Electron Capture by U^{91+} and U^{92+} and Ionization of U^{90+} and U^{91+}

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(Received 8 August 1983)

Experimental cross sections at energies of 962 and 437 MeV/nucleon are reported for $U^{92+} \rightleftarrows U^{91+}$ and $U^{91+} \rightleftarrows U^{90+}$ in Mylar, Cu, and Ta, as well as equilibrium charge-state distributions in these materials. At 962 MeV/nucleon a beam containing over 85% bare U^{92+} nuclei is obtained.

PACS numbers: 34.70.+e, 29.25.Cy, 34.50.Hc

A knowledge of the electron-capture and ionization cross sections for relativistic very heavy ions has application to the determination of nuclear charge from energy-loss measurements —where the rate of energy loss is charge-state dependent— and to the design of an ultrarelativistic heavy-ion accelerator—where the use of higher charge states allows for a smaller and more energy-efficient accelerator.

In this Letter we report measurements, at energies of 962 and 437 MeV/nucleon, of the cross sections for the capture of an electron by U^{92+} and U^{91+} and for the ionization of U^{91+} and U^{90+} in Mylar, Cu, and Ta. These are the first experimental cross sections for capture and loss of an electron by a relativistic heavy ion of nuclear charge > 18. We find that beams containing nearly 50% bare U^{92+} are produced by stripping 437-MeV/nucleon uranium in a 90-mg/cm^2 Cu target and that beams containing over 85% bare U^{92+} are produced by stripping 962-MeV/nucleon uranium in 150-mg/cm^2 Cu or 85-mg/cm^2 Ta targets.

Relativistic U^{68+} ions are obtained from the Lawrence Berkeley Laboratory Bevalac[1]—a heavy-ion linear accelerator (Super-HILAC) and a synchrotron (Bevatron) operating in tandem. 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 proportional counter. At the proportional counter, the separation between adjacent uranium charge states is about 1 cm. The convolution of the beamwidth and the position resolution of the proportional counter 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 a near-equilibrium charge-state distribution. No increase in the beam width is observed.

We determine the cross sections for capture and ionization by a least-squares fit[2] of single-electron capture and loss cross sections to curves of the relative charge-state populations of U^{89+}–U^{92+} versus target thickness (Fig. 1). This is a model-independent fit which is blind

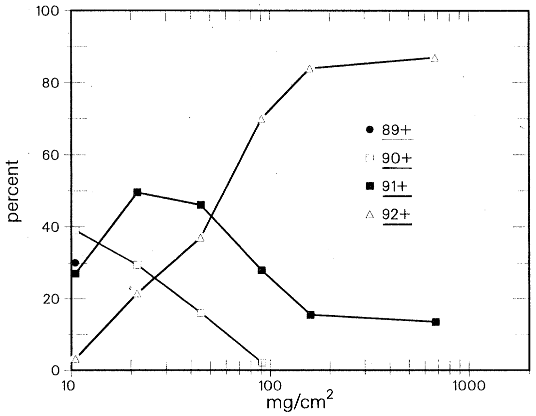

FIG. 1. Observed charge-state distributions of 962-MeV/nucleon uranium (incident charge state 68+), after passing through copper targets, as a function of target thickness.

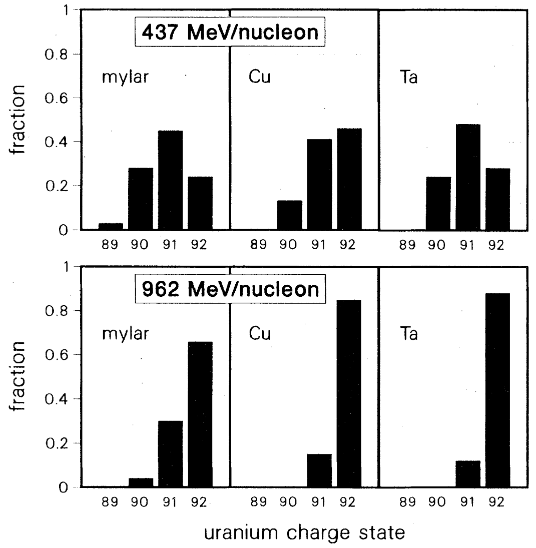

FIG. 2. Charge-state distributions of uranium at energies of 962 and 437 MeV/nucleon for equilibrium-thickness targets of Mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). At 437 MeV/nucleon, Cu produces higher charge states than does Ta.

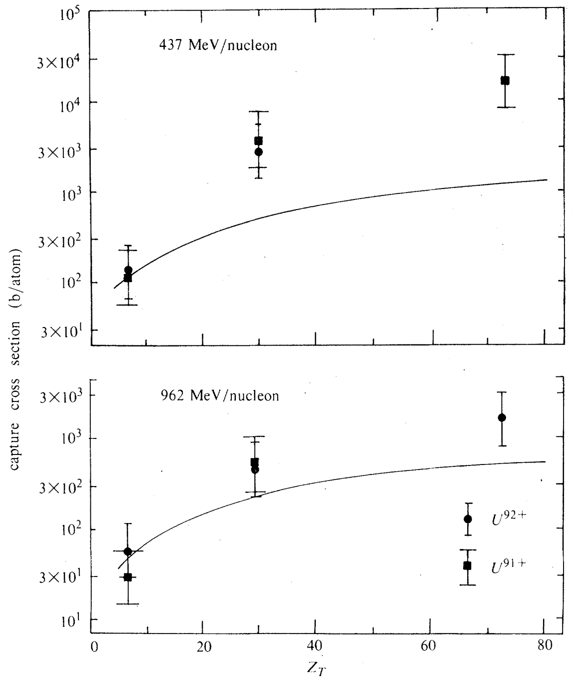

FIG. 3. Cross sections for capture of an electron by U^{92+} and U^{91+} at energies of 962 and 437 MeV/nucleon as a function of Z_T. Experimental points are for Mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). $\sigma_{\rm REC}$ for U^{92+}, calculated from Eq. (1), is shown as the continuous curve.

to the atomic states involved and to the mechanisms for capture and loss.

