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ELECTRON CAPTURE BY U^{91+} AND U^{92+} AND IONIZATION OF U^{90+} AND U^{91+}

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Electron capture by U^{91+} and U^{92+} and ionization of U^{90+} and U^{91+}

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We report experimental cross sections at 962 MeV/nucleon and 437 MeV/nucleon for $U^{92+} \rightleftarrows U^{91+}$ and $U^{91+} \rightleftarrows U^{90+}$ in mylar, Cu, and Ta and equilibrium charge state distributions in these materials and in the interstellar medium. At 962 MeV/nucleon we produce a beam containing over 85% bare U^{92+} nuclei.

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The rate of energy loss of a cosmic ray (or other heavy charged particle) in matter depends upon the difference between the nuclear charge and the number of bound electrons. A knowledge of the charge state therefore removes a possible ambiguity from the determination of the nuclear charge by energy-loss measurements. The charge state of the cosmic ray in turn depends upon the medium, and the complete charge state distribution of a cosmic ray passing from the interstellar medium to the atmosphere or to a target can be determined at any point from the cross sections for electron capture and loss.

The cross section for producing bare uranium nuclei (U^{92+}) from partially-stripped uranium also has application to the design of an ultrarelativistic very-heavy-ion accelerator, where the use of high charge states makes for a smaller and more energy-efficient accelerator. What has not been known is the minimum energy at which most of the ions can be stripped to bare nuclei. The cross section for capture of an electron by bare nuclei also places an upper limit to the residual gas pressure in the accelerator.

In this letter we report the measurement at 962 MeV/nucleon and 437 MeV/nucleon, of the cross sections for the capture of an electron by U^{92+} and U^{91+}, and for ionization of U^{91+} and U^{90+} in high- and low- nuclear charge targets. These are the first experimental cross sections for capture and loss of an electron by a relativistic heavy ion of nuclear charge >18. We show that beams containing nearly 50% bare U^{92+} can be produced at 437 MeV/nucleon and that beams containing over 85% bare U^{92+} can be produced at 962 MeV/nucleon.

Relativistic U^{68+} ions are obtained from the Lawrence Berkeley Laboratory's Bevalac[1] - the combination of a heavy ion linear accelerator (Super-HILAC) and a synchrotron (Bevatron). After extraction from the Bevalac, the U^{68+} ions pass through a mylar ($C_5H_4O_2$), Cu, or Ta target located upstream of a magnetic spectrometer. The resulting uranium charge states are spatially separated in the magnetic spectrometer and detected by a position-sensitive ionization chamber. At the ionization chamber, the separation between adjacent uranium charge states is about 1 cm. The convolution of the beam width and the position-resolution of the ionization chamber is about 0.2 cm full-width at half-maximum. An energy loss of a few percent or less is observed for uranium ions in targets of sufficient thickness to produce an equilibrium charge state distribution. No increase in the beam width is observed.

We determine the cross sections for capture of an electron by U^{91+} and U^{92+}, and for ionization of U^{90+} and U^{91+}, by a least squares fit[2] to curves of the relative charge state populations of U^{89+} - U^{92+} versus target thickness. For each target medium, one of the targets was of near-equilibrium thickness. Because a small number of targets were used to cover a large range of target thicknesses, the useful data for determining the cross sections for U^{90+} - U^{92+} is limited to from three to six (average 4.2) charge state distributions. Examining the effect of using different subsets of our data on the experimental cross sections, we estimate the error in the *absolute* cross section to be a factor of two.

Fig. 1 shows the experimental cross sections for capture of an electron by U^{92+} and U^{91+} at incident energies of 962 MeV/nucleon and 437 MeV/nucleon in targets of different nuclear charge (Z_T): mylar (effective $Z_T \approx 6.6$); Cu (Z_T =29); and Ta (Z_T =73). Relativistic uranium captures electrons by radiative electron capture (the inverse of photoionization). and by charge exchange. We first consider radiative electron capture. Neglecting the binding energy of the electrons in the target atom, the cross section[3] for radiative electron capture σ_{REC} may be written in terms of σ_ϕ, the photoionization cross section, and X, the fraction of the shell of the uranium atom which is unoccupied.

$$\sigma_{REC} = \frac{[(\gamma-1) + B_n/mc^2]^2 X \sigma_\phi}{[\gamma + 2B_n/mc^2]^2 - 1} \tag{1}$$

Here B_n is the binding energy of an electron in the n^{th} shell, m is the electron mass, and c is the speed of light. Also, $\gamma = (1 - \beta^2)^{-1/2}$, and β = v/c, where v is the uranium velocity. At 962 MeV/nucleon ($\gamma = 2.0$) and at 437 MeV/nucleon ($\gamma = 1.5$) photon energies from radiative electron capture into the K shell are 0.66 MeV and 0.37 MeV respectively. (Capture into higher shells lowers the photon energies by ≈ 0.1 MeV.) The total cross sections for photoionization[4] of all shells by 0.66 MeV and 0.37 MeV photons are 25 b and 90 b respectively. Multiplying Eq. (1) by the number of electrons in the target atom, we obtain σ_{REC} for U^{92+} shown in Fig. 1, and a value about half as large for U^{91+}.

