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Electron impact ionization and dielectronic recombination of sodium-like iron ions

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Abstract

Absolute rates and cross sections for dielectronic recombination and ionization of Na-like Fe^{15+} ($1s^22s^22p^63s$) ions were measured at electron impact energies between 0 and 1030 eV using the Heidelberg heavy ion storage ring TSR with the cooling device as an electron target. In the region where excitation–autoionization and related resonant processes are relevant, variations of the ionization cross sections below 0.5% were observed with an energy resolution of 4 to 5 eV FWHM. The theoretical calculations are in good overall agreement with the measured cross sections but do not reproduce all the details of the rich resonance structures revealed by our experiment. In the lower energy range we made use of the magnetically expanded electron beam with a transverse temperature corresponding to only $kT_\perp = (15 \pm 3)$ meV. This resulted in an excellent energy resolution in the measurements of dielectronic recombination associated with 3s → 3p, 3d, 4l core excitations. Here, theory and experiment are in very good agreement.

Ionization and recombination in electron–ion collisions are among the most fundamental atomic collision processes. Their importance for all kinds of plasmas has stimulated theoretical and experimental studies since the first systematic investigations of gas discharge phenomena a hundred years ago. The ion that has received the most attention over the last 15 years is Fe^{15+}. Iron is an abundant element in the solar corona and in fusion plasmas. This fact together with the relatively simple structure of sodium-like iron with only one active electron has made Fe^{15+} a testing ground for theoretical calculations of electron-impact ionization [1–4] and of electron–ion recombination [5,6].

But this "quasi-one-electron" system is not as simple as it may appear at first sight, because there are several, non-negligible processes activating inner-shell electrons during electron-impact ionization or recombination [7]. Besides direct "knock-on" ionization (DI)

$$Fe^{15+}(1s^22s^22p^63s) + e^- \rightarrow Fe^{16+}(1s^22s^22p^6) + 2e^- \quad (1)$$

there are contributions to the ionization cross section due to inner-shell excitation with subsequent autoionization, such as:

$$\begin{aligned} &Fe^{15+}(1s^22s^22p^63s) + e^- \\ &\rightarrow Fe^{15+}(1s^22s^22p^53snl)^{**} + e^- \\ &\rightarrow Fe^{16+}(1s^22s^22p^6) + 2e^-. \end{aligned} \quad (2)$$

This mechanism is called excitation–autoionization (EA). And yet there is a further important indirect ionization process. It involves dielectronic capture of a free electron into a Rydberg state with simultaneous excitation of an inner-shell electron and subsequent emission of two electrons

$$\begin{aligned} &Fe^{15+}(1s^22s^22p^63s) + e^- \\ &\rightarrow Fe^{14+}(1s^22s^22p^53snln'l')^{**} \\ &\rightarrow Fe^{16+}(1s^22s^22p^6) + 2e^-. \end{aligned} \quad (3)$$

This latter process is termed resonant-excitation-double-autoionization (REDA). The doubly excited intermediate state formed in the first step of the REDA process can decay alternatively by the emission of photons instead of elec-

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trons. The total process is then termed dielectronic recombination (DR), e.g.

$$Fe^{15+}(1s^2 2s^2 2p^6 3s) + e^-$$
$$\rightarrow Fe^{14+}(1s^2 2s^2 2p^5 3s nl n'l')^{**}$$
$$\rightarrow Fe^{14+}(1s^2 2s^2 2p^6 3s^2) + \text{photons}. \quad (4)$$

No experiments have been published so far for recombination of Fe^{15+} ions with electrons. The only direct measurements published on electron impact ionization of Fe^{15+} ions were carried out by Gregory et al. in 1987 at Oak Ridge [8]. They used an ECR ion source and well established crossed-beams techniques. Intensity problems did not allow them to get sufficient statistics for a visualization of cross section details as predicted by theory [4].

