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Resonant electron impact ionization and recombination of Li-like Cl^{14+} and Si^{11+} at the Heidelberg Test Storage Ring

J. Kenntner [a,*], J. Linkemann [b], N.R. Badnell [c], C. Broude [a], D. Habs [a], G. Hofmann [d], A. Müller [b], M.S. Pindzola [e], E. Salzborn [d], D. Schwalm [a], A. Wolf [a]

[a] *Max-Planck-Institut für Kernphysik and Universität Heidelberg, 69117 Heidelberg, Germany*
[b] *Institut für Strahlenphysik, Universität Stuttgart, 70550 Stuttgart, Germany*
[c] *Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 0NG, UK*
[d] *Institut für Kernphysik, Universität Giessen, 35392 Giessen, Germany*
[e] *Department of Physics, Auburn University, Auburn, AL 36849-5311, USA*

Abstract

Absolute cross sections for dielectronic recombination and electron-impact ionization of Li-like Cl^{14+} and Si^{11+} ions have been measured with high energy resolution at the Heidelberg heavy ion storage ring TSR, using the electron cooler as a free electron target. Recombination and ionization rates were recorded simultaneously for the whole energy range from 0 up to the second ionization threshold. We discuss excitation-autoionization steps, dielectronic ionization and dielectronic recombination resonances associated with $1s \to 2l$ and $1s \to 3l$ excitations. The results agree well with theory, but the distorted wave calculations overestimate direct ionization by $\sim 20\%$.

1. Introduction

Electron-impact ionization and recombination are important collision processes in hot plasmas. In merged beams experiments, dielectronic recombination (DR) has been studied in great detail [1], and heavy ion storage rings proved to be well suited for the investigation of highly charged ions. In contrast, the direct observation of electron-impact ionization was so far limited to ions in lower charge states [2]. It was shown, however, that indirect processes can make significant contributions to the ionization cross section. The most important indirect processes are excitation-autoionization (EA), an excitation of an inner shell electron followed by Auger emission (leading to distinct *steps* in the cross section), and dielectronic ionization, a resonant capture of the projectile exciting an inner shell electron (dielectronic capture), followed by Auger emission of two electrons (giving rise to *peaks* in the ionization cross section). To study indirect ionization processes, Li-like ions provide an ideal model system. The electronic structure is complex enough to supply a variety of indirect processes, yet simple enough to allow detailed theoretical calculations and to identify individual ionization mechanisms in the experimental data.

We have measured and calculated the electron-impact ionization cross section up to the second ionization threshold for Li-like Si^{11+} and Cl^{14+}, together with inner shell DR resonances connected to configurations $1s2s2lnl'$ and $1s2s3lnl'$. At lower center of mass energies, we also investigated outer shell DR resonances $1s^2 2pnl$ and $1s^2 3lnl'$, but they will not be presented in this paper. Earlier DR measurements and calculations in the lithium isoelectronic sequence have been performed for several charge states up to $Z = 79$ [3,4], but the experiments with highly charged ions were limited to outer shell DR resonances. Electron-impact ionization, on the other hand, has been experimentally studied only for ions up to $Z = 9$ [5], showing good agreement with theoretical calculations [6]. Recent calculations of indirect ionization processes for Li-like ions with $Z = 18$–54 showed the persistence of indirect ionization processes up to very highly charged ions [7,8].

We use the intense ion beams in the heavy ion storage ring TSR [9] together with the electron cooler [10] as a free electron target to study indirect ionization processes, continuing earlier experiments on DR [3,11]. By simultaneously measuring the ionization and recombination cross sections we obtain a direct measurement of the branching ratio for double autoionization and radiative stabilization of doubly excited states populated by dielectronic capture.

The calculations were done in the independent-processes and isolated-resonance approximation using semirelativis-

* Corresponding author. Tel. +49 6221 516 347, fax +49 6221 516 540, E-mail: kenntner@mickey.mpi-hd.mpg.de.