The second process for electron capture is nonradiative charge exchange. Precise calculations of the relativistic cross sections for nonradiative charge exchange with a complex target atom are not yet available. Present calculations[5] of the charge exchange cross sections from *hydrogenlike* targets by 962 MeV/nucleon and 437 MeV/nucleon U^{92+} find a strong dependence on the nuclear charge of the target. In low Z_T targets these cross sections are much smaller than σ_{REC} and in high- Z_T targets they are somewhat larger.

On the basis of the nonradiative charge exchange cross section being negligible in mylar, our experimental data in Fig. 1 are in satisfactory agreement with σ_{REC} calculated from Eq (1). The increase, with increasing Z_T, of the experimental capture cross section over σ_{REC} is consistent with the increasing importance of nonradiative charge exchange for increasing Z_T and decreasing projectile energy.

To calculate the cross sections for ionization of U^{90+} and U^{91+}, we note that the relativistic Bethe theory[6,7] for energy loss of a heavy charged particle in matter predicts the cross sections for ionization and excitation of the target by the projectile. Reversing the role of the target and the projectile, we calculate the cross section (σ_i) for ionization of $U^{90+,91+}$.

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

Here a_0 is the Bohr radius of hydrogen, α is the fine structure constant, B_K is the binding energy of a K shell electron in units of Rydbergs (1 Ry $\approx$ 13.6 eV). The quantities β and γ have the same meaning as in Eq (1), Z_T is again the nuclear charge of the target, 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. Within the experimental error, the agreement in Fig. 2 between measured cross sections and cross sections calculated from the Bethe theory is satisfactory.

The equilibrium charge state distributions for 962 MeV/nucleon and 437 MeV/nucleon uranium in various media are shown in Fig. 3. The distributions are calculated from the measured capture and loss cross sections in mylar, Cu and Ta and compared with observed distributions from thick targets. The cumulative error in each distribution is less than 5%. For the interstellar medium (90% H, 10% He) we obtain σ_{REC} by a linear extrapolation of the experimental cross sections for mylar, and we obtain σ_i by a $Z_T^2 + Z_T$ extrapolation of the experimental cross sections for mylar and Cu. Fig. 3 shows that in the interstellar medium 65% of the uranium nuclei at 962 MeV/nucleon will carry one or more electrons. At 437 MeV/nucleon about 90% of the uranium in the interstellar medium will carry one or more electrons including $\approx$ 9% which will carry two- K shell and one- L shell electrons. Entry into the atmosphere results in a net ionization and a Cu target increases the charge state still further.

At 962 MeV/nucleon we obtained beams containing more than 85% bare U^{92+} nuclei by stripping U^{68+} in Cu and Ta targets of 150 mg/cm^2 and 85 mg/cm^2 respectively. We observed no deterioration in beam quality. It is clearly possible at these energies to produce beams of bare uranium nuclei for acceleration to ultrarelativistic energies and beams of few- electron uranium for atomic physics tests of quantum electrodynamics.

We thank Mr. Douglas MacDonald, Mr. Ismael Flores, and Dr. Jose Alonso for their assistance in setting up the experiment and analyzing the data; and Professor Richard Marrus and Dr. Howel Pugh for their encouragement and support. We especially thank the operators and staff of the Bevalac whose skill and dedication made this experiment possible. This work was supported by the Director, Office of Energy Research: Office of Basic Energy Sciences, Chemical Sciences Division; and Office of High Energy and Nuclear Physics, Nuclear Science Division, of the U.S. Department of Energy under Contract No. DE-AC-03- 76SF00098, and by NASA.

FOOTNOTES

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

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[3]see for example, P.H. Fowler, V.M. Clapham, V.G. Cowen, J.M. Kidd, and R.T. Moses, Proc. Roy. Soc. (London) A. **318**, 1 (1970).

[4]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.

