Electron-impact-ionization cross-section measurements for Ti^{11+} and Cr^{13+}

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Absolute cross sections for ionization of the Na-like ions Ti^{11+} and Cr^{13+} due to electron impact have been measured over the energy ranges 300–800 eV and 500–1500 eV, respectively. These measurements confirm predictions by Griffin, Pindzola, and Bottcher [Phys. Rev. A **36**, 3642 (1987)] concerning the magnitude of indirect processes for these ions.

A recent paper by Griffin, Pindzola, and Bottcher[1] dealt with configuration-average distorted-wave theory applied to ionization of Na-like ions by electron impact. Their study covered Na-like Ti, Cr, Fe, and Ni, and included investigations of the importance of excitation to autoionizing configurations, of configuration interaction, and of the branching between radiative stabilization and autoionization following excitation of target electrons by the incident electron. The paper includes plots of total ionization cross sections and rate coefficients that take into account excited states through the $n=5$ shell. Other multiply charged Na-like ions have been studied both experimentally[2] and theoretically.[3]

One of the trends observed experimentally in the scaling of ionization cross sections is an increasing ratio of indirect to direct ionization with increasing charge along an isoelectronic sequence. The peak direct ionization cross section decreases steadily along an isoelectronic sequence as the ion Z (and charge) increases, while the excitation thresholds and cross sections for inner-subshell electrons are relatively unaffected; thus, excitation-autoionization is expected to become relatively more important with increasing charge. However, as the radiative lifetimes of the excited intermediate states become shorter (again with increasing charge), the fraction of those excited states that autoionize becomes smaller, as more of the ions stabilize radiatively. One of the important predictions by Griffin, Pindzola, and Bottcher was that for the Na-like ions from Ti^{11+} through Ni^{17+}, the increasing importance of inner-shell excitation is balanced by a decreasing autoionizing fraction of the excited ions. Indirect ionization was therefore calculated to contribute an almost constant 80% of the total peak ionization cross section for each ion. The most dramatic change in the autoionizing-to-total branching ratio occurs between Ti^{11+} and Cr^{13+}, which are predicted to have branching ratios of 0.81 and 0.63, respectively. The present study was undertaken in part to test the accuracy of the total ionization calculations discussed above. Additional results for other multiply charged Ti and Cr ions have been published.[4,5]

The present data were measured using the Oak Ridge National Laboratory (ORNL) electron-ion crossed-beams apparatus. Both the apparatus[6] and ion source[7] have been described previously, so only those details unique to this experiment or of particular importance to the results will be discussed here. Ion beams for the experiment were extracted at 10-kV potential from the ORNL ECR ion source. A 0.001-in-thick Ti foil was inserted into the source ECR plasma region to produce ions for the Ti^{11+} beam, while an Inconel foil was used for the Cr^{13+} beam. Typical ion beam currents in the collision region were 20 nA (electrical) of Ti^{11+} and 2 nA of the mass-53 isotope of Cr^{13+}. The mass-53 Cr isotope (with 10% abundance) was used in the experiment because the 13-times-charged primary isotope (mass 52) has the same mass-to-charge ratio as O^{4+}, which is always present as an impurity in the ion source. Measurements taken with the $^{52}Cr^{13+}$ ion beam in the presence of the O^{4+} component would have required normalization; also, a higher background was observed in the signal detector with the major isotope beam so that statistics were actually accumulated faster using the weaker beam.

The incident ion beam crossed a magnetically confined electron beam[8] at 90° and was separated from the further-ionized signal ions in a double-focusing magnetic analyzer. The absolute cross section was determined at each energy based on the ion and electron beam velocities and currents, the overlap and sizes of the beams at their intersection, the absolute efficiency of the signal ion

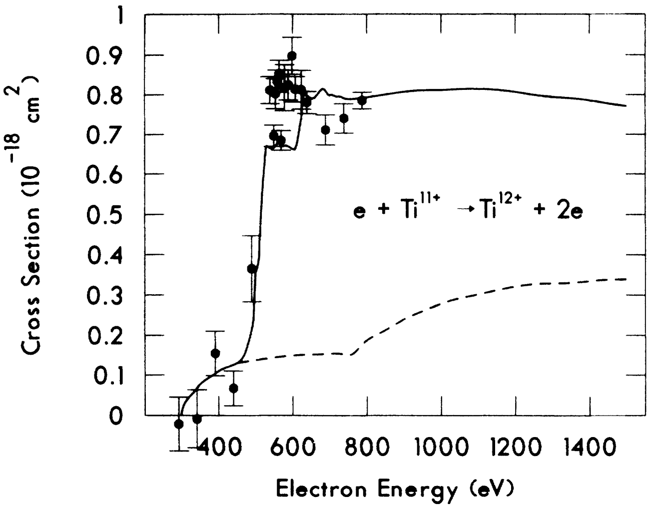

FIG. 1. Electron-impact-ionization cross section of Ti^{11+}. The solid points are the present data; the dashed curve is a distorted-wave calculation (Ref. 1) for direct ionization only, while the solid curve includes excitation autoionization. Uncertainties are relative at the 1-s.d. level.

