Electron-Impact Excitation of Si^{3+} ($3s \rightarrow 3p$) Using a Merged-Beam Electron-Energy-Loss Technique

E. K. Wåhlin, J. S. Thompson, and G. H. Dunn[a]
Joint Institute for Laboratory Astrophysics, University of Colorado
and National Institute of Standards and Technology, Boulder, Colorado 80309

R. A. Phaneuf and D. C. Gregory
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

A. C. H. Smith
University College London, London WC1E 6BT, United Kingdom
and Joint Institute for Laboratory Astrophysics, University of Colorado
and National Institute of Standards and Technology, Boulder, Colorado 80309
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

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For the first time, absolute cross sections for electron-impact excitation of a multiply charged ion have been measured using an electron-energy-loss technique. Cross sections for $e+\mathrm{Si}^{3+}(3s\,{}^2S_{1/2}) \rightarrow e+\mathrm{Si}^{3+}(3p\,{}^2P_{1/2,3/2})-8.88$ eV have been measured with an accuracy of ±20% (at 90%-confidence level) over a narrow energy range (±0.6 eV) about the threshold energy with an energy resolution of 0.2 eV. Results are in good agreement with close-coupling calculations.

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This paper introduces a new technique for measurements of cross sections for electron-impact excitation of multiply charged ions and gives results for excitation of Si^{3+}. The study of multiply charged ions, their structure and the dynamics of their interactions with other particles, is the object of intense current interest,[1] propelled in part by the role such ions play in fusion, astrophysical, laser, and other high-temperature plasmas and in part by the fact that new technology has appeared which makes purposeful experimental studies of multiply charged ions possible and palatable. Technological advances starting with the inventions of the electron-cyclotron-resonance (ECR) ion source and the electron-beam ion source (EBIS) ushered in this capability. Now, ion storage rings dedicated to such studies have been built and results are forthcoming.[2] The invention of the electron-beam ion trap[3] (EBIT) and sophisticated use[4] of the EBIS have also added exciting new avenues for such investigations. Stimulating results on dielectronic and radiative recombination of ions and electrons, electron-impact ionization of ions, ion-neutral collisions, and spectroscopy are forthcoming regularly.

In this climate there stands out a paucity of experimental information on electron-impact excitation of multiply charged ions, highlighting the need for a new technique for such measurements. Nearly all measurements of excitation cross sections for ions in the past have been made by detecting the fluorescence resulting from collisions in a crossed-beam geometry. A large number of absolute measurements have been performed for singly charged ions.[5] However, the $\lesssim 10^{-4}$ detection efficiencies, decreasing cross sections with increasing charge, growing difficulty of achieving high target densities, and escalating difficulty in performing absolute radiometry for the progressively shorter wavelengths associated with highly charged ions combine to make the measurements ever more difficult as the ionic charge increases. Hence, absolute experimental results exist for only a few (Al^{2+}, C^{3+}, N^{4+}, and Hg^{2+}) ions of charge greater than one. An electron-energy-loss technique using crossed beams has been used for a few singly charged ions by Chutjian and co-workers[6] to obtain relative inelastic differential cross sections over the angular range 6°-17°.

It is only recently, with the breakthrough brought by the EBIT, that there has been any advance in this area. With this method,[3] excitations of very highly charged heavy ions with noble-gas-like structures have been studied by measuring x-ray emissions from the trapped ions, and putting the measurements on an absolute scale by normalizing to observation and theory for radiative recombination of the species under study. As exciting as this development is, there is still the need for a method to study excitation of states other than those that radiate and to investigate intermediate charge states where radiation and autoionization have competitive lifetimes. The technique we demonstrate here addresses this need.

The Si^{3+} target has been chosen, since theoretical calculations for sodiumlike species should be of relatively high quality; thus, in a sense, we at once test both the new method and the theory. Also, the physics of silicon ions is important for the modeling of edge plasmas of tokamaks, and silicon is an abundant and often observed astrophysical species.

In our method, reported in more detail elsewhere,[7] electrons are merged[8] with ions using a trochoidal analyzer (crossed electric and magnetic fields), and, after colliding with the ions along the interaction path, are demerged using a second such analyzer. The inelastically scattered electrons are detected with a position-sensitive detector (PSD). The magnetic field was adopted to achieve a detection efficiency of nearly unity (compared with $\lesssim 10^{-4}$ for the fluorescence or differential monchromator methods), and the crossed fields lead to both a convenient merging method and a way to disperse the electrons in the presence of the magnetic field. The virtues of the method are thus (1) it yields absolute measurements, (2) detection efficiency is high (≈ 0.7), (3) it permits measurements near the critical threshold region, and (4) it yields total cross sections for excitation of nonradiating as well as radiating states. The technique should thus be adaptable to use with the storage rings which have recently come on line. The difficulties with the method will be apparent below.