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[6]H.A. Bethe, Ann. Phys. (Leipzig) **5**, 325 (1930); C. Møller, Ann. Phys. (Leipzig) **14**, 531 (1932).

[7]Tests of the Bethe theory for $\approx$ 1 GeV/nucleon uranium and gold are reported by: S.P. Ahlen and G. Tarlé, Phys. Rev. Lett. **50**, 1110 (1983); and C.J. Waddington, P.S. Freier, and D.J. Fixen, Phys. Rev. A **28**, 464 (1983).

FIGURES

Figure 1. - Cross sections for capture of an electron by U^{92+} and U^{91+} at 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). Values of σ_{REC} for U^{92+}, calculated from Eq (1), are shown as the continuous curve.

Figure 2. - Cross sections for ionization of U^{91+} and U^{90+} at 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 loss cross sections calculated from Eq(2) for U^{91+} (upper curve) and U^{90+} (lower curve).

Figure 3. - Charge state distributions of uranium at 962 MeV/nucleon and 437 MeV/nucleon for equilibrium thicknesses targets of interstellar medium (IM) ($Z_T \approx 1$), mylar ($Z_T \approx 6.6$), Cu (Z_T =29), and Ta (Z_T =73). At 437 MeV/nucleon, the Cu target produces higher charge states than the Ta target.

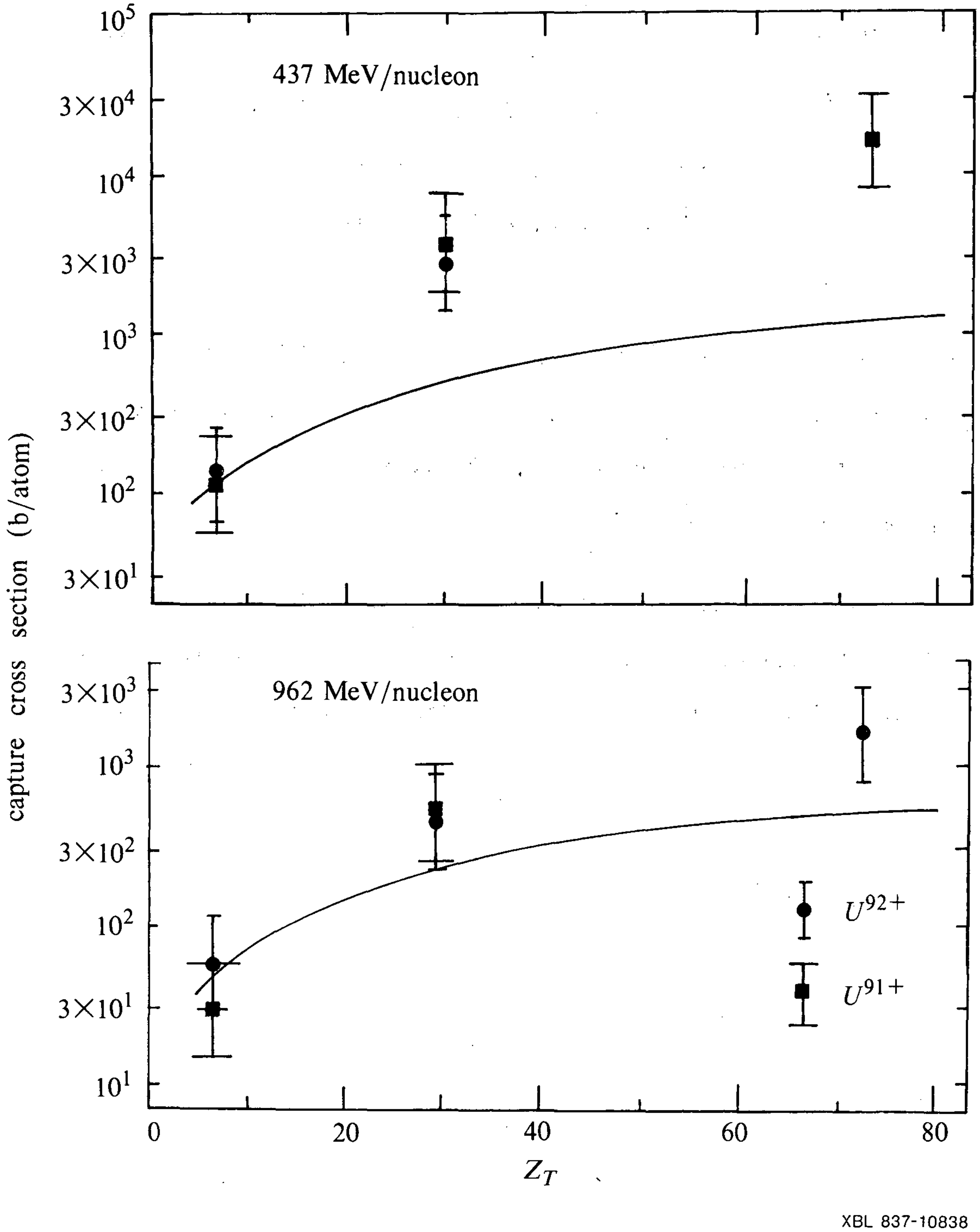
437 MeV/nucleon
962 MeV/nucleon
capture cross section (b/atom)
Z_T
U^{92+}
U^{91+}
XBL 837-10838

