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HIGH-RESOLUTION MEASUREMENTS OF ELECTRON-IMPACT IONIZATION CROSS SECTIONS FOR LI-LIKE IONS

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Résumé

Pour une expérience avec des faisceaux croisés des électrons et des ions une technique experimentale a été développée qui permet de mesurer des sections efficaces pour l'ionisation des ions par impact électronique avec une imprécision moins de 0.1 %. A ce degré de précision il est possible de réaliser une spectroscopie des états excités intermédiaires des ions qui contribuent à l'ionisation nette vers le processus de l'autoionisation simple et multiple.

Pour les ions B^{2+}, C^{3+}, N^{4+} et O^{5+} de la série isoélectronique de Li nous avons fait des mesures quantitatives des contributions de "excitation-autoionisation" (EA), de "resonant excitation-double autoionisation" (REDA) et de "resonant-excitation auto-double-ionisation" (READI). Dans ces mesures il a été possible de séparer l'énergies des états ioniques contribuants.

Abstract

For crossed electron and ion beams we have developed an experimental technique which allows to measure cross sections for electron impact ionization of ions with relative uncertainties less than 0.1 %. At this level of accuracy it is possible to do ion spectroscopy of intermediate excited states contributing to net ionization via single and multiple autoionization processes. For ions B^{2+}, C^{3+}, N^{4+} and O^{5+} along the Li isoelectronic sequence we have performed quantitative measurements of state-resolved contributions from excitation-autoionization (EA), resonant-excitation-double autoionization (REDA) and resonant-excitation auto-double-ionization (READI).

Electron impact ionization of ions is a fundamental process in hot plasmas. Intensive research during the last ten years has not only provided a substantial amount of cross section data but also revealed new physical insights into ionization mechanisms. Beside direct ejection of an electron from the ion the most important indirect process contributing to single ionization is excitation of an inner-shell electron with subsequent autoionization (EA)(1).

An exotic higher order mechanism was predicted by LaGattuta and Hahn(2): resonant excitation followed by double autoionization (REDA). This process involves capture of the projectile electron into a bound state of the one less charged ion with simultaneous excitation of an inner-shell electron. It is analogous to the first step of a dielectronic recombination (DR) process, however, the highly excited intermediate state does not decay by the emission of photons (as in DR) but by two sequential Auger processes emitting one electron each, thus leading to a net ionization of the ion. Another resonant process was first mentioned in a publication by Henry and Msezane(3): resonant excitation with subsequent auto-double-ionization (READI). Again the first step is a dielectronic capture of the projectile electron but

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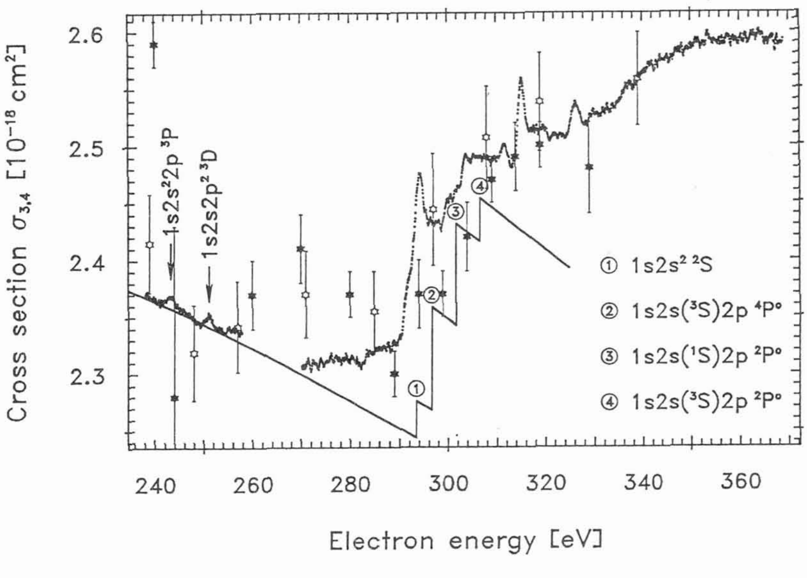
now the intermediate state decays by simultaneous emission of two electrons. Recently, a theoretical effort was made to predict the possible contribution of READI to electron impact ionization of ions along the lithium isoelectronic sequence.[4] The result was not promising to ever see READI in such an ion, for the maximum ratio of resonant versus direct single ionization of the 2s-electron for ions with atomic numbers $Z \leq 5$ was predicted to be between 0.6×10^{-3} and 6.5×10^{-3} for 2 eV energy width. That means the predicted READI resonances should sit on a "background" of direct ionization which is about 1000 times higher than the peak itself and explains why a serious attempt[5] to measure these resonances for O^{5+} ions had failed.

