Electron Impact Ionization of U^{88+}-U^{91+}

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We channeled 405-MeV/nucleon uranium ions in Si single crystals to determine the electron impact ionization cross section for berylliumlike–hydrogenlike uranium by 222-keV electrons. Our cross sections are 3.9, 11.0, 16.0, and 31.0 b (+100%, −50%), respectively, for ionizing $1s$, $1s^2$, $2s$, and $2s^2$ electrons. Our $1s$ and $1s^2$ results disagree with present theory. Our $2s$ and $2s^2$ results are not accurate enough to distinguish between theories.

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In this Letter we report a novel application of channeling: the measurement of electron impact ionization cross sections for few-electron (relativistic) uranium ions. Until now there has been no way to make such measurements, which require, in addition to the very high charge state ions, a dense electron gas of known thickness.

We obtain very high charge state uranium ions from the Lawrence Berkeley Laboratory's Bevalac and a dense electron gas of known thickness by channeling[1,2] the uranium ions through a Si single crystal. In the single crystal the atoms are arranged in a periodic structure with "channels" along which there are no nuclei. Ions traveling in these channels make only large-impact-parameter collisions with the distant Si nuclei and thus do not acquire enough energy to ionize their tightly bound electrons.

For each combination of ion and crystal, there is a maximum transverse energy beyond which the ion will be deflected out of the channel. For few-electron uranium at 405 MeV/nucleon, this transverse energy is reached when the angle between the ions and the crystal axis is about 0.01°. In our measurements, the necessary small transverse energy is achieved by our collimating the uranium ions with circular apertures of 0.30 and 0.15 cm in diameter separated by 10.6 m (C2 and C3, respectively, in Fig. 1). This defines a maximum beam divergence half-angle of 0.21 mrad (0.012°) and decreases the beam intensity by about a factor of 5000, yielding an average count rate of one channeled ion per second.

In our experiment we use 405-MeV/nucleon uranium. Seen in the rest frame of the uranium, the electrons in the crystal have an energy of 222 keV. (The binding energy of U^{91+} is ≈ 133 keV.) We measure ionization cross sections of incident charge states from hydrogenlike U^{91+} through berylliumlike U^{88+}. These charge states (and bare U^{92+}) are prepared by our stripping U^{40+} ions at the exit of the Bevalac and magnetically separating the resulting charge states (Fig. 1). The ions lose roughly 2-MeV/nucleon energy in the stripper. The ions are then collimated and channeled along the ⟨110⟩ axis of a 0.11- or a 0.37-mm-thick Si single crystal. We use thick crystals because the charge changing cross sections are very small at relativistic energies. With thick crystals we can ignore the effects of small layers of dirt, oxides, and disoriented atoms on the crystal surface.

After the ions exit the Si crystal, the resultant ion charge states are again magnetically analyzed (M4 in Fig. 1), and then detected by a position-sensitive proportional counter. The raw data for the determination of the cross section for each incident charge state are the

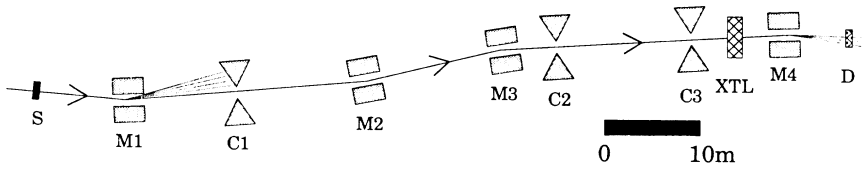

FIG. 1. Diagram of the beam line and apparatus. M1–M4 are dipole bending magnets and C1–C3 are collimators. Six quadrupole doublets used for focusing are not shown. The spacing of the components along the beam line is to scale but everything else is schematic. 407-MeV/nucleon U^{40+} from the Bevalac is stripped at S and the resulting charge states are analyzed by M1. C1 selects a single uranium charge state and C2 and C3 collimate the beam. After the beam passes through the crystal XTL, the resultant charge states are analyzed by M4, and detected by a position-sensitive detector (D).

relative charge state fractions of the ions exiting the crystals.

At 405 MeV/nucleon the cross section for ionization of uranium ions in collisions with Si nuclei is much larger than for ionization of uranium ions in collisions with electrons. The purpose of channeling the ions is to reduce or eliminate collisions with the Si nuclei. Figure 2(a) shows that the percentage of incident U^{89+} ions which exits the 0.11-mm-thick Si crystal without changing charge state increases from about 7% to 50% as the ⟨110⟩ axis of the crystal is rotated into alignment with the beam. Figure 2(b) shows similar data for U^{89+} passing through the 0.37-mm Si crystal. Figures 3(a) and 3(b) compare the charge state distributions at the exit of the 0.37-mm-thick crystal for incident U^{89+} ions traversing the crystal in a random direction [Fig. 3(a)] and along the ⟨110⟩ axis [Fig. 3(b)]. Figures 3(a) and 3(b) also show that the U^{89+} and U^{90+} exiting the crystal have lost less energy when they channel in the crystal rather than when they traverse the crystal in a random direction. This reduction in the energy loss is the usual signature for channeling of heavy ions.

