14th International Conference on the Physics of Highly Charged Ions (HCI 2008) IOP Publishing
Journal of Physics: Conference Series **163** (2009) 012028 doi:10.1088/1742-6596/163/1/012028

Experimental rate coefficient for dielectronic recombination of neonlike iron forming sodiumlike iron

E. W. Schmidt[1], D. Bernhardt[1], J. Hoffmann[2], M. Lestinsky[2,3], D. V. Lukić[3,4], A. Müller[1], D. A. Orlov[2], D. W. Savin[3], S. Schippers[1] and A. Wolf[2]

[1]Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Giessen, Germany
[2]Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[3]Columbia Astrophysics Laboratory, Columbia University, New York, NY, 10027, USA

E-mail: `Eike.W.Schmidt@iamp.physik.uni-giessen.de`

Abstract. The rate coefficient for dielectronic recombination (DR) of Ne-like Fe^{16+} forming Na-like Fe^{15+} was measured employing the merged electron-ion beams technique at the heavy-ion storage-ring TSR of the Max-Planck-Institut für Kernphysik in Heidelberg, Germany. In the electron-ion collision energy range of 240–840 eV the merged-beams recombination rate coefficient is dominated by DR associated with $2s^2\,2p^6\,{}^1S_0 \rightarrow 2s^2\,2p^5\,3d\ {}^1P_1$ core excitation. The experimental Fe^{16+} DR plasma rate coefficient is derived from the measured merged-beams rate coefficient. It is in good agreement with recent theoretical results.

1. Introduction

In our ongoing effort of providing reliable DR rate coefficients for astrophysical applications we have measured the dielectronic recombination (DR) rate coefficient of Ne-like Fe^{16+} forming Na-like Fe^{15+} employing the merged electron-ion beams technique at a heavy-ion storage-ring. The present measurement bridges the gap between our previous recombination experiments for Fe^{13+}–Fe^{15+} and Fe^{17+}–Fe^{22+} ions (see [1] and references therein). Moreover, it is the first merged-beams measurement for an ion of the Ne-like isoelectronic series. Therefore, this measurement represents an important benchmark for theoretical calculations.

Because of the closed-shell structure of the Ne-like $\mathrm{Fe}^{16+}(1s^2\,2s^2\,2p^6)$ parent ion DR can only proceed via core excitations where the principal quantum number N of the "active" core electron changes by $\Delta N \geq 1$. In open L-shell ions, in contrast, also $\Delta N = 0$ core-excitations are also possible which lead to DR resonances at rather low energies. Conversely, $\Delta N = 1$ resonances appear usually at higher energies because of the higher excitation energies involved. For Fe^{16+}, DR proceeds dominantly via the $2p^6 \rightarrow 2p^5\,3d\ {}^1P_1$ core excitation [2]. The corresponding series of $2p^5\,3d\ ({}^1P_1)\ nl$ DR resonances ranges from about 300 eV to the series limit at 825.7347 eV [3]. Accordingly, the electron-ion collision energy range 240–840 eV was investigated in the present experiment.