We have used the Heidelberg storage ring TSR to measure electron-impact ionization and recombination of Fe^{15+} ions. The cooling device served as an electron target in a merged-beams geometry. By variation of the cathode voltage the electron–ion impact energy was set with high resolution between 0 and 1030 eV (center-of-mass frame). This range covers $n = 2 \rightarrow 3$, $2 \rightarrow 4$, $3l \rightarrow 3l'$, and $3 \rightarrow 4$ transitions of electrons in the ion core. With a combination of two ion detectors on both sides of the circulating stored ion beam it has become possible for the first time to observe both the ionization and the recombination channels simultaneously for a given ion species. We recorded both the number of ionized Fe^{16+} ions and the number of recombined Fe^{14+} ions while the energy of the cooler electron beam was scanned in small steps with intermittent phases of injection of new ions and subsequent cooling. Absolute cross sections σ and rates $\alpha = \langle v\sigma \rangle$ were determined where α is the product of the relative electron–ion velocity and the cross section, convoluted with the experimental distribution $f(v)$ of relative velocities. The distribution $f(v)$ is characterized by electron beam temperatures $T_\perp$ and $T_\parallel$ perpendicular and parallel to the beam direction (see e.g. Ref. [9]).

In the experiments the voltage of the cathode was switched between a fixed reference energy and continuously increasing energies in up to 1250 steps, each step taking ~ 20 ms. The ionization detector registered a high background of about 300 kHz arising from Fe^{16+} ions produced by electron stripping in the residual gas, while the true ionization signal was less than 40 kHz. With these counting rates it took us about 13 h of pure data recording time to obtain statistical uncertainties as low as 0.5% in the interesting energy range of the ionization cross section. The recombination channel was relatively clean (4 kHz background, ~ 3 kHz signal) and it was straight-forward to observe the different series of DR resonances present in the investigated energy range.

In the center-of-mass energy range $E = 240$–1030 eV the experimental energy spread amounts to $\Delta E = 0.17 \sqrt{E(eV)}$ eV (corresponding to $T_\parallel \approx 2.5$ meV as determined by fitting the narrowest peaks) which is sufficient to see fine details in the ionization cross section. Uncertainties in the absolute energy calibration are less than 5 eV in

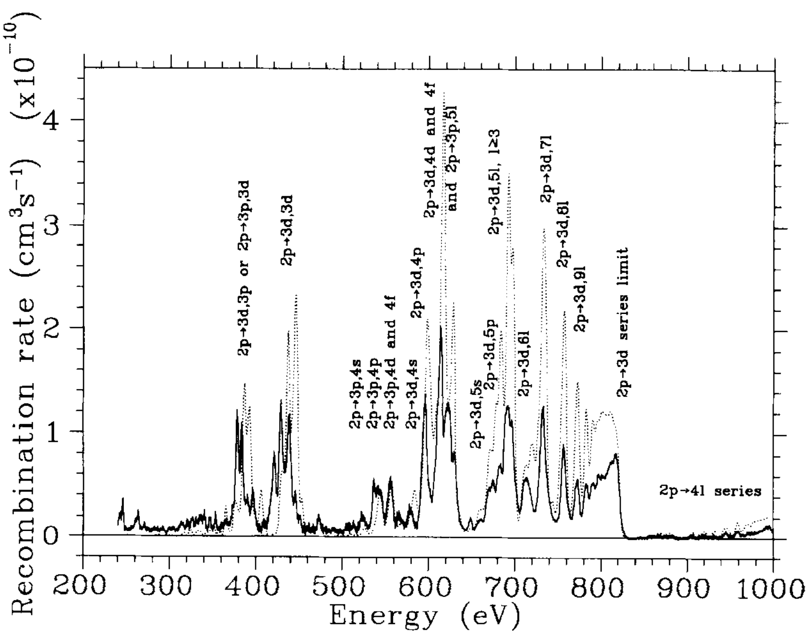

Fig. 1. Present experimental (solid line) and theoretical (dotted line) data for DR of Fe^{15+} in the energy range 240 to 1000 eV. The resonances in this range are associated with electron excitations $2p \rightarrow 3p$, $2p \rightarrow 3d$. The theory curve has been convoluted with the experimental energy distribution function.

this same energy range. Systematic uncertainties of the ionization cross sections σ as well as the recombination rates $\alpha = \langle v\sigma \rangle$ amount to $\pm 20\%$.