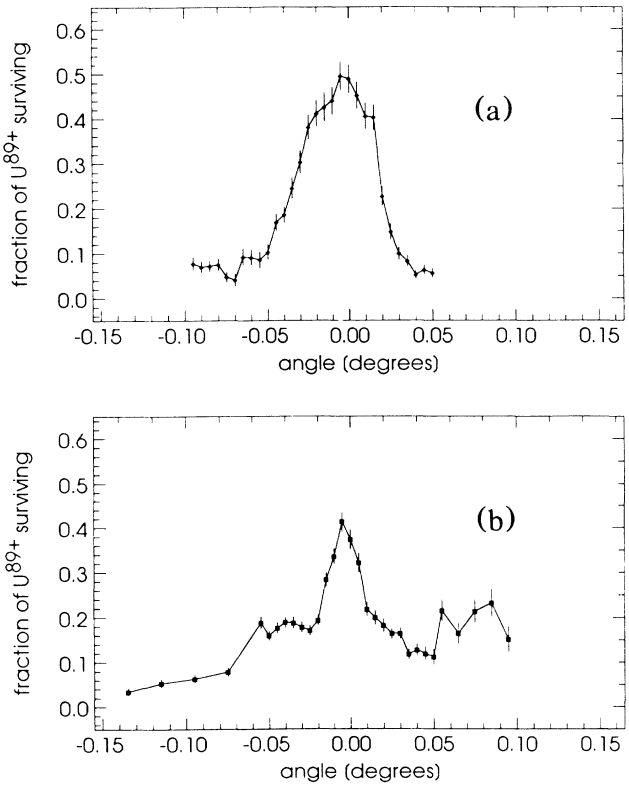

FIG. 2. Rocking curve showing the fraction of U^{89+} observed surviving passage through (a) the 0.11-mm Si crystal and (b) the 0.37-mm Si crystal as a function of angle between the uranium ions and the ⟨110⟩ axis. The expected channeling half-angle (including thermal vibrations), calculated from the formulas in Ref. 1, is 0.011° (0.19 mrad). The half-angle in (a) is 0.025°, possibly because of the crystal being bent in its mount. The channeling half-angle of the central peak (b) is 0.011°, consistent with the predicted value. The high fraction of U^{89+} at larger angles may be due to planar channeling effects. When this crystal was moved to a fully random orientation, the U^{89+} fraction was less than 2% [Fig. 3(a)].

Even if an ion has small transverse energy and is aligned with the crystal axis it may not channel if, for example, it enters the crystal too close to a row of nuclei. Ions which do not channel present a large background of ionization from ion-atom collisions and we subtract them from our measurement. Because of the much larger ionization probability for ions in the random direction in the crystal, we assume that all ions which lose several electrons have failed to channel. Thus in Fig. 3(b), the U^{91+} and U^{92+} come from U^{89+} ions which did not channel.

Comparing the fractions of U^{91+} in Figs. 3(a) and 3(b), we find that 80% of the U^{89+} aligned with the ⟨110⟩ axis channeled in the 0.37-mm-thick crystal. Including all of our measurements using incident ions of U^{88+}, U^{89+}, and U^{90+}, we find that 79% ± 2% of the incident ions aligned with the ⟨110⟩ axis channel in the 0.37-mm-thick Si crystal and 38% ± 2% channel in the 0.11-mm-thick crystal. We think that the smaller channeling fraction for the 0.11-mm crystal is the result of the thinner crystal being bent in its mount more than the thicker crystal. This is also reflected in a much wider acceptance angle for the 0.11-mm-thick crystal [Fig. 3(a)] than for the 0.37-mm-thick crystal [Fig. 3(b)].

Previous experiments at low energies[2-4] have mea-

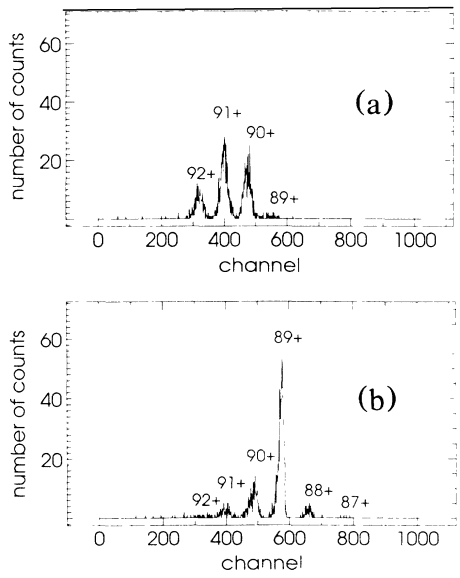

FIG. 3. Observed charge state distributions from 405-MeV/nucleon U^{89+} exiting the 0.37-mm-thick Si single crystal. (a) The ions pass through a random direction of the crystal. (b) The ions are aligned with the ⟨110⟩ axis of the crystal. Approximately 80% of the ions in (b) have channeled.

sured large differences between charge state distributions for channeled and unchanneled ions and have obtained total charge changing cross sections[4] for oxygen ions. Ours is the first experiment to measure the electron density as seen along the path of the channeled ions, allowing us to extract cross sections for electron impact ionization.