Our apparatus is illustrated schematically in Fig. 1. The entire apparatus is immersed in a highly uniform magnetic field of approximately 4×10^{-3} T. Electrons from the gun enter the **E**×**B** field region of the merger where they execute trochoidal trajectories. After two cyclotron periods they arrive at the exit of the merger where they become merged with the 30-keV ion beam. The electrons interact with the ions in an electric-field-free region of length 7 cm, and then enter another **E**×**B** field region which separates the electrons and ions and disperses the electrons. The primary electron beam is collected in a Faraday cup, while those electrons which have undergone inelastic collisions strike the PSD. The ions, which are relatively unaffected by the **E**×**B** fields, are deflected through 90° by electric-field plates and are collected in a Faraday cup. A probe is inserted into the interaction path to measure the three-dimensional spatial distributions of the two beams.

Cross sections for the inelastic-scattering process can then be determined from the equation

$$\sigma=\frac{R}{\epsilon}\,\frac{v_e v_i}{|v_e-v_i|}\,\frac{qe^2}{I_e I_i}\,\frac{1}{\Omega}\,, \tag{1}$$

where R is the event count rate at the desired location on the PSD, ϵ is the detection efficiency for the scattered electrons, and v_e, v_i, I_e, and I_i are the velocities and currents of the electrons and ions, respectively. The quantity $1/\Omega$ is the beam overlap factor determined from the beam density distributions $G(x,y,z)$ and $H(x,y,z)$ for the electrons and ions, respectively, from the relationship

$$\Omega=\frac{\int G(x,y,z)H(x,y,z)\,dx\,dy\,dz}{\int G(x,y,z)\,dx\,dy\int H(x,y,z)\,dx\,dy}\,. \tag{2}$$

The quantities G and H are determined by measuring the two-dimensional beam intensity distributions at a number of positions z (at least seven) along the interaction path using a fluorescent-screen–digital-video-camera technique, which is fully described elsewhere.[9]

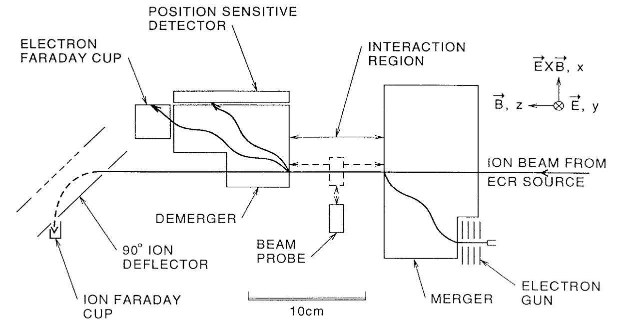

FIG. 1. Schematic diagram of the merged-beam electron-energy-loss apparatus.

Both beams are chopped and four histogram memories are gated so as to record count rate and position information for the conditions (1) beams off (D), (2) ion beam on ($I+D$), (3) electron beam on ($E+D$), and (4) both beams on ($R+I+E+D$), where R represents the count rate due to electron-ion interactions. On alternate cycles the relative phase of the beam switching is reversed so that subtle pressure-modulation and other spurious effects are minimized; the cycle rate is high (1 kHz) to further minimize pressure-modulation effects. The detection system was calibrated absolutely by direction an electron beam onto the PSD and comparing count rates with directly measured beam currents of a few femtoamperes. The intensity and position of the signal R is determined by arithmetic manipulation of the four recorded histograms. Careful computer modeling of electron trajectories with knowledge of beam density profiles G and H was performed to predict coordinate loci for the signal, which were verified by measurement. This modeling provides assurance that the demerger was adjusted to deflect most of the inelastically scattered electrons onto the PSD and to correct for any small fraction that missed.

The ion beam of Si^{3+} from the ORNL ECR source was collimated to a diameter of 1.5 mm; the electron-beam diameter was normally smaller. The ion- and electron-beam currents were typically 30 and 100 nA, respectively. Despite an operating vacuum of 1.2×10^{-8} Pa, background count rates from the ion and electron beams were typically 500 and 100 $\mathrm{s}^{-1}\,\mathrm{nA}^{-1}$, respectively. The extraordinarily high ion background is mainly due to a small fraction of the incident ions in doublet and quartet states of the Na-like $2p^53s3p$ configuration[10] which are metastable against autoionization with lifetimes in the 1–10-μs range and which emit electrons in the detector region. The electron background had approximately equal components due to scattering from background gas and from surfaces. The "dark" rate D

was very small (a few per second), and the signal rate R was typically tens of counts per second. The dead time associated with the detection system was determined to be 3.58 ± 0.2 μs. A high level of accuracy for the dead time was required in this particular experiment because of the high backgrounds encountered. Also, the high backgrounds made the measurements very susceptible to modulation of the trajectories (and thus the background) of one beam by the space charge of the other. Such modulation will be evident at energies below the excitation threshold. Great care was exercised to eliminate this source of spurious signals.