Fig. 1

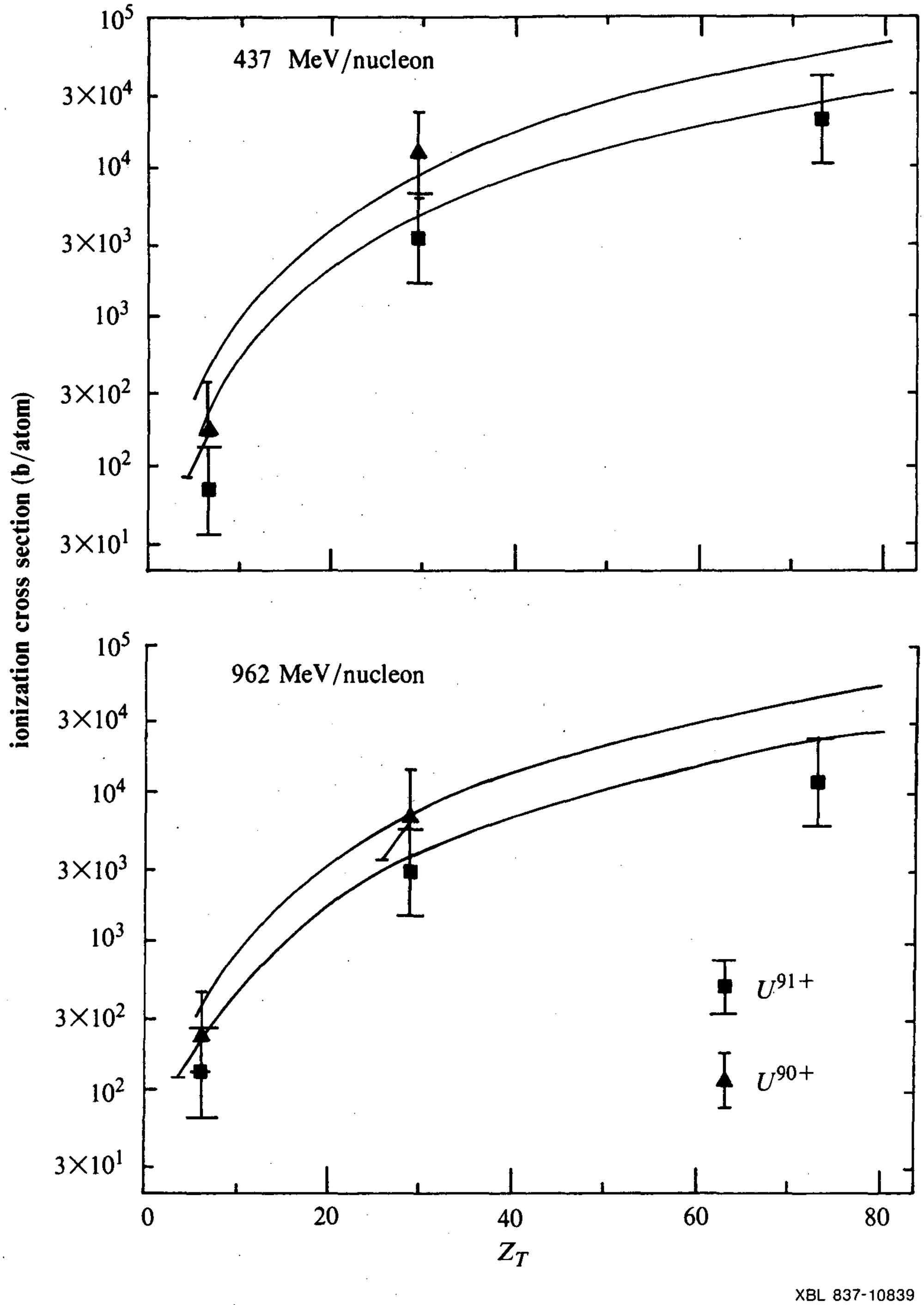
437 MeV/nucleon
962 MeV/nucleon
ionization cross section (b/atom)
10^5
3×10^4
10^4
3×10^3
10^3
3×10^2
10^2
3×10^1
0
20
40
60
80
Z_T
U^{91+}
U^{90+}
XBL 837-10839