---

[4] Permanent address: Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia

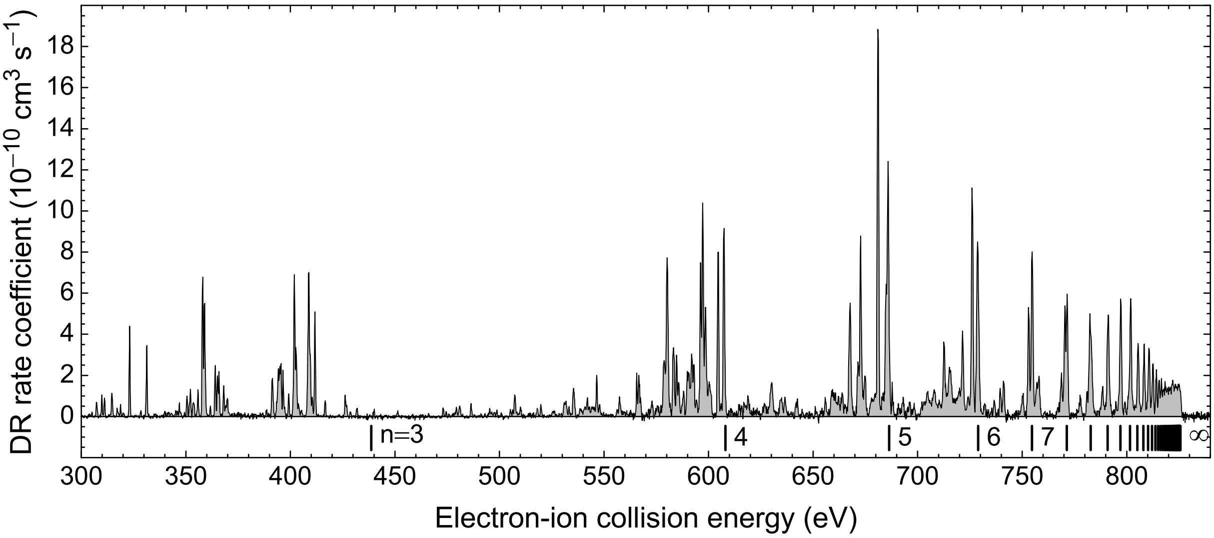

Figure 1. Experimentally derived merged-beams dielectronic recombination (DR) rate coefficient of Fe^{16+} forming Fe^{15+}. The vertical bars below the spectrum mark the resonance positions of the $2s^2\,2p^5\,3d\ {}^1P_1\,nl$ Rydberg series calculated in a hydrogenic approximation by using the Bohr formula. The $2s^2\,2p^6\,{}^1S_0 \rightarrow 2s^2\,2p^5\,3d\ {}^1P_1$ excitation energy was taken from [3].

2. Experiment

The experiment was performed at the heavy-ion storage-ring TSR of the Max-Planck-Institut für Kernphysik (MPI-K) in Heidelberg. Here only a brief account on the experimental and data-analysis procedures for electron-ion recombination measurements can be given. Details can be found in previous publications (e.g. [4] and references therein). The $^{56}\mathrm{Fe}^{16+}$ ion beam was provided by the MPI-K accelerator facility at an energy of about 5 MeV/u. Ion bunches were continuously injected into the TSR and cooled permanently by the TSR electron cooler in one of the straight sections of the storage-ring. This continuous injection and cooling scheme enhances the duty cycle as compared to the usual measurement procedure, where the ion current in the storage-ring is accumulated and cooled before the recombination measurement starts.

In another straight section of the TSR, the ion beam was overlapped with the electron beam of the TSR electron target. The electron-ion collision energy E_{rel} was varied by changing the laboratory energy of the target electron beam. The longitudinal electron beam temperature was $kT_{\|} = (6.7 \pm 0.3) \times 10^{-5}$ eV as determined from the DR resonance line-shapes in the 800–815 eV energy range. Correspondingly, the experimental energy spread $\Delta E \approx [16(\ln 2)\,E_{\mathrm{rel}} kT_{\|}]^{1/2}$ varied from 0.47 eV to 0.63 eV across the experimental collision-energy range.

Recombined ions were separated from the primary beam in the first ring dipole-magnet downstream of the electron target and were detected by a single-particle detector with nearly 100% detection efficiency. Finally, the experimental merged-beams DR rate coefficient (figure 1) was derived by subtracting from the measured recombination spectrum all contributions due to radiative recombination (RR) and electron capture from the residual gas. The uncertainty of the merged-beams recombination rate coefficient is ±20% at a 67% confidence level over the entire energy range. It should be noted, that in the present experiment the use of the continuous injection scheme leads to a larger uncertainty of the ion current measurement and, consequently, of the merged-beams recombination rate coefficient than usual. This uncertainty stems mostly from uncertainties in the ion current measurement. Moreover, the subtraction of the continuous recombination background leads to an additional uncertainty of the merged