We measure the electron density integrated along the paths of the channeled ions by comparing a cross section for electron capture by the channeled ions with a previously measured[5] capture cross section for ions in the random direction. What makes this comparison possible is that the only capture process involved in either case is radiative electron capture (REC), which to a good approximation involves only the electrons in the target (and not the target nucleus) and thus scales linearly with the electron density. (REC is the process in which a free or loosely bound electron is captured by the ion with the simultaneous emission of a photon.) For relativistic ions in low-atomic number (Z) targets, REC has been shown to be the dominant electron capture mechanism, both for channeled ions[6] and for ions in random directions (amorphous materials), where cross sections have been measured[5,7-9] and agree with theory.[5,7-9]

The production of U^{88+} by REC from the incident U^{89+} can be seen in Fig. 3(b) [but not easily in Fig. 3(a) because of competition from the large ionization cross sections]. Comparing capture using incident charge states U^{89+}-U^{92+}, we find the average electron density in the $\langle 110 \rangle$ channel to be 0.44 ± 0.01 of the electron density in the bulk material—roughly 6.2 electrons per Si nucleus. The quoted uncertainty is only statistical and does not reflect the much larger systematic uncertainties in our measurements and in the measurements in Ref. 9.

Our electron impact ionization cross sections for hydrogenlike U^{91+}-berylliumlike U^{88+} by 222-keV electrons are listed in Table I and are compared with theory. We obtain cross sections by a least-squares fit of (capture and ionization) cross sections to the curves of charge state yield versus target thickness. We estimate the uncertainty in the cross sections to be a factor of 2 (from 50% smaller to 100% larger), because of systematic uncertainties in combining a large number of measurements made with only two target thicknesses, uncertainties in determining the channeling fractions, other possible effects not included in our analysis, uncertainties in capture cross sections, and uncertainties in the limits of the validity of our approximations.

Our cross sections for ionization of U^{91+}-U^{88+} by 222-keV electrons are compared to calculations of K-shell and L-shell ionization by Scofield,[11] Younger,[12-14] and Lotz,[15] and L-shell ionization by Pindzola and Buie.[10] Our U^{90+} and U^{91+} (K-shell) cross sections of 3.9 and 11.0 b (Table I), determined to a factor of 2, are not in agreement with the K-shell ionization cross sections extrapolated from Scofield,[11] or with the calculations of Younger,[12-14] or with the formula of Lotz.[15] We do not think that ionization of excited states, populated by electron excitation, makes a significant contribution to our measured U^{91+} or U^{90+} cross sections. This is because the mean free time between ionizing collisions ($\approx 10^{-12}$ s) is much longer than the radiative lifetime of all of the low-lying states of U^{91+} and U^{90+} except the $1s2s\,^3P_0$ state of U^{90+}, which is not easily populated.[16]

To compare our experimental results with calculations of L-shell cross sections (Table I), we subtract our U^{90+} cross section of 11.0 b from our measured ionization cross section of 27.0 b for U^{89+} (one L-shell electron) and 42.0 b for U^{88+} (two L-shell electrons). Our L-shell results are not sufficiently accurate to distinguish between the different calculations.[10-15]

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TABLE I. Electron impact ionization cross sections (b).

Ion	State	Expt.	PB[a]	Sco[b]	Younger	Lotz[f]
U^{91+}	$1s$	3.9		1.5	0.8[c]	0.7
U^{90+}	$1s^2$	11.0		3.0	1.7[d]	1.4
$U^{89+}-U^{90+}$	$2s$	16.0	13.0	29.0	9.4[c]	12.0
$U^{88+}-U^{90+}$	$2s^2$	31.0	26.0	57.0	19.8[e]	24.0

[a]Extrapolated from Ref. 10.
[b]Extrapolated from Ref. 11.
[c]Extrapolated from Ref. 12.
[d]Extrapolated from Ref. 13.
[e]Extrapolated from Ref. 14.
[f]Extrapolated from Ref. 15.

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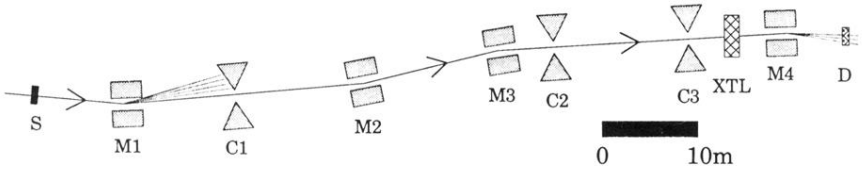

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