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Dielectronic Recombination of Iron *L*-Shell Ions

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Abstract

An experimental program to study low temperature dielectronic recombination (DR) in the iron L-shell ions Fe^{17+} to Fe^{23+} is currently in progress at the TSR heavy-ion storage ring in Heidelberg, Germany. L-shell iron ions play an important role in determining the line emission and thermal and ionization structures of cosmic photoionized plasmas. Successful modelling of these plasmas requires accurate ionization and recombination rates, particularly for low temperature DR which is the dominant recombination mechanism for most iron ions in photoionized plasmas. The dependence of DR on the detailed atomic structure makes it challenging to determine the needed DR rate coefficients theoretically, especially in many-electron systems. Our systematic survey of Li- to F-like Fe-ions is designed to produce high-resolution DR spectra which can be used to benchmark theory for ions of increasing complexity and to provide absolute low-temperature DR rates required in astrophysics.

1. Introduction

Heavy-ion storage rings are the instruments of choice for the study of recombination of ions with electrons at low collision energies. Electron-cooler devices installed at storage rings permit recombination experiments between ions of a single, select charge state and cold electrons, resulting in recombination spectra of high energy resolution and accurate absolute recombination rate coefficients [1].

Radiative recombination (RR) is a non-resonant process. The cross section varies smoothly with energy and the recombination rate smoothly with charge state. Dielectronic recombination (DR), on the other hand, is a resonant process. The energy dependence of the cross section depends on the details of the atomic structure. The rate coefficient does not vary smoothly with charge state. Until recently most studies of DR have mostly focused on simple systems, such as lithium and sodium-like ions, where theory is accurate enough to permit meaningful comparisons with experiment [2]. Obviously, real-world plasmas do not restrict themselves to these simple isoelectronic sequences, and experimental data are needed to check the theoretical rates which are typically used to model these plasmas.

In astrophysics an important class of plasmas are those which are photoionized. These are predicted to form in the media surrounding active galactic nuclei, cataclysmic variable stars, and X-ray binaries. In these sources a central radiation source photoionizes the surrounding gas. This ionization is balanced by RR and DR. Line emission caused by RR and DR can be observed by satellite-based X-ray telescopes and can be used to determine the ionization and thermal structure of the gas, if the appropriate ionization and recombination rates are known. In particular, *L*-shell iron (Fe^{16+} to Fe^{23+}) has been identified as a useful diagnostic tool [3], and it has been shown that the lack of accurate low-temperature DR rates ($kT < 100$ eV) is limiting our ability to model the objects mentioned above [4]. To improve our understanding of DR in *L*-shell iron, an experimental program is underway and will soon be completed. So far, the charge states $Fe^{17+,18+}$ have been measured and analyzed [4], and significant discrepancies between theoretical and experimental rate coefficients have been found. Recently, new data for $Fe^{19+,20+,21+}$ have been taken [5] and are presented here, together with the old results from $Fe^{17+,18+}$ for comparison.

2. Experiment

The measurements are carried out at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany. Iron beams are accelerated and stripped to the desired charge state in the Van-de-Graaff Tandem/LINAC facility and injected into the heavy-ion storage ring TSR. Large circulating Fe^{q+} currents of $10 - 100$ μA are accumulated using multiturn-injection stacking and electron cooling. In the electron cooler, a magnetically guided, cold electron beam ($B \approx 40$ mT) is merged with the ions over a distance of about 1.5 m. Cooling is achieved by matching the velocities of the electrons and the ions. Once the beam is cold, the device is used as an electron target for recombination experiments. The acceleration voltage of the electron beam is shifted to introduce a velocity difference between the electrons and the ions. In this way, recombination between Fe^{q+} ions and electrons is studied at center-of-mass collision energies from a few meV up to a few hundred eV. Recombined ions are separated from the stored beam using a dipole bending magnet and due to their high kinetic energy are detected in a scintillator with high ($> 95\%$) efficiency. Figure 1 displays the spectra for $Fe^{17+,\dots,21+}$. The accuracy of the absolute rate coefficients determined from the data is limited by the ion current measurement, uncertainties in the electron beam density profile, and the detection efficiency. Furthermore, ions recombining into Rydberg states above a certain principal quantum number n_c are field-ionized in the bending magnet before reaching the detector; and electric fields in the cooler will enhance DR into Rydberg states through mixing of l-levels [6]. However, both effects do not play a significant

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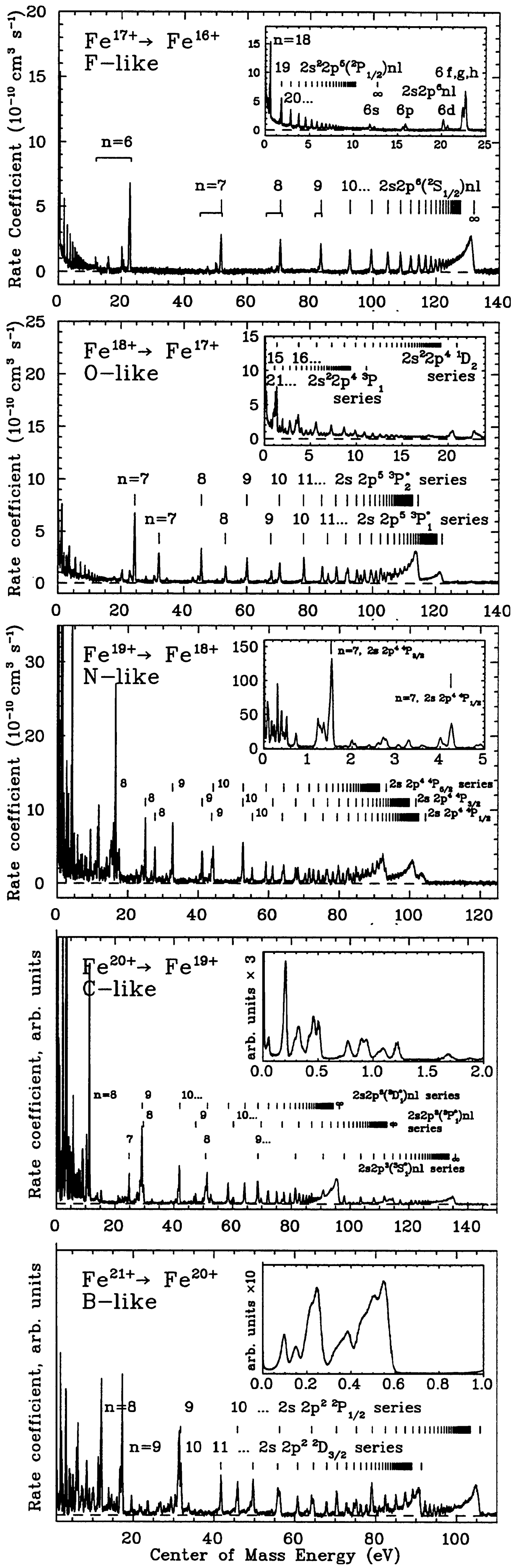