Fig. 2

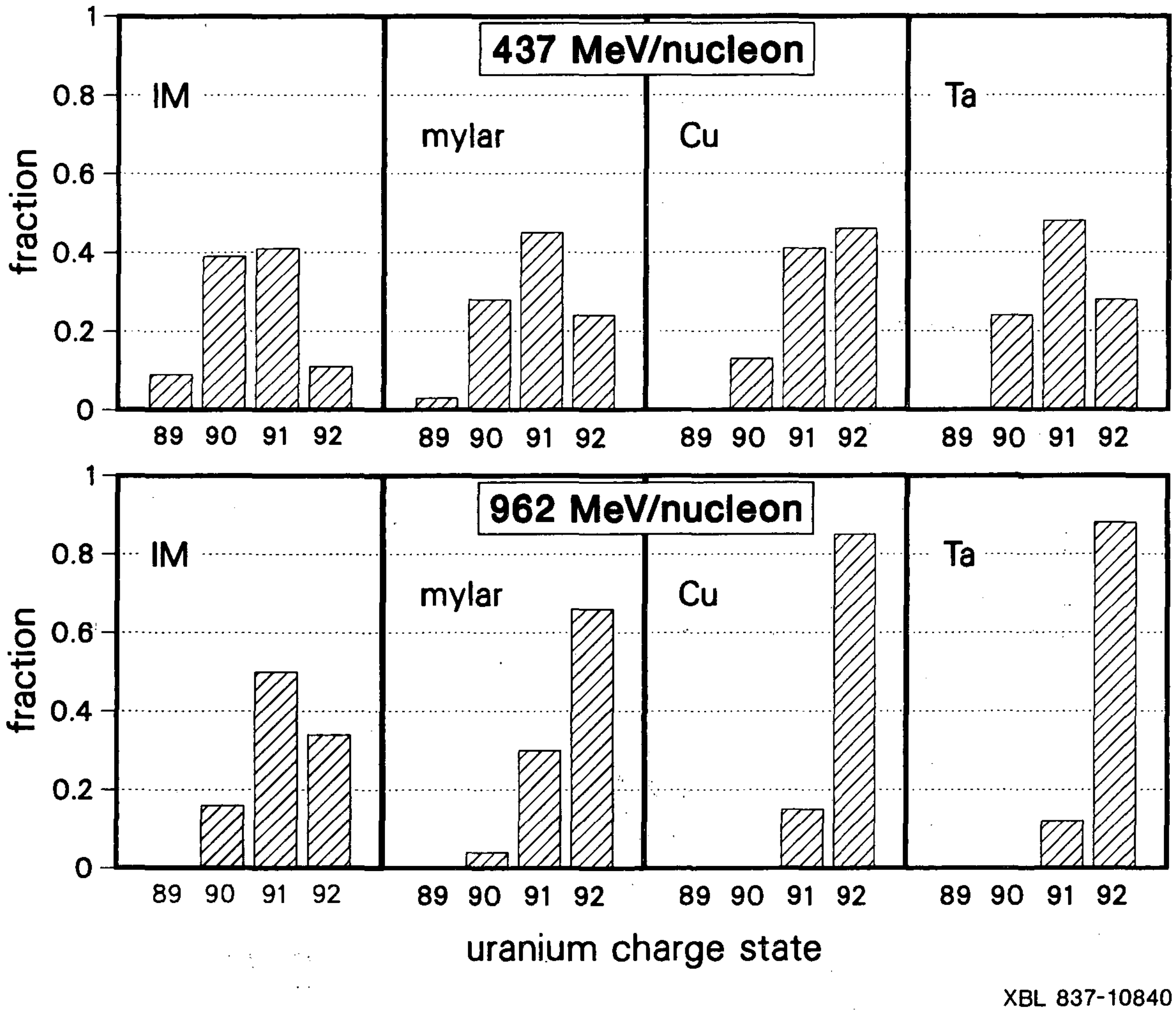
437 MeV/nucleon
962 MeV/nucleon
IM
mylar
Cu
Ta
fraction
0
0.2
0.4
0.6
0.8
1
89 90 91 92
uranium charge state
XBL 837-10840

Fig. 3