IOP Publishing Journal of Physics: Conference Series **58** (2007) 223–226
doi:10.1088/1742-6596/58/1/047 13th International Conference on the Physics of Highly Charged Ions

Electron-ion recombination measurements of Fe^{7+}, Fe^{8+}, Fe^{13+} motivated by active galactic nuclei x-ray absorption features

E W Schmidt[1], S Schippers[1], C Brandau[1,4], D Bernhardt[1], A Müller[1], M Lestinsky[2], F Sprenger[2], J Hoffmann[2], D A Orlov[2], M Grieser[2], R Repnow[2], A Wolf[2], D Lukić[3], M Schnell[3] and D W Savin[3]

[1]Institut für Atom - und Molekülphysik, Justus-Liebig-Universität, D-35392 Giessen, Germany
[2]Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany
[3]Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027, USA
[4]Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany

E-mail: eike.w.schmidt@iamp.physik.uni-giessen.de

Abstract. Recent spectroscopic models of active galactic nuclei have indicated that the recommended electron-ion recombination rate coefficients for iron ions with partially filled M-shells are incorrect in the temperature range where these ions form in photoionized plasmas. We have investigated this experimentally for Fe^{7+} forming Fe^{6+}, Fe^{8+} forming Fe^{7+}, and Fe^{13+} forming Fe^{12+}. The recombination rate coefficient was measured employing the electron-ion merged beams method at the Heidelberg heavy-ion storage-ring TSR. The measured energy range encompassed at least all dielectronic recombination (DR) resonances associated with core excitations within the M-shell of the parent ions. Already in our first measurement, that is for Fe^{13+} [1], we find unusually strong DR resonances at low electron-ion collision energies leading to low temperature plasma DR rate coefficients orders of magnitude larger than the recommended rate coefficient.

1. Introduction

In recent observations of active galactic nuclei (AGN) with the x-ray telescopes Chandra and XMM-Newton an absorption feature around 15–17 Å has been identified as an unresolved transition array (UTA) due mainly to $2p \rightarrow 3d$ inner shell absorption in moderately charged iron ions with an open M-shell. Based on atomic structure calculations and photoabsorption modeling Behar *et al* [2] pointed out that the shape and the equivalent width of the UTA can be used for diagnostics of the AGN absorber. Netzer *et al* [3] noted a disagreement between the predicted and the observed structure of the NGC 3783 feature. They suggested that this disagreement is due to underestimation of the low-temperature dielectronic recombination (DR) rates for iron M-shell ions. The widely used compilation of Arnaud and Raymond [4] is largely based on LS-coupling theoretical work by Jacobs *et al* [5] and Hahn [6] which had the purpose to produce DR data for modeling the coronal equilibrium which forms at temperatures higher than those of photoionized gas such as is found in AGNs. Until recently, the only DR measurements for M-shell iron ions exists for Na-like Fe^{15+} [7, 8]. This state of affairs provided the motivation for the present measurements of the Fe^{7+}, Fe^{8+} and Fe^{13+} recombination rate coefficients.

2. The merged-beams experiment at the TSR storage ring

The experiment was performed at the heavy-ion test storage ring (TSR) at the Max-Planck-Institut für Kernphysik (MPI-K) in Heidelberg, Germany. The different aspects of the merged beams technique at the MPI-K electron cooler have been described in [9, 10, 11, 12] and reviewed by Müller and Wolf [13]. In contrast to previous experiments, where the electron beam of the cooler was also used as an electron target for recombination experiments, in the present experiments a newly installed separate electron beam [14] was used. This additional electron beam is hereafter denoted as the electron target. As in the electron cooler, the electron beam of the electron target is also guided by a magnetic field and overlaps the ion beam over a straight section of ≈ 1.5 m length.

Conceptually the experimental procedures for measuring recombination rate coefficients with the electron target are the same as those that were applied previously with the electron cooler. However, there are advantages when a separate electron target is used for recombination measurements. First, the electron cooler can be used continuously for the cooling of the ion beam. Thus, the low velocity and spatial spread of the ion beam is maintained at all times. Second, the electron target was specifically designed for providing an electron beam with a very low initial energy spread [14]. Both of these results in a higher experimental resolving power in the present measurement as compared to previous measurements with the electron cooler.

