Resonant Transfer and Excitation for U^{90+} Projectiles in Hydrogen

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(Received 10 July 1990)

Resonant transfer and excitation (RTE), resulting from simultaneous electron capture and *K*-shell excitation in a single collision, has been measured for 97–150 MeV/u U^{90+} ions in hydrogen. Distinct maxima, attributed to RTE contributions from the formation of intermediate excited states, were observed superimposed on a monotonically decreasing background due to single-electron capture. This measurement, the first for a very heavy projectile, provides a test of relativistic dielectronic-recombination theory.

PACS numbers: 34.50.Fa, 34.70.+e

Resonant transfer and excitation[1] (RTE) has been measured in collisions of U^{90+} with H_2, thereby extending significantly the projectile range for which RTE has been investigated and providing a test of relativistic dielectronic-recombination theory.[2,3] RTE is one manifestation of the electron-electron interaction in ion-atom collisions, and involves the capture of a target electron simultaneously with the excitation of the projectile in a single collision, leading to the formation of an intermediate doubly excited state of the projectile. The decay of this doubly excited state through either x-ray[4,5] or Auger electron[6] emission has been used to identify and measure RTE in collisions of multiply charged ions with light gaseous targets through the observation of resonances in the energy dependence of the cross sections for x rays associated with electron capture or for Auger electron emission. RTE, which involves the capture of an electron bound to a target atom, has been shown[1,4,5,7] to be analogous to dielectronic recombination[8] (DR) for which the captured electron is free. In addition to its fundamental interest, DR is an important process in high-temperature astrophysical and fusion plasmas.[9] Since RTE cross sections can be calculated from DR cross sections by averaging over the momentum distribution of the target electrons,[10] measurements of RTE provide a test of DR theory.

RTE involving *K*-shell excitation has been explored for several projectile species with atomic number *Z* in the range 8–32 and a variety of projectile charge states (hydrogenlike to neonlike).[1,4,5,11-15] For these relatively low-*Z* projectiles, theoretical calculations[7,16] of RTE cross sections have shown excellent agreement with experiment. Additionally, at its resonance maximum, RTE has been observed to account for nearly half of the total single-electron-capture cross section in $Ca^{q+}+H_2$ collisions,[17] making RTE measureable in a "singles" noncoincidence experiment. This latter result suggested that the single-electron-capture cross section for very energetic, heavy, multiply charged ions might be dominated by RTE.[18]

There have been several recent theoretical studies of DR and RTE for highly stripped U ions incident on various targets,[2,3] partly motivated by previous unsuccessful attempts[19] to measure RTE for U^{89+} in C. In these calculations, the relativistic energy levels, Auger, and radiative rates required to determine the DR cross sections are obtained using the multiconfiguration Dirac-Fock model.[2,3] The cross sections calculated by both Chen[2] and Pindzola and Badnell[3] are in excellent agreement with each other for U^{89+} projectiles. The latter authors have also calculated the RTE cross sections for U^{90+} in H_2. RTE resonances are expected[2,3] in the energy range 110–180 MeV/u (26–43 GeV), based on the calculated Auger energies of U^{90+}.

RTE for U^{90+} in H_2 has been measured by studying the energy dependence of the total single-electron-capture cross section. The measurements were carried out at the Lawrence Berkeley Laboratory using the Bevalac facility. A schematic of the apparatus is shown in Fig. 1. Uranium ions, with an initial charge state of 68+ and the desired energy, were extracted from the Bevalac and further stripped in a 20-mg cm^{-2} Al foil. The energy loss in this foil varies from 3.8 to 3.0 MeV/u at beam energies from 100 to 150 MeV/u. The charge-state distribution of the beam leaving the foil, measured with a wire chamber, was compared with a prediction using measured cross sections[20,21] and was found to be in excellent agreement with the calculation if the highest observed charge state was assigned a value of 92+. The U^{90+} charge state could therefore be readily identified. This procedure was repeated at each energy, and, together with the scaling of the analyzing magnet field, ensured that an incident U^{90+} beam was used for all the present measurements. Beyond the charge-state selection mag-