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tic distorted waves, following the approach for few-electron highly charged ions described in Ref. [8]. Direct ionization, EA and dielectronic ionization contributions were calculated separately and added before the cross section was folded with the resolution function.

2. Experiment

Beams of 115 MeV Cl^{14+} and of 115 MeV Si^{11+} ions were stored in the TSR at ion currents of about 200 μA ($\approx 10^8$ ions) and mean lifetimes of ~ 2 min (average vacuum 7×10^{-11} mbar, $\sim 90\%$ H_2). The electron beam with a density of $1-5 \times 10^7$ cm^{-3} was guided by a longitudinal magnetic field of 58(40) mT for Cl^{14+} (Si^{11+}) and overlapped the ion beam over a length of 1.5 m (2.7% of the ring circumference of 55.4 m).

Ions having undergone a charge changing reaction were separated from the circulating beam in the first dipole magnet downstream of the electron cooler. Recombined ions were detected with a microchannel plate detector (MCP) for Cl^{14+} and a CsI(pure) scintillation crystal [12] for Si^{11+}. Ionized ions were detected by a channel electron multiplier (CEM) with a converter plate [13]. The MCP could be used for count rates up to 200 kHz without efficiency reduction, while the CEM and the scintillation detector were capable of counting up to 500 kHz and 2 MHz, respectively. All detectors had a measured detection efficiency of $> 95\%$.

The cross section measurement was performed by changing the electron energy and recording the recombination and ionization countrates as a function of energy. The experimental setup, measuring technique and data analysis have been described in detail elsewhere [3]. The acceleration voltage of the electron cooler was set by a precision power supply and could be modulated in addition by a fast high-voltage amplifier with a maximum amplitude of 1.8 kV. This voltage range was scanned within one beam lifetime with up to 1600 energy steps, switching between a fixed reference energy and the variable scanning energy every 25 ms. The reference point was set in a region without step or peak features in the cross sections, and the countrates recorded there were used to subtract the background due to charge changing collisions of the ions with residual gas molecules. The recorded data allow to determine correctly normalized differences of cross sections at the given scanning energies with respect to the reference point. The direct electron impact ionization cross section, which is nonzero at the reference point of the indirect ionization scans, was determined in three overlapping scans at subsequently higher energies, with the reference point of the lowest scan below the ionization threshold.

For 10^8 stored ions, electron capture from residual gas molecules led to recombination count rates of 180 kHz for

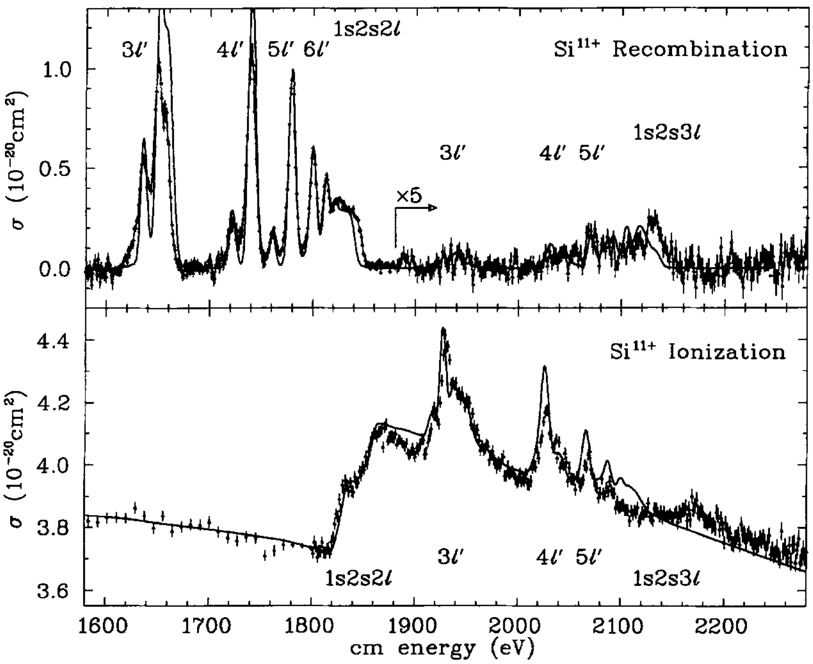

Fig. 1. Measured and calculated cross section for recombination (upper) and ionization (lower) of Li-like Si^{11+} ions in the energy range of $1s2snln'l'$ intermediate states. The theoretical cross section (solid line) only includes contributions with $n \leq 3$ and $n' \leq 66$. It was convoluted with the experimental energy resolution. The direct ionization calculation has been reduced by 24% to match the measured cross section below 1820 eV.