The most serious limitation of this method is that an electron beam, upon entering the $\mathbf{E}\times\mathbf{B}$ regions, experiences a potential difference across the beam height, which makes it appear that the beam has a much greater energy spread. The dispersion is greatly sacrificed to this so-called "shear effect," and this leads to the most critical difficulty with the measurements, that of separating inelastically scattered from elastically scattered electrons. The trochoidal analyzer energetically disperses electrons at an angle Θ determined by the transverse drift velocity $\rho = E/B$ and the longitudinal (along B) velocity v_l, such that $\Theta = \tan^{-1}(\rho/v_l)$. Some electrons elastically scattered at large angles from the Si^{3+} ions will have the same range of v_l as the inelastically scattered electrons of interest and will thus appear at the detector over the same locus of positions. To partially obviate this problem, we introduced limiting apertures at the entrance of the demerger to prevent electrons elastically scattered at angles greater than 20° in the laboratory frame from entering the analyzer. This allows separation of inelastically and elastically scattered electrons for at least a small range of energies above threshold. As presently configured, our modeling shows separation for a range of 2 eV above threshold, but we limited measurements to 0.6 eV. In this energy range, backscattered electrons in the center-of-mass frame are still forward scattered in the laboratory frame, and are thus collected, as verified by our modeling.

Our absolute-cross-section measurements are shown in Fig. 2. The bars on the points represent relative uncertainties at a 90%-confidence level (1.7σ). They have been determined by adding in quadrature the uncertainties from the counting statistics (11%), possible spurious signals (8%) (e.g., space-charge modulation of backgrounds), incomplete collection of signal (8%), and the beam overlap factor (5%). An additional systematic uncertainty of 11%, also at 90% confidence, comes from the dead-time correction (10%), detector calibration (3%), and beam-current measurements (0.5% each beam). The total absolute uncertainty near the maximum of the cross section is $\pm 20\%$ at a 90%-confidence level, and the point at 9.2 eV shows total uncertainty by the use of double error bars.

Also shown in Fig. 2 are seven-state R-matrix close-coupling calculations by Badnell, Pindzola, and Griffin,[11] which have been convoluted with a Gaussian of 0.20 eV full width at half maximum to allow a direct comparison with our results. The theoretical cross section was shifted up in energy by 0.17 eV to bring the threshold energy into agreement with the spectroscopic value. The convolution smooths out a large number of narrow resonances in the threshold region. The agreement of the theoretical curve with the experimental data is seen to be very good in both magnitude and shape. In point of fact, however, the theory did not take into account the 0.057-eV energy difference between the $P_{1/2}$ and $P_{3/2}$ levels. The true cross section would thus be the sum of two cross sections separated by 0.057 eV and in the ratio 1 to 2 for the two levels, respectively. When these cross sections are modeled as step functions and convoluted with an energy distribution, good agreement is obtained with either a 0.15- or 0.20-eV-wide distribution.

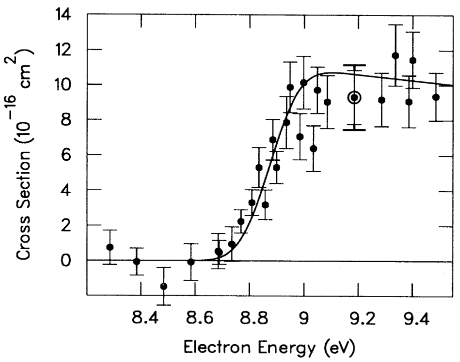

FIG. 2. The cross section for $3s \rightarrow 3p$ excitation of Si^{3+} by electron impact. The points are the present absolute measurements, and the curve represents seven-state close-coupling calculations (Ref. 11) convoluted with a 0.20-eV FWHM electron energy distribution. The error bars denote total relative uncertainties at a 90%-confidence level. The outer bar on the 9.2-eV measurement represents the total absolute uncertainty.

We conclude that the experimental data are consistent with a step at threshold of a magnitude given by the close-coupling theory, and the energy resolution for the experiment in the center-of-mass frame is approximately 0.15–0.20 eV. Finally, we have established the feasibility of measuring absolute total excitation cross sections for multiply charged ions using the merged-beam energy-loss technique.

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