The equilibrium charge-state distributions (Fig. 2) are determined from the ratios of capture and ionization cross sections. Using the cross-section ratios avoids extrapolation to infinite-thickness targets. For all energies and targets one or more targets were of near-equilibrium thickness. The difference between the charge-state distributions observed for our thickest Cu and Ta targets and the equilibrium distributions for these materials was less than 5% of the total counts. The use of extremely thick targets offers no advantage over our present method because of the slowing down of the uranium in the target. We estimate the uncertainty in determining the equilibrium distributions, mostly due to statistics and a small background, to be less than 5% of the total counts.

The *absolute* cross sections, shown in Figs. 3 and 4, have an estimated error of a factor of 2.

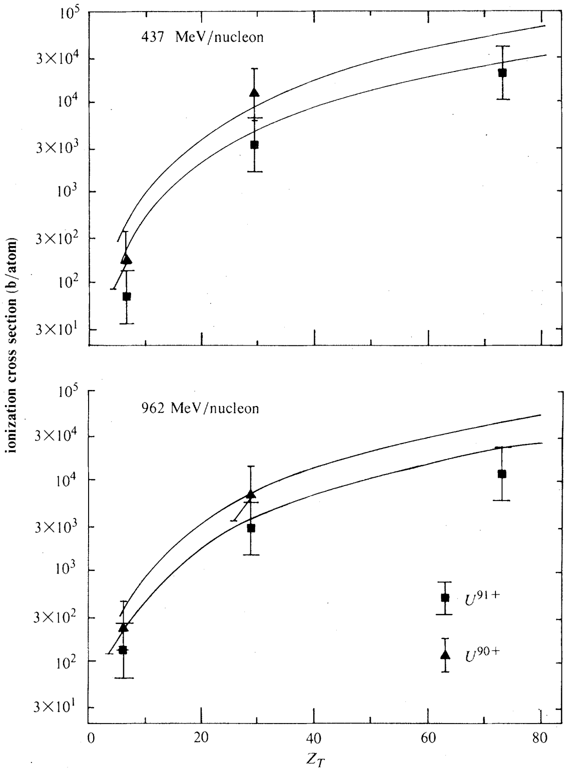

FIG. 4. Cross sections for ionization of U^{91+} and U^{90+} at energies of 962 and 437 MeV/nucleon as a function of Z_T. Experimental points are for Mylar ($Z_T \approx 6.6$), Cu ($Z_T = 29$), and Ta ($Z_T = 73$). The continuous curves are the loss cross sections calculated from Eq. (2) for U^{91+} (upper curve) and U^{90+} (lower curve).

The error is relatively large because only a few targets were used to cover a large range of target thicknesses and the useful data for determining the cross sections are limited to from three to six (average 4.2) charge-state distributions.

Figure 3 shows the experimental cross sections for capture of an electron by U^{92+} and U^{91+} at energies of 962 and 437 MeV/nucleon in 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. With neglect of binding energy of the target-atom electrons, the cross section[3] per target electron for radiative electron capture, σ_{REC}/electron, 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:

$$\frac{\sigma_{\mathrm{REC}}}{\text{electron}} = \frac{[(\gamma - 1) + B_n/mc^2]^2 X \sigma_\varphi}{[\gamma + 2B_n/mc^2]^2 - 1}. \qquad (1)$$

Here B_n is the binding energy of an electron in the nth shell, m is the electron mass, and c is the speed of light. Also, $\gamma = (1-\beta^2)^{-1/2}$ and $\beta = v/c$, where v is the uranium velocity. At 962 MeV/nucleon ($\gamma \approx 2.0$) and at 437 MeV/nucleon ($\gamma \approx 1.5$) photon energies from radiative electron capture into the K shell are 0.66 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- and 0.37-MeV photons are 25 and 90 b, respectively. Multiplying by the number of electrons in the target atom, we obtain values of σ_{REC} for U^{92+} shown in Fig. 3. σ_{REC} for U^{91+} is about half as large.

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- 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.

With the assumption of a negligible contribution to the capture cross section from nonradiative charge exchange in Mylar, our experimental data for Mylar are in satisfactory agreement with σ_{REC} calculated from Eq. (1). The difference between the experimental capture cross section and σ_{REC} for heavier targets in Fig. 3 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 by 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 $U^{90+,91+}$:

$$\sigma_i = 4\pi a_0^2 \left(\frac{\alpha}{\beta}\right)^2 \frac{1}{B_K} (Z_T^2 + Z_T) f_K \left\{ \ln \frac{(2\beta\gamma/\alpha)^2}{(0.048\, B_K)} \right\}. \qquad (2)$$

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 ≈ 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. 4 between measured cross sections and cross sections calculated from the Bethe theory is satisfactory.

In conclusion, we find that beams containing more than 85% bare U^{92+} nuceli can be obtained by stripping U^{68+} in Cu and Ta targets of 150 mg/cm^2 and 85 mg/cm^2, respectively, and that beams containing about 50% bare U^{92+} nuclei can be obtained by stripping 437-MeV/nucleon uranium in 90 mg/cm^2 Cu. Our data are consistent with radiative electron capture being the dominant process at these energies for electron capture from light targets. 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.

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