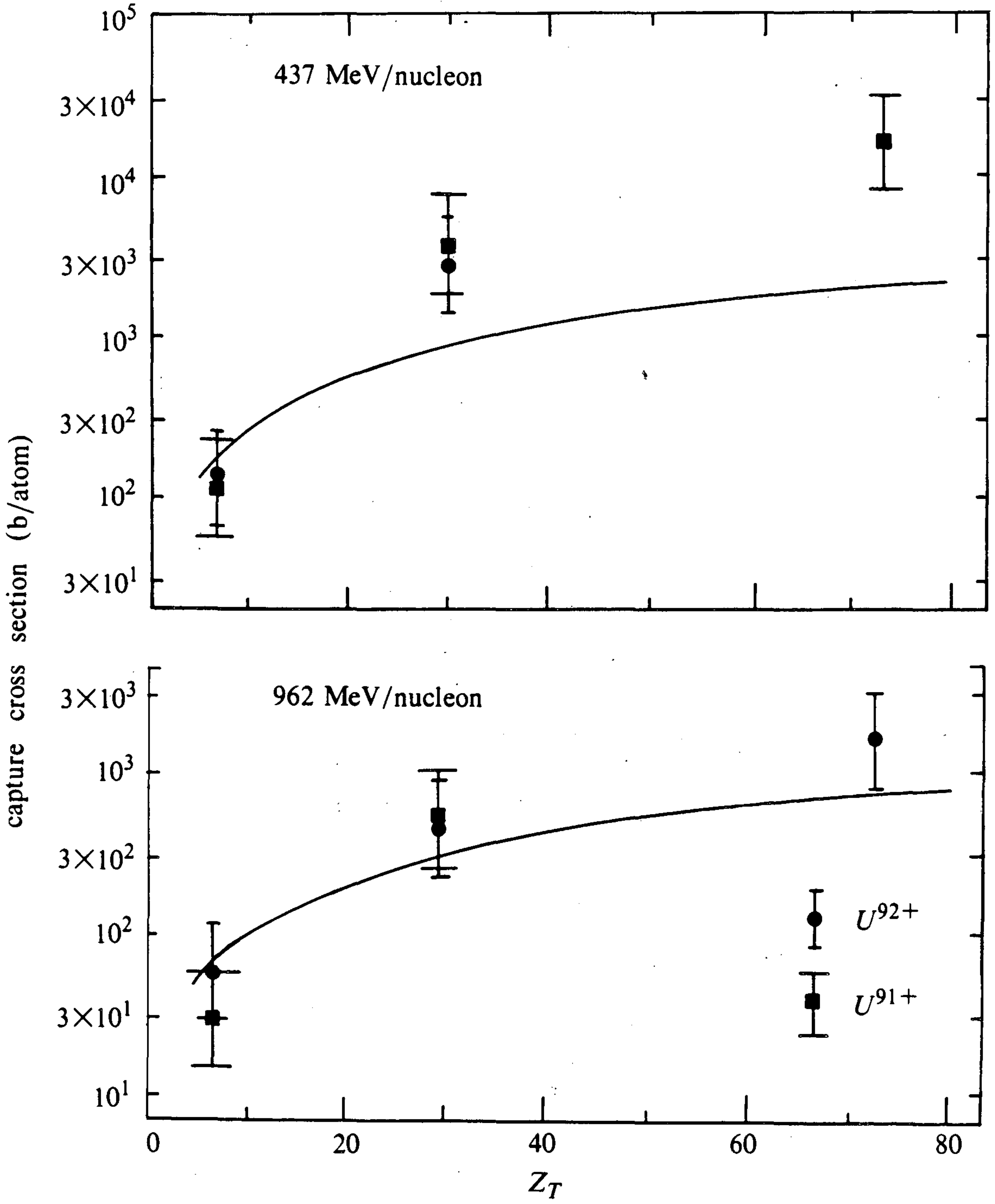

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Figure 5

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