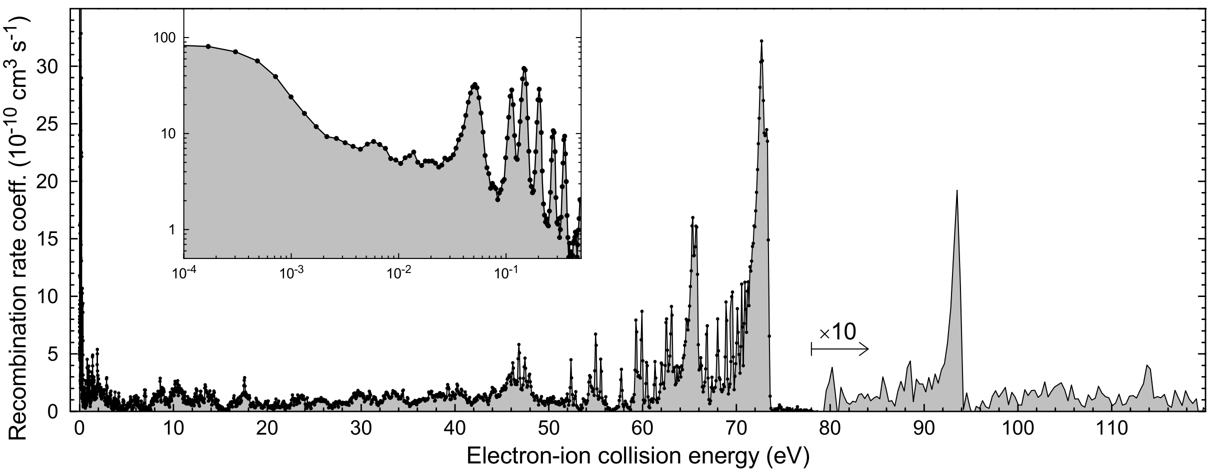

Figure 1. Measured Fe^{7+} forming Fe^{6+} merged beams electron-ion recombination rate coefficient in the energy range 0-120 eV. The inset shows the rate coefficient below 0.5 eV in more detail. Up to 74 eV the spectrum is dominated by resonances associated with dielectronic recombination (DR) via $3p^6\,3d \rightarrow 3p^5\,3d^2$ core excitations. Resonances at higher energies are associated with higher core excitations.

3. Results

The measured merged-beams dielectronic recombination rate coefficients are shown in Figures 1, 2, and 3. All three recombination spectra exhibit large DR resonances at low electron-ion collision energies. For example, for Fe^{13+}, the rate coefficient below 2.3 eV exceeds all other resonances in height by an order of magnitude. At near-zero eV collision energy it is two orders