Cl^{14+} and 80 kHz for Si^{11+}, while the DR signal at, e.g., the 1s2s2l3l resonance, led only to a count rate of ~ 1 kHz for both ions. In the ionization channel, the background countrates due to electron loss in collisions with residual gas molecules were 80 kHz for Cl^{14+} and 300 kHz for Si^{11+}. The maximum count rate resulting from direct electron-impact ionization was $\sim 10\%$ of the background rate, whereas EA steps or dielectronic ionization resonances contributed only $< 1\%$ to the total countrate. This signal-to-noise ratio, which is much lower than in previous DR experiments, makes long measurement times at high count rates necessary, and puts high demands on the control of experimental parameters during the beam time. The experimental linewidth is mostly due to the ion energy spread, which was monitored during the measurement using the Schottky noise signal of the circulating ion beam. At the high c.m. energies investigated, the ion beam could not be electron cooled during the measurement; therefore its relative energy spread increased up to $\sim 3 \times 10^{-3}$ due to Coulomb collisions (intra-beam-scattering). This results in a linewidth of 7 eV (FWHM) at $E_{cm} = 2$ keV and 9 eV at $E_{cm} = 3$ keV. The systematical errors are estimated to be $0.05\ \mathrm{eV} \times \sqrt{E_{cm}(\mathrm{eV})}$ for the energy scale and 20% for the absolute cross section scale.

3. Results and discussion

Dielectronic recombination resonances of Si^{11+} resulting from the excitation of a 1s electron to $n = 2$ or 3 are presented in Fig. 1 (upper panel). The theoretical cross section was folded with the resolution function as discussed above, the linewidth scaling $\alpha \sqrt{E_{cm}}$. Two Rydberg series of DR resonances can be identified, the 1s2s2lnl' series below 1850 eV, and the 1s2s3lnl' series at higher energies. The double peak structure of the 1s2s2lnl' series is due to the energy splitting between 1s2s2pnl and 1s2s^2nl, the smaller peaks lower in energy beeing related to the second configuration. The KLL (1s2s2l2l') peak of this Rydberg series at $E_{cm} \approx 1370$ eV was also measured. The agreement with the calculations, shown by the solid line, is good. Due to the very low cross section of $< 5 \times 10^{-22}$ cm^2, the statistical error of the 1s2s3lnl' resonances is high, but there is good agreement with the calculations.

The ionization channel is shown in the lower part of Fig. 1. The 1s2s2l EA steps above 1820 eV coincide with the 1s2s2lnl' series limits in the recombination channel. Higher in energy there is a Rydberg series due to the intermediate states 1s2s3lnl', autoionizing two times and thus leading to net ionization. When these states are stabilised radiatively, they lead to the DR resonances at the same energy in the recombination channel. By a direct comparison of the cross sections one derives a branching ratio of $\sim 5\%$ for 1s2s3l3l' DR versus ionization.

To get agreement with the measured direct ionization

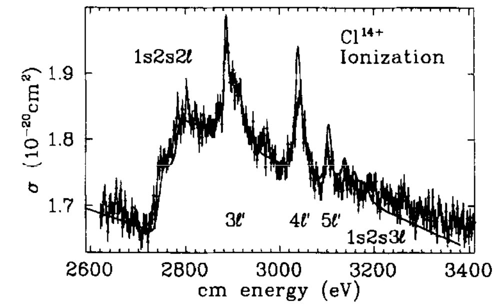

Fig. 2. Measured and calculated cross section for ionization of Li-like Cl^{14+} ions in the energy range of 1s2s$nln'l'$ intermediate states. The theoretical cross section includes states with $n \le 3$ and $n' \le 87$. A direct ionization cross section of 1.69×10^{-20} cm^2 was used at the reference energy $E_{cm} = 2616$ eV.