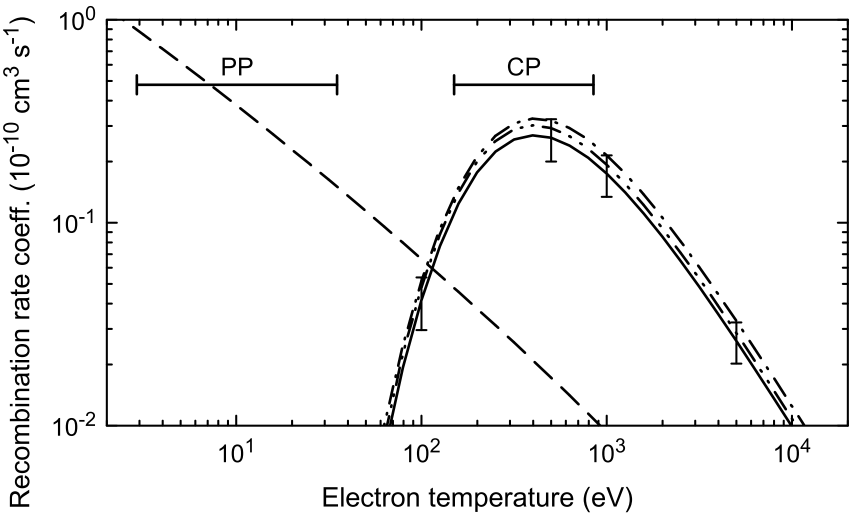

Figure 2. Plasma recombination rate coefficients of Fe^{16+} forming Fe^{15+}. The solid line represents the experimentally derived DR plasma rate coefficient. The error bars give the systematic errors. Also shown are the recent theoretically calculated results of [5] (dash-dotted curve) and [2] (dash-dot-dotted curve). The dashed curve is a theoretically calculated radiative-recombination (RR) plasma rate coefficient [6]. The temperature ranges where Fe^{16+} is expected to form in photoionized plasmas (PP) and collisionally ionized plasmas (CP) are marked.

beams rate coefficient of $\pm 2 \cdot 10^{-12}$ cm^3 s^{-1} in the 240–840 eV energy range.

3. Results and Discussion

The resulting merged-beams DR rate coefficient is shown in Figure 1. In accord with the theoretical expectation [2], the spectrum is dominated by $2s^2\,2p^5\,3d\ (^1P_1)\ nl$ DR resonances associated with the $2s^2\,2p^6\,{}^1S_0 \rightarrow 2s^2\,2p^5\,3d\ {}^1P_1$ core excitation. The corresponding Rydberg series limit at about 825 eV is clearly visible. No DR resonances have been detected at electron-ion collision energies below 300 eV.

In case of $\Delta N = 0$ DR field ionization of loosely bound high-n Rydberg states in the charge analyzing dipole magnet can have drastic effects on the recombination spectrum [7] since recombination to states with a Rydberg quantum number n exceeding the field ionization cutoff n_F is essentially not detected. For $\Delta N = 1$ DR the DR resonance strength drops more rapidly with increasing n than for $\Delta N = 0$ DR [8; 9]. In the present experiment resonances with $n > n_F = 53$ would contribute only negligibly to the DR rate coefficient close to the $2s^2\,2p^5\,3d\ (^1P_1)\ nl$ series limit.