As an example Fig. 1 shows the present experimental (solid line) and theoretical (dotted line) data for DR of Fe^{15+} in the energy range from $E = 240$ to 1000 eV. The present calculations are based on the independent-processes – and – isolated-resonance appoximation using semirelativistic distorted waves as described in Ref. [10]. The resonances seen in Fig. 1 are associated with electron excitation 2p → 3p, 2p → 3d and $2l \to 4l'$. The theoretical prediction – convoluted with the experimental velocity distribution function – overestimates the DR rate by roughly a factor of 2. In that same energy range the ionization cross section rises from its threshold at 489 eV to a flat maximum determined by the direct process. Above 710 eV the EA mechanism has its onset and the cross section rises by about a factor 5 within a narrow energy span of little more than 100 eV. At the high end of the investigated energy range some correspondence of features in the ionization cross section with peaks in the DR rates can be found (see Fig. 2). At identical energies resonances are found in the ionization as well as in the recombination channel. This is a consequence of their common origin from intermediate excited states populated by dielectronic capture. These states decay by photon or electron emission and thus finally contribute either to DR or to REDA. Fig. 2 shows the experimental data in the energy range 820 to 1030 eV together with the present theoretical calculations (dotted lines) for recombination (a) and ionization (b). In Fig. 2b the calculation carried out previously by Chen et al. [4] is also indicated (dashed curve). Again, as in Fig. 1, the calculated DR rates are roughly a factor 2 higher than the experimental data. For ionization the theoretical results are in remarkable agreement with the overall size of the experimental cross section (note the suppression of zero on the cross section axis), however in the fine details of the ionization spec-

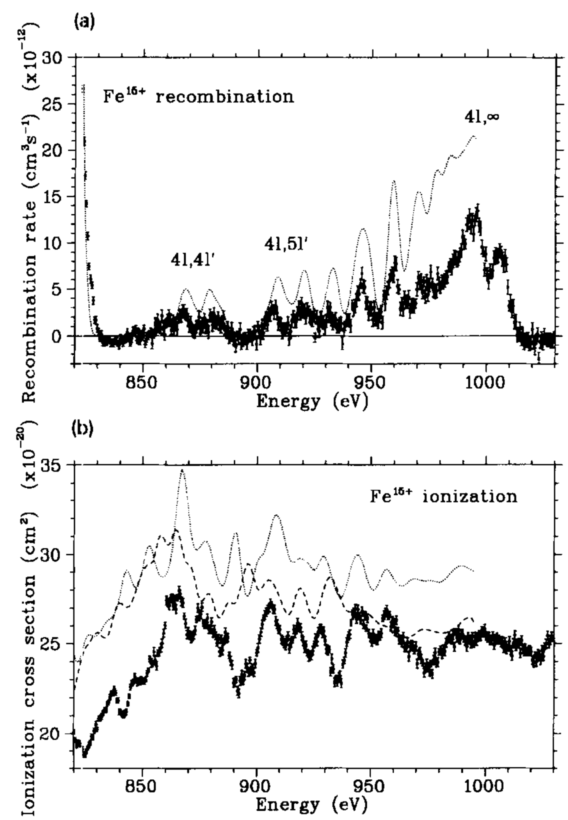

Fig. 2. (a) Present experimental and theoretical data (dotted line) for DR of Fe^{15+} in the range of e + 2s, 2p → $4lnl'$ transitions ($n = 4,5,\ldots,\infty$), convoluted with the experimental energy distribution function. (b) Experimental ionization data of Fe^{15+} in comparison with the present theoretical prediction (dotted line) and a calculation by Chen et al. [4] (dashed line). Theoretical data are convoluted with the experimental energy distribution function. Note the suppression of zero on the cross section axis.