cross section, which was recorded from well below the threshold at 523 eV, the calculated value of the direct ionization cross section (obtained in the configuration-average approximation and using semirelativistic distorted-wave functions [8]) had to be reduced by 24%. This discrepancy is larger than our estimated sytematical error of 20%. The good agreement for the DR cross section suggests that errors in the ion current and electron density normalization are small, and the good agreement seen for the EA steps and ionization resonances indicates that the discrepancy should not be due to a reduced efficiency of the ionization detector.

The energy region of the 1s2s$nln'l'$ resonances for Cl^{14+} ionization is shown in Fig. 2. The similarity with the Si^{11+} data is obvious, the agreement with the calculation for EA and dielectronic ionization is again good. The cross section was measured relative to a reference point at $E_{cm} = 2616$ eV with significant contributions from direct electron impact ionization. The value of the cross section at the reference energy was determined to be $\sigma(2616\ \mathrm{eV}) = 1.69(8) \times 10^{-20}$ cm^2, which is $\sim 20\%$ lower than the calculated cross section, indicating an overestimation of the direct ionization cross section by theory which is in the same range as for Si^{11+}. While the 1s2s3lnl' series of DR resonances could not be resolved from the statistical uncertainties in the Cl^{14+} recombination data, the DR cross section of the 1s2s2lnl' series, in the energy range below the EA steps, is in good agreement with the calculation.

There are some common features in the comparison of experimental and theoretical indirect ionization data for Si^{11+} and Cl^{14+}. For the 1s2s3lnl' Rydberg series of dielectronic resonances, the agreement in the cross sections is very good for 1s2s3l3l', but the measured ionization cross section decreases more rapidly for higher n than calculated. For $n \ge 6$, the experimental dielectronic ionization cross section can not be distinguished from the statistical fluctuations whereas it should be significantly higher according to the calculations. The excess in experimental rate above the 1s2s3*lnl'* series limit is due to 1s2s3*l* and higher EA steps as well as 1s2s4*lnl'* and higher dielectronic ionization resonances, which were not included in the calculations.

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References

[1] W.G. Graham, W. Fritsch, Y. Hahn and J.A. Tanis, eds., Recombination of Atomic Ions, vol. 296 of NATO Advanced Study Institute, Series B: Physics (Plenum, New York, 1992).
[2] A. Müller, in: Physics of Ion Impact Phenomena, ed. D. Mathur (Springer, Heidelberg, 1991).
[3] G. Kilgus, D. Habs, D. Schwalm, A. Wolf, N.R. Badnell and A. Müller, Phys. Rev. A 46 (1992) 5730.
[4] W. Spies et al., Phys. Rev. Lett. 69 (1992) 2768.
[5] G. Hofmann, A. Müller, K. Tinschert and E. Salzborn, Z. Phys. D 16 (1990) 113.
[6] K.J. Reed and M.H. Chen, Phys. Rev. A 45 (1992) 4519.
[7] M.H. Chen and K.J. Reed, Phys. Rev. A 45 (1992) 4525.
[8] N.R. Badnell and M.S. Pindzola, Phys. Rev. A 47 (1993) 2937.
[9] E. Jaeschke et al., Proc. Europe. Particle Accelerator Conf., Rome, 1988, ed. S. Tazzari (World Scientific, Singapore, 1989) p. 365.
[10] M. Steck et al., Nucl. Instr. and Meth. A 287 (1990) 324.
[11] G. Kilgus et al., Phys. Rev. Lett. 64 (1990) 737.
[12] G. Miersch, D. Habs, J. Kenntner, D. Schwalm and A. Wolf, to be published.
[13] K. Rinn, A. Müller, H. Eichenauer and E. Salzborn, Rev. Sci. Instr. 53 (1982) 829.