Stimulated by the very first recent observation of strong narrow resonances in the ionization of heavy metal ions[6] we made an attempt to identify READI and REDA resonances and EA contributions in electron impact ionization of Li-like ions. Our B^{2+}, C^{3+}. N^{4+} and O^{5+} principal experimental setup has been described earlier[7,8]. The ions were produced in the Giessen electron cyclotron resonance ion source[9]. While we usually sweep the electron beam across the ion beam and thus obtain absolute cross sections[7] we left the electron gun in a fixed position with optimum beam overlap and did fast electron-energy scans. The resulting relative measurements were calibrated against a number of absolute cross section measurements which were taken by using our usual technique. The absolute cross sections thus obtained for the ionization of Li-like ions are in agreement with measurements of Crandall et al.[10] The uncertainty of the present measurements is about 0.1 % statistical and about 10 % total.

As a representative example of these measurements we will discuss here the electron impact single ionization of C^{3+} ions. Using the new technique we scanned the energy range from 238 eV to 369 eV which covers all possible energies for resonant electron capture into C^{3+} ions. Cross sections ranging from 2.3 to 2.6×10^{-18} cm^2 were measured at more than 2000 individual energies. Fig. 1 shows the data smoothed over bins of 7 adjacent energies together with the data of Crandall et al. [10] and the data taken with our usual technique[7,8]. The scan data were normalized to the absolute cross section measurements.



A wealth of structures is revealed arising from various K-shell excitation processes leading to a net ionization of C^{3+}. Beside direct single ionization via

$$e + C^{3+}(1s^2 2s) \rightarrow C^{4+}(1s^2) + 2e \qquad (1)$$

the most prominent contribution with a threshold at about 290 eV is due to direct excitation of the K-shell with subsequent autoionization

$$\begin{aligned} C^{3+}(1s^2 2s) + e \rightarrow\ & C^{3+}(1s2s2l) + e \\ & \lfloor\rightarrow C^{4+}(1s^2) + e \end{aligned} \qquad (2)$$

Also clearly visible are a number of resonance features which arise from dielectronic capture with subsequent two-electron emission.

$$\begin{aligned} C^{3+}(1s^2 2s) + e \rightarrow\ & C^{2+}(1s2snl\ n'l') \\ & \lfloor\rightarrow C^{4+}(1s^2) + 2e \end{aligned} \qquad (3)$$

The energy range 238 eV to 258 eV contains (READI) resonances 1s2s2l2l' which can only contribute to the measured cross section through auto-double-ionization, i.e. emission of correlated electrons because any single Auger process would lead to a bound state of a C^{3+} ion. The two resonances at 243.3 eV and 251.3 eV can be assigned to states $1s2s^2 2p\ ^3P$ and $1s2s2p^2\ ^3D$, respectively. The experimental energies agree well with calculations by Safronova and Lisina (243.0 eV and 251.2 eV).[11].

From the data of Fig. 1 four steps can be distinguished related to EA contributions via 1s2s2l states. These steps can be assigned to the excitation of ground state C^{3+} ions to states $1s2s^2\ ^2S$, $1s2s(^3S)2p\ ^4P^o$, $1s2s(^1S)2p\ ^2P^o$ and $1s2s(^3S)2p\ ^2P^o$.

The features at 294 eV and 315 eV are assigned to capture resonances $1s2s^2nl$ and $1s2p^2nl$ which can contribute to net ionization by sequential emission of two electrons (REDA) or by single autoionization plus field ionization (when entering the analyzing magnet) or by simultaneous emission of two electrons (READI). The shape of the resonance at 315 eV suggests interference of various amplitudes of ionization mechanisms contributing to single ionization. It involves excitaton of two electrons and therefore the observed resonance strength would not have been expected that high.

The data for the other Li-like ions studied here look very similar. It appears that even more structure becomes visible for the higher-Z members of the isoelectronic sequence.

Fig. 1: Cross sections for electron impact single ionization of C^{3+} ions. Our scan data were smoothed over bins of 7 adjacent points of the original measurement. The READI peaks are indicated. The solid line is the sum of the direct ionization (represented by $0.85\cdot\sigma_{2s}$; where σ_{2s} is Younger's calculation[12] and the excitation-autoionization contributions calculated by Henry[13]. The full stars are mesurements by Crandall et al. [10], the open stars show present absolute cross sections.

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