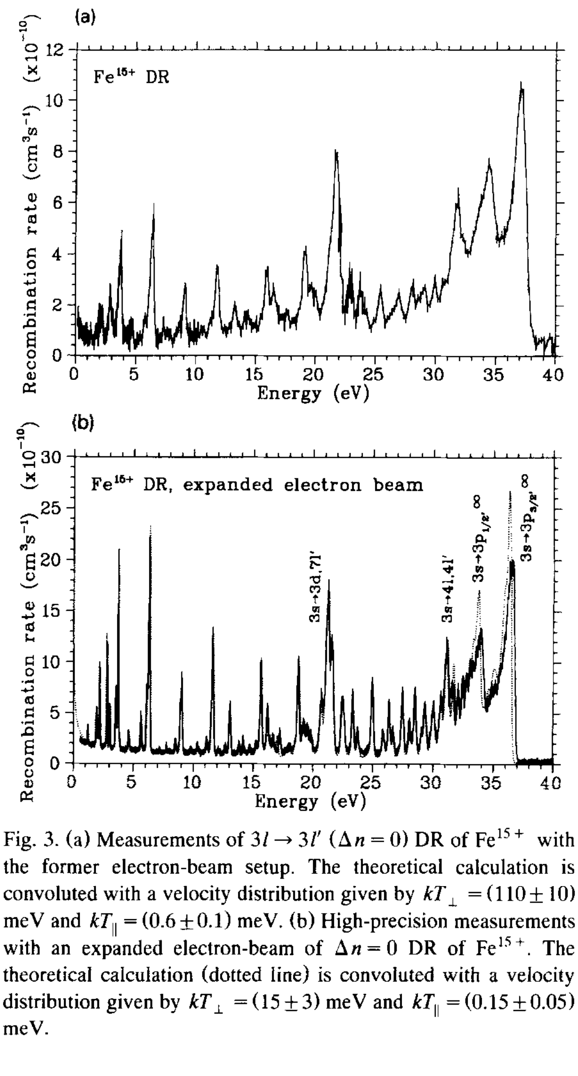

Fig. 3. (a) Measurements of $3l \to 3l'$ ($\Delta n = 0$) DR of Fe^{15+} with the former electron-beam setup. The theoretical calculation is convoluted with a velocity distribution given by $kT_\perp = (110 \pm 10)$ meV and $kT_\parallel = (0.6 \pm 0.1)$ meV. (b) High-precision measurements with an expanded electron-beam of $\Delta n = 0$ DR of Fe^{15+}. The theoretical calculation (dotted line) is convoluted with a velocity distribution given by $kT_\perp = (15 \pm 3)$ meV and $kT_\parallel = (0.15 \pm 0.05)$ meV.

trum the theories disagree among each other and with the experiment.

At low center-of-mass energies it was possible to cool the ion beam intermittently after every single energy step. At the same time we made use of the technique of adiabatic transverse expansion [11] of the electron beam. Starting with a perpendicular electron beam temperature of $kT_{\perp} = 0.11$ eV at the cathode (where k is Boltzmann's constant) we lowered the magnetic guiding field B by a factor of 7.4 along the beam axis. Thus, the temperature of the expanded beam could be reduced to (15 ± 3) meV$/k$. The new arrangement yielded also a lower temperature of $kT_{\parallel} = 0.15 \pm 0.05$ meV instead of 0.6 ± 0.1 meV. This resulted in an excellent resolution, particularly for the measurements of outer-shell DR (3s → 3p, 3d, 4l) in the energy range up to 40 eV. Absolute uncertainties in the peak energies are less than 1 eV at 40 eV and less than 0.5 eV at 10 eV.

Figs. 3a and 3b present a comparison of our measurements using the two arrangements without (a) and with (b) adiabatic expansion of the electron beam. The series of resonances $e + 3s \rightarrow 3p_{1/2}nl$ and $e + 3s \rightarrow 3p_{3/2}nl$ are resolved very nicely with series limits at 34.0 and 36.6 eV, respectively. Within the energy range represented in Fig. 3 there are clear signatures of 3s → 3d7l resonances, distributed between 14.3 and 21.7 eV (with the largest peaks from 21.2 to 21.7 eV). Resonances arising from 3d8l intermediate configurations appear between 31.5 and 36.0 eV. Some contributions corresponding to transitions e + 3s → 4l4l' are also present. Fig. 3b includes our theoretical result (dotted line). Apart from discrepancies at the series limits theory and experiment are in excellent agreement. For the present comparison field-ionization effects have been taken into account. The motional electric fields in the dipole magnets of the ring define a maximum principal quantum number n_f of the stored ions. In the present experiment we calculate $n_f \approx 86$.

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