The DR plasma rate coefficient as a function of electron temperature was derived by convoluting the merged-beams DR rate coefficient with a Maxwellian electron energy distribution. Experimental field-ionization effects were disregarded. By extrapolation of the measured $2s^2\,2p^5\,3d\ (^1P_1)\ nl$ DR resonance strengths to $n > n_F$ we estimated that this introduces only a negligible additional uncertainty of the plasma rate coefficient of at most 0.6% at temperatures higher than 90 eV. The absolute uncertainty of the merged-beams rate coefficient background leads to a relative uncertainty of the plasma rate coefficient of below 10% above 90 eV electron temperature. Adding these uncertainties in quadrature to the 20% relative uncertainty of the merged beams rate coefficient, yields a total uncertainty of the experimental DR plasma rate coefficient of 22% at a 67% confidence level, in the 90–10000 eV temperature range.

The temperature ranges where Fe^{16+} ions form in photoionized plasmas (PP) and collisionally ionized plasmas (CP) can be inferred from ionization balance calculations [10; 11] suggesting that Fe^{16+} reaches more than 10% of its peak abundance in a PP (CP) in the 3–35 eV (150–850 eV) temperature range. In figure 2 the present experimental DR plasma rate coefficient is compared with recent theoretical results [2; 5]. A comparison with earlier theoretical plasma rate coefficients for DR and RR can be found in [2]. As an additional reference a recently calculated RR plasma rate coefficient [6] is also given. Fe^{16+} RR dominates over DR in the PP temperature range, whereas DR dominates in the CP zone.

Within the experimental error margin both recent theoretical DR results agree with the experimental result. In the CP temperature range the theoretical result of [2] ([5]) is up to 14% (23%) larger than the experimental DR plasma rate coefficient. The unusually good agreement between the experimental and theoretical Fe^{16+} DR rate coefficients is due to the fact that only high energy $\Delta N = 1$ DR resonances contribute significantly to the plasma rate coefficient. At high energies the theoretical uncertainties of DR resonance positions are not as critical as for low-energy $\Delta N = 0$ DR where uncertainties in DR resonance positions of 0.1 eV can result in order of magnitude uncertainties of the low-temperature plasma rate coefficient [1].

Acknowledgments

The excellent support of the MPI-K accelerator and storage-ring crews is gratefully acknowledged. This work was supported in part by the German federal research-funding agency DFG under contract no. Schi 378/5. M.L., D.V.L., and D.W.S. were supported in part by the NASA Astronomy and Physics Research and Analysis program and the NASA Solar and Heliospheric Physics program.

References

[1] Schippers S 2008 *J. Phys. Conf. Ser.* these proceedings (*Preprint* arXiv:0808.3366 v1[astro-ph])

[2] Zatsarinny O, Gorczyca T W, Korista K, Badnell N R and Savin D W 2004 *Astron. Astrophys.* **426** 699–705

[3] Ralchenko Y, Jou F C, Kelleher D E, Kramida A E, Musgrove A, Reader J, Wiese W L and Olsen K 2007 *NIST Atomic Spectra Database (version 3.1.1)* (Gaithersburg, MD: National Institute of Standards and Technology) `http://physics.nist.gov/asd3`

[4] Schmidt E W *et al.* 2007 *Phys. Rev.* A **76** 032717

[5] Gu M F 2003 *Astrophys. J.* **590** 1131–1140

[6] Badnell N R 2006 *Astrophys. J. Suppl. Ser.* **167** 334–342

[7] Schippers S, Müller A, Gwinner G, Linkemann J, Saghiri A A and Wolf A 2001 *Astrophys. J.* **555** 1027–1037

[8] Savin D W *et al.* 2002 *Astrophys. J.* **576** 1098–1107

[9] Schippers S, Schnell M, Brandau C, Kieslich S, Müller A and Wolf A 2004 *Astron. Astrophys.* **421** 1185–1191

[10] Kallman T R, Palmeri P, Bautista M A, Mendoza C and Krolik J H 2004 *Astrophys. J. Suppl. Ser.* **155** 675–701

[11] Bryans P, Badnell N R, Gorczyca T W, Laming J M, Mitthumsiri W and Savin D W 2006 *Astrophys. J. Suppl. Ser.* **167** 343–356