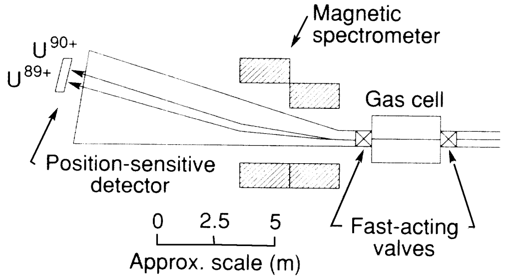

FIG. 1. Schematic diagram of the experimental apparatus.

net and suitable collimation, the beam passed through a 2.41-m-long gas cell.[22] Differential pumping and fast-acting beam-line valves at the entrance and exit of the gas cell, which opened only when the 160-ms beam pulse was present, allowed the gas cell to be operated at gas pressures of up to 6 Torr. The pressure in the gas cell was measured using a capacitance manometer.

The charge-state components emerging from the gas cell were dispersed with a magnetic spectrometer onto a position-sensitive scintillation counter, with a separation of about 2 cm between the U^{90+} and U^{89+} components, allowing them to be counted separately. The U^{89+} peak was found to sit on a background which was determined to be associated with the U^{90+} beam and independent of the gas-cell pressure. The total counts in the U^{89+} peak were found by integrating the peak region and subtracting the background contribution which was generally less than 10% of the total number of U^{89+} counts. At each energy the fraction of U^{89+} in the beam was measured at three different gas pressures including zero. The maximum observed U^{89+} fraction was 0.02. Single-collision conditions were verified by the linear target-thickness dependence of the U^{89+} fraction, and the electron-capture cross section was obtained from the slope of the U^{89+} fraction versus target thickness.

The relative uncertainties in the measured electron-capture cross sections were taken to be the standard deviation of the total number of counts at that particular energy, with the uncertainty in determining the background correction added in quadrature. Different techniques for the determination of the background contribution associated with the U^{90+} beam were found to change the determined U^{89+} fractions by less than 2%. Other possible sources of relative uncertainty in the cross-section determination were small compared to the statistical and background uncertainties. For example, a drift in the gas-pressure measurement or manometer linearity over the course of the experiment were mitigated against by making the measurements at nonsequential energies and by making measurements at several pressures at each energy. Also, the effect of possible nonuniformity of the particle-detection efficiency across the surface of the position-sensitive detector was minimized by adjusting the final-charge-state analysis magnet so that, at all energies, the U^{90+} and U^{89+} beams were at the same position on the detector, i.e., equidistant from the center of the detector.

Sources of absolute uncertainty in the electron-capture cross-section measurement arise from the measurement of the beam intensity and target thickness. The manometer was calibrated by the manufacturer both before and after the experiment and was found to agree with their standard to better than 1%. It is estimated that the gas-cell length, including end effects, adds a 1.3% uncertainty. By studying (1) the variation of charge-state fractions at different positions on the detector, (2) the count-rate dependence for various scintillator photomultiplier-tube voltages, and (3) by substituting other larger-area scintillator detectors, it was determined that uncertainty in detection efficiency could introduce a 10% contribution to the absolute uncertainty in the measured cross sections. The absolute uncertainty in the measured cross sections is therefore estimated to be ± 12%.

The energy of the U^{68+} beam exiting the Bevalac can be determined from the Bevalac magnetic field and beam radius. The uncertainty in these parameters gives an energy uncertainty of less than ±0.2 MeV/u over the region of the present measurements. The U^{90+} beam, having been created in passing through the Al foil, has an energy loss up to 4% of the initial beam energy; the energy-loss calculation is believed to be accurate to ± 10%. The absolute uncertainty in the U^{90+} beam energy is therefore estimated to be ±0.5 MeV/u.

The measured total single-electron-capture cross sections are shown in Fig. 2(a). Two prominent peaks and some indication of a third peak superimposed on a monotonically decreasing background are observed. The monotonically decreasing background, on which these peaks lie, is attributed to radiative and nonradiative electron capture;[18,20,21] the maxima are attributed to the contribution of RTE to the total electron-capture cross section. The three peaks arise from the formation, with increasing energy, of the $1s2s^2+1s2s2p_{1/2}+1s2p_{1/2}^2$, $1s2s2p_{3/2}+1s2p_{1/2}2p_{3/2}$, and $1s2p_{3/2}^2$ intermediate states. Another three peaks are expected,[2] starting at about 151 MeV/u, due to the formation of the $1s2l3l'$ intermediate state.