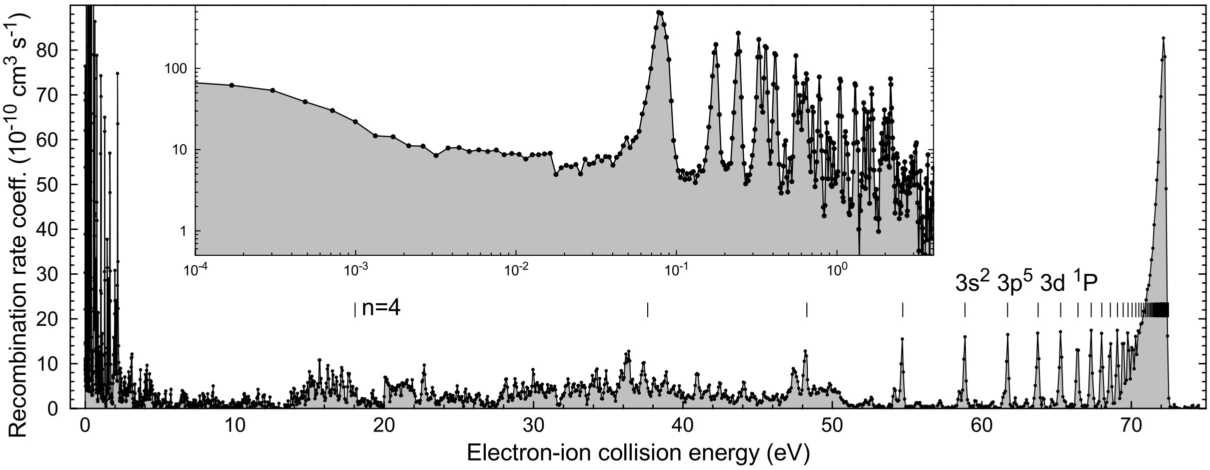

Figure 2. Measured Fe^{8+} forming Fe^{7+} merged beams electron-ion recombination rate coefficient in the energy range 0-75 eV. The inset shows the rate coefficient below 4 eV in more detail. The resonances are associated with DR via $3p^6 \rightarrow 3p^5\,3d$ core excitations. The vertical bars denote DR resonance positions as expected on the basis of the hydrogenic Rydberg formula.

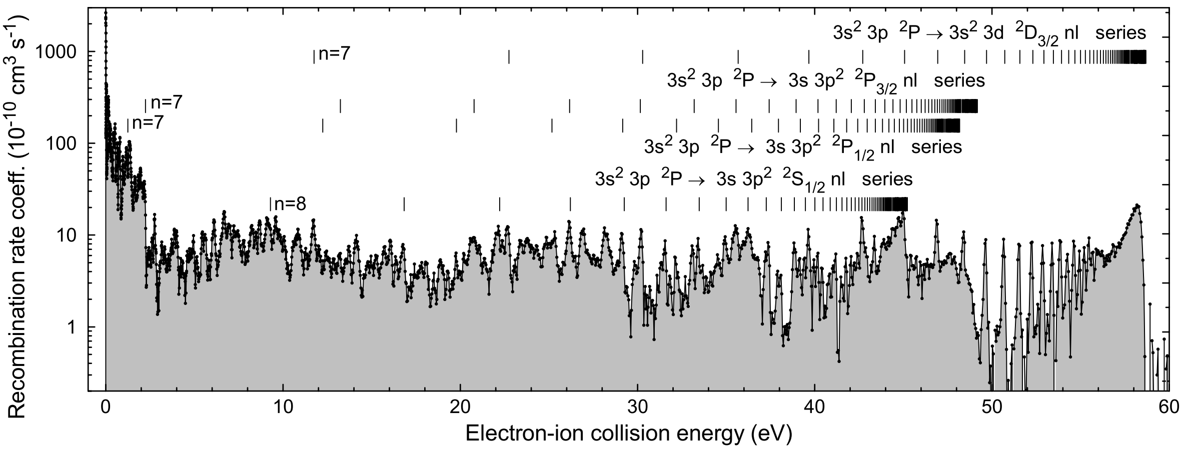

Figure 3. Measured Fe^{13+} forming Fe^{12+} merged beams electron-ion recombination rate coefficient in the energy range associated with DR resonances via $3p_{1/2} \rightarrow 3p_{3/2}$, $3s \rightarrow 3p$ and $3p \rightarrow 3d$ core excitations. The vertical bars denote DR resonance positions as expected on the basis of the hydrogenic Rydberg formula. Only the $(3s^2\,3d\ ^2D_{3/2})\,nl$ series of Rydberg resonances can unambiguously be identified. Note that the resonances below 2.3 eV exceed all other resonances in height by an order of magnitude.

of magnitude larger than predicted by a semiclassical calculation of the radiative recombination (RR) process. This high rate coefficient is attributed to a large dielectronic recombination resonance below 1 meV and the recombination rate enhancement at low energies. The rate enhancement is an artifact of the merged-beams technique and increases the measured rate coefficient at low energies by factors of typically 2–3 [15].

The plasma recombination rate coefficient needed for astrophysical plasma modeling is derived by convolving the cross section derived from the experimental merged beams recombination rate coefficient with a Maxwell-Boltzmann electron energy distribution. As detailed by Schippers *et al* [12, 16], there are three issues in deriving the cross section that require special consideration: the experimental energy spread, the recombination rate enhancement at low energies, and field ionization of high Rydberg states in the storage-ring bending magnets.