Fig. 1. $\Delta n = 0$ dielectronic recombination spectra for $\mathrm{Fe}^{17+,\ldots,21+}$. Note the compressed scale for the rate coefficient in the inserts for Fe^{19+} to Fe^{21+}, which show resonances extending far beyond the range of the main plots.

role in the present measurements, and we estimate the overall accuracy of the absolute rate coefficients to be $\approx 20\%$.

3. Results

Recombination spectra of $\Delta n = 0$ DR onto Fe^{17+} (fluorine-like) through Fe^{21+} (boronlike) are shown in Fig. 1. In all cases, $2s^2\,2p^r \to 2s\,2p^{r+1}$ transitions produce the prominent Rydberg series dominating the spectrum, with series limits above 50 eV. However, there is also DR due to fine-structure core excitations. This is particularly apparent in Fe^{17+} and Fe^{18+}, where the corresponding Rydberg series are indicated; in these cases, strong resonances of the $2s^2\,2p^r \to 2s\,2p^{r+1}$ type are not present below $E_{\mathrm{coll}} = 10$ and 20 eV, respectively. In the other charge states, these resonances do appear in the region where fine-structure DR is occuring. The low energy, fine-structure resonances frequently cause DR rates more than 10 times higher than the rates at higher energies where $2s \to 2p$ DR dominates the $\Delta n = 0$ DR process. In such a situation the total DR rate at low energy depends sensitively on the position of these lines with respect to the threshold. The $\mathrm{Fe}^{19+,20+,21+}$ data feature resonances even well below $E_{\mathrm{coll}} = 1$ eV. In this region the experimental resolution of the electron cooler is optimal and the absolute energy calibration is best. Fine structure, relativistic effects, and finite linewidths can be studied in this portion of the spectrum. This makes these ions suitable for a comparison with advanced theories [7], which so far have been applied successfully to Li-like ions [2,8,9], to test them against ions of increasingly complex electronic structure.

For application in astrophysics, the spectra are convoluted with a Maxwellian electron velocity distribution, and total DR rates are obtained as a function of the electron temperature. In photoionized gas (see above) the fractional abundance of e.g. Fe^{17+} is predicted to peak at $kT_{\mathrm{e}} \approx 15$ eV. Theoretically obtained rates used so far in modelling these plasmas have not taken into account fine-structure core excitations. Consequently they underestimate the DR rate by a factor of 2 [4]. In Fe^{18+}, which peaks at somewhat higher temperatures where this mechanism plays a smaller role, theories yield DR rates 1.6 times higher than experimentally observed. It was shown by Savin *et al.* [4] that this significantly affects interpretations of observations of photoionized plasmas. For the higher charge states studied, the details of the structure of the Rydberg resonances from the $2s^2\,2p^r \to 2s\,2p^{r+1}$ transitions will influence the Maxwellian rate coefficients at electron temperatures of ≈ 10 eV. The simplified theoretical methods underlying many of the available DR rates for astrophysical modelling can be expected to account for these details only at rather low accuracy. In general, the comparison of our experimentally derived rate coefficients with the available calculations underlines the need to check systematically the dielectronic recombination rates entering the models used to describe photoionized nebulae.

References

1. Müller, A. and Wolf, A., in Accelerator-Based Atomic Physics Techniques and Applications, (Eds S. M. Shafroth and J. C. Austin), (AIP, Woodbury, NY, 1997), 147.
2. Gwinner, G. *et al*., Phys. Rev. Lett. **84**, 4822 (2000); Tokman, M. *et al*., to be published.
3. Kahn, S. M. and Liedahl, D. A., in "Physics of Multiply Charged Ions", (Ed. D. Liesen), (Plenum, New York, 1995), 169.
4. Savin, D. W. *et al*., Astrophys. J. Lett. **489**, L115 (1997); Savin, D. W. *et al*., Astrophys. J. Suppl. Ser. **123**, 687 (1999).
5. Savin, D. W. *et al*., in "Atomic Data Needs for X-Ray Astronomy", (Eds M. A. Bautista, T. R. Kallman and A. K. Pradhan), (NASA/CP-2000-209968, 2000), p. 143.
6. Bartsch, T. *et al*., Phys. Rev. Lett. **82**, 3779 (1999).
7. See e.g. Lindroth, E., these proceedings.
8. Zong, W. *et al*., Phys. Rev. A **56**, 386 (1997).
9. Kieslich, S. *et al*., these proceedings.