A smooth function can be fitted to the radiative and nonradiative electron-capture background using the experimental data points below 109.9 MeV/u and from 138 to 145 MeV/u, where the RTE cross section is expected to be zero,[2,3] shown in Fig. 2(a). The RTE cross section for U^{90+} in H_2 can thus be found by subtracting this background from the measured total electron-capture cross section. The RTE cross section, determined in this manner, is also shown in Fig. 2(b). It is seen that the magnitude and positions of the maxima in the measured RTE cross sections are in excellent agreement with the calculated values of Pindzola and Badnell.[3] The absolute uncertainty in the measured RTE cross section in-

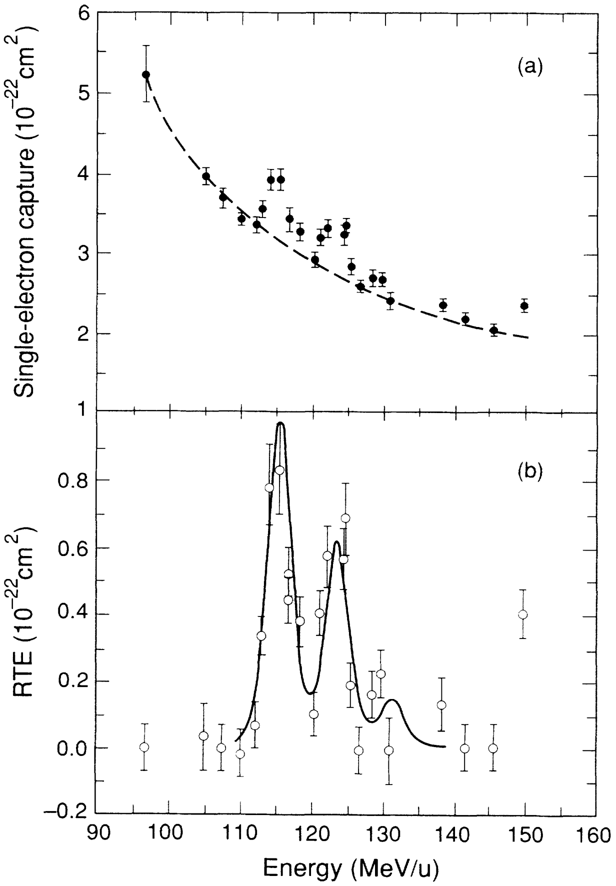

FIG. 2. Experimental and theoretical cross sections for U^{90+} in H_2. (a) Solid circles, measured total single-electron-capture cross section. Dashed curve, empirical fit to electron-capture background (see text). Error bars show the relative uncertainty in the measured cross sections. (b) Open circles, experimentally determined RTE cross section (total single-electron-capture cross section minus empirical fit). Solid curve, theoretical calculations of RTE cross section (Ref. 3). Error bars show the absolute uncertainty in the experimentally determined cross sections.

cludes uncertainties in the total electron-capture cross section and from fitting the electron-capture background. It is emphasized that the magnitudes of both the measured and calculated cross sections are absolute and have not been normalized to one another.

In summary, these measurements have significantly extended the study of RTE into a region where relativistic effects play an important role. This first test of relativistic RTE and hence DR theory shows excellent agreement with the experimental cross sections.

This work was supported by the Science and Engineering Research Council of Great Britain, the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences, and Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The authors wish to thank the entire operations staff at the Bevalac, particularly Bruce Rude and Hugh Ellision for their skilled contributions to this experiment, Dr. Hank Crawford for lending us the position-sensitive detector and Mel Flores for making it work, and the SAS Collaboration at the Bevalac for making the gas cell available for our use. We also wish to thank Dr. Nigel Badnell and Dr. Harvey Gould for their advice on theoretical and technical aspects of this work.

Note added.— A calculation performed subsequent to submission of this paper[23] extends the calculation of the RTE cross section for U^{90+} to 180 MeV/u, and shows a second series of peaks lying at higher energies. The experimental point at 150 MeV/u [Fig. 2(b)] lies on the calculated curve at the first peak of the second series.

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