4. Conclusions and outlook

As already shown by Schmidt *et al* [1] for Fe^{13+}, the experimental plasma recombination rate coefficient at low plasma temperature is several orders of magnitude larger than the recommended data [4]. It is even more than one order of magnitude larger than the RR rate coefficient and the DR rate coefficient assumed by Netzer [17] and Kraemer et al. [18]. A similar disagreement between our experimentally derived and the recommended plasma rate coefficients also exists for Fe^{7+} and Fe^{8+}.

This work emphasizes that reliable low temperature DR rate coefficients can at present only be obtained from storage-ring measurements especially for ions with strong DR resonances at low electron-ion collision energy. Our present result immediately influences the interpretation of astrophysical observations of active galactic nuclei.

Acknowledgments

We gratefully acknowledge the excellent support by the MPI-K accelerator and TSR crews. This work was supported in part by the German federal research-funding agency DFG under contract no. Schi 378/5. DL, MS, and DWS were supported in part by the NASA Space Astrophysics Research Analysis program, the NASA Astronomy and Astrophysics Research and Analysis program, and the NASA Solar and Heliospheric Physics program.

References

[1] Schmidt E W, Schippers S, Müller A, Lestinsky M, Sprenger F, Grieser M, Repnow R, Wolf A, Brandau C, Luki'c D, Schnell M and Savin D W 2006 *Astrophys. J.* **641** L157–60 (*Preprint* astro-ph/0603340)
[2] Behar E, Sako M and Kahn S M 2001 *Astrophys. J.* **563** 497–504
[3] Netzer H, Kaspi S, Behar E, Brandt W N, Chelouche D, George I M, Crenshaw D M, Gabel J R, Hamann F W, Kraemer S B, Kriss G A, Nandra K, Peterson B M, Shields J C and Turner T J 2003 *Astrophys. J.* **599** 933–48
[4] Arnaud M and Raymond J 1992 *Astrophys. J.* **398** 394–406
[5] Jacobs V L, Davis J, Kepple P C and Blaha M 1977 *Astrophys. J.* **211** 605–16
[6] Hahn Y 1989 *J. Quant. Spectrosc. Radiat. Transfer* **41** 315–21
[7] Linkemann J, Kenntner J, Müller A, Wolf A, Habs D, Schwalm D, Spies W, Uwira O, Frank A, Liedtke A, Hofmann G, Salzborn E, Badnell N R and Pindzola M S 1995 *Nucl. Instrum. Methods* B **98** 154–7
[8] Müller A 1999 *Int. J. Mass Spectrom.* **192** 9–22
[9] Kilgus G, Habs D, Schwalm D, Wolf A, Badnell N R and Müller A 1992 *Phys. Rev.* A **46** 5730–40
[10] Lampert A, Wolf A, Habs D, Kenntner J, Kilgus G, Schwalm D, Pindzola M S and Badnell N R 1996 *Phys. Rev.* A **53** 1413–23
[11] Pastuszka S, Schramm U, Grieser M, Broude C, Grimm R, Habs D, Kenntner J, Miesner H J, Schüßler T, Schwalm D and Wolf A 1996 *Nucl. Instrum. Methods* A **369** 11–22
[12] Schippers S, Müller A, Gwinner G, Linkemann J, Saghiri A A and Wolf A 2001 *Astrophys. J.* **555** 1027–37
[13] Müller A and Wolf A 1997 in *Accelerator-based atomic physics techniques and applications*, ed J C Austin and S M Shafroth (Woodbury: AIP Press) p 147
[14] Sprenger F, Lestinsky M, Orlov D A, Schwalm D and Wolf A 2004 *Nucl. Instrum. Methods* A **532** 298–302
[15] Gwinner G, Hoffknecht A, Bartsch T, Beutelspacher M, Eklöw N, Glans P, Grieser M, Krohn S, Lindroth E, Müller A, Saghiri A A, Schippers S, Schramm U, Schwalm D, Tokman M, Wissler G and Wolf A 2000 *Phys. Rev. Lett.* **84** 4822–5
[16] Schippers S, Schnell M, Brandau C, Kieslich S, Müller A and Wolf A 2004 *Astron. Astrophys.* **421** 1185–91
[17] Netzer H 2004 *Astrophys. J.* **604** 551–5
[18] Kraemer S B, Ferland G J and Gabel J R 2004 *Astrophys. J.* **604** 556–61