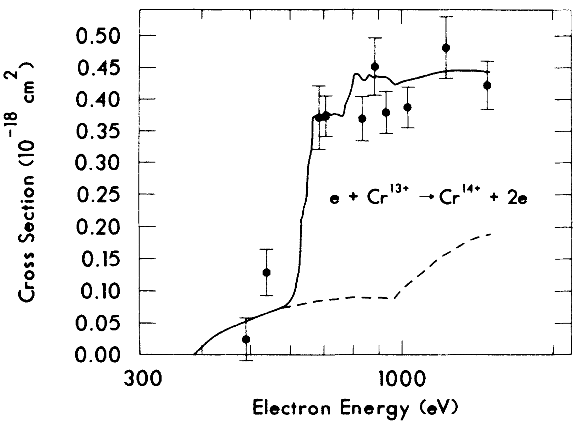

FIG. 2. Electron-impact-ionization cross section of Cr^{13+}. Curves and data are as in Fig. 1.

detection and counting system, and the signal count rate. Typical electron currents near the peak cross sections were 5 mA for Ti^{11+} (at 600 eV collision energy) and 9 mA for Cr^{13+} (at 950 eV). Signal and background count rates for Ti^{11+} were 8 and 90 Hz, respectively, while these count rates were 0.2 and 0.75 Hz, respectively, for Cr^{13+}. Absolute uncertainties for both measurements were dominated by counting statistics. Based on previous measurements where specific detailed data could be compared to calculations, the interaction energy is considered to be accurate to better than 1 eV, with an energy spread in the electron beam of less than 2 eV.

Cross section results for electron-impact ionization of Ti^{11+} are plotted in Fig. 1 and listed in Table I along with relative uncertainties at the equivalent of one standard deviation for statistics (1 s.d.). The two curves shown in the figure are distorted-wave calculations[1] for direct ionization (dashed curve) and direct plus excitation-autoionization, including configuration-interaction and

TABLE I. Cross-section measurements for electron-impact ionization of Ti^{11+} and Cr^{13+}. The uncertainties listed are relative at the equivalent of 1 s.d. for statistics; absolute uncertainties are dominated by the statistics.

	Ti^{11+}		Cr^{13+}
Energy (eV)	Cross section (10^{-18} cm^2)	Energy (eV)	Cross section (10^{-18} cm^2)
292	−0.022±0.067	490	0.024±0.034
341	−0.009±0.072	539	0.129±0.036
391	0.154±0.056	686	0.371±0.050
440	0.067±0.043	720	0.373±0.032
490	0.365±0.082	835	0.369±0.035
539	0.811±0.034	885	0.449±0.043
549	0.696±0.027	931	0.379±0.033
554	0.802±0.038	1028	0.387±0.032
559	0.834±0.028	1225	0.481±0.048
564	0.851±0.035	1480	0.422±0.038
569	0.684±0.025		
578	0.817±0.058		
589	0.824±0.038		
599	0.897±0.046		
608	0.813±0.032		
624	0.812±0.049		
639	0.780±0.028		
688	0.711±0.038		
738	0.740±0.037		
788	0.785±0.021		

branching effects (solid curve). The largest increase in the calculated cross section, at about 500 eV, is due to excitation of 2*p* electrons to 3*p* and 3*d* autoionizing levels, while the smaller step at 600 eV is the result of 2*p* to 4*d* excitations. Experiment and theory agree quite well in shape and magnitude over the entire energy range studied here, with the exception of the interval from 550 to 600 eV. In that energy range, the experimental cross section actually appears to be larger than that found at slightly higher energies, despite the fact that the 2*p*-4*d* excitation should not be contributing at the lower energies. The experimental results also appear to be "unstable" in the 550–600-eV energy range, with several measurements only a few electron volts apart in energy being more than 1 s.d. apart in cross section. We suspect that the enhancement and sharp features in the cross section are the results of resonant-excitation double autoionization (REDA), an indirect ionization process that was predicted some time ago (see Lagattuta and Hahn in Ref. 3) but only recently distinctly observed.[9] We do not clearly resolve individual features or even the shape of the enhancement, but suggest that the energy range 550 to 600 eV in Ti^{11+} is a likely candidate for future experimental or theoretical studies of the REDA effect.

Cross-section measurements for ionization of Cr^{13+} are plotted in Fig. 2 and listed in Table I, along with relative uncertainties at the 1-s.d. level. The dashed curve in Fig. 2 is the distorted-wave calculation[1] for direct ionization, while the solid curve includes excitation-autoionization with configuration interaction and branching taken into account. Theory and experiment are in excellent agreement considering the rather large experimental uncertainties that resulted from rather weak target ion beam currents. The peak cross section is only about half that of Ti^{11+}, but the same 2*p*-3*p*, 2*p*-3*d*, and 2*p*-4*d* transitions to autoionizing levels dominate the indirect contribution. The two measurements between the 2*p*-3*d* and 2*p*-4*d* onsets (650 to 750 eV) have rather large uncertainties, and show no cross section enhancement corresponding to that observed for Ti^{11+}.

The present measurements confirm the cross-section predictions of Griffin, Pindzola, and Bottcher for the Na-like ions Ti^{11+} and Cr^{13+}. These cross sections are of particular interest because of the rather sharp difference in the fraction of excited ions that are predicted to stabilize radiatively for these ions. Accurately predicting such changes is important to model plasmas satisfactorily for fusion energy and other applications.

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