

Recombination rate coefficients for astrophysical applications from storage-ring experiments

S. Schippers, S. Böhm, A. Müller

*Institut für Kernphysik, Strahlencentrum der Justus-Liebig-Universität,
35392 Giessen, Germany*

G. Gwinner, M. Schnell, D. Schwalm, A. Wolf

Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany

D. W. Savin

*Columbia Astrophysics Laboratory, Columbia University, NY 10027,
USA*

Abstract. The basic approach for measuring electron-ion recombination rate coefficients in merged-beams electron-ion collision experiments at heavy-ion storage rings is outlined. As an example experimental results for the low temperature recombination of C IV ions are compared with the recommended theoretical rate coefficient by Mazzotta et al. The latter deviates by factors of up to 5 from the experimental one.

1. Introduction

One important process that governs the charge state balance in a plasma is dielectronic recombination (DR). Accordingly, DR rate coefficients form a basic ingredient in plasma modeling codes that are employed for the analysis of spectra, e. g., obtained from astrophysical observations. In order to be able to infer a reliable description of the plasma properties from such calculations, accurate rate coefficients for the basic atomic collision processes in a plasma are required. To date, most DR rate coefficients used for plasma modeling stem from theoretical calculations. The calculation of DR rate coefficients is a challenging task since an infinite number of states is involved in this process. Approximations and computational simplifications are needed in order to make DR calculations tractable. It turns out that different calculations yield rate coefficients differing by up to orders of magnitude. In this situation benchmarking experiments are vitally needed in order to guide the development of the theoretical methods and to provide accurate DR rate coefficients for plasma modelers.

In the past decade electron-ion collision experiments employing merged beams at heavy-ion storage rings have proven to be the primary approach for obtaining accurate experimental DR rate coefficients (Müller & Wolf 1997; Müller & Schippers 2001). Several fundamental issues have been addressed in this research such as the high resolution spectroscopy of dielectronic resonances, the interference between radiative and dielectronic recombination and the influence of

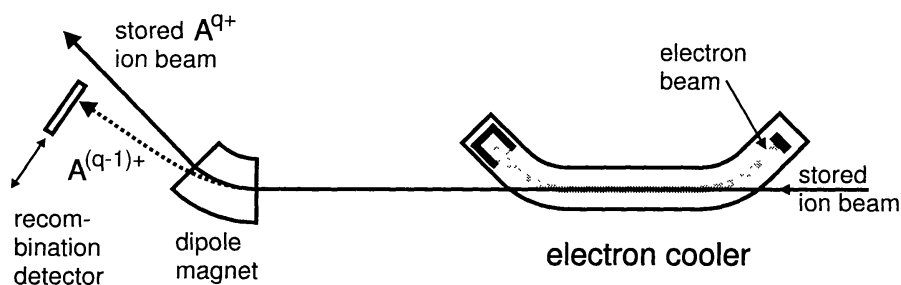


Figure 1. Sketch of the experimental setup. The beam of ions with parent charge state q enters the electron cooler from the right. In the bending magnet behind the electron cooler recombined $A^{(q-1)+}$ ions are bent less than the circulating parent A^{q+} ions. After charge state separation the recombined ions are counted by a single-particle detector with nearly 100% efficiency.

external electromagnetic fields on DR (for recent concise reviews see Schippers 1999; Schippers et al. 2000). Moreover, the electron-impact ionization of highly charged ions can also be studied at heavy-ion storage rings. From the measured cross sections plasma rate coefficients are readily derived as has been done, for example, for Fe XVI (Müller 1999).

In order to meet astrophysical needs, a dedicated experimental program on DR of L-shell iron ions is currently being carried out at the heavy-ion storage ring TSR of the Max-Planck-Institut für Kernphysik in Heidelberg, Germany. Already the first results for Fe XVIII, Fe XIX (Savin et al. 1997; Savin et al. 1999) revealed distinct differences between experimental and theoretical DR rate coefficients, especially at low temperatures where these ions may form in photoionized plasmas. Results for more highly charged ions ranging from Fe XX (Savin et al. 2001) up to Fe XXIV have also been obtained already and will be published in the near future. In the following, the state of affairs is exemplified by comparing the measured C IV DR rate coefficient (Schippers et al. 2001) with the recent recommendation by Mazzotta et al. (1998).

2. Outline of the Experimental Procedure

Electron-ion recombination experiments at a heavy-ion storage ring is conceptually simple. An ion beam with a unique charge-to-mass ratio from an accelerator is injected into the storage ring. By using multiple injection and electron-cooling techniques ion currents up to a few hundred μA or even a few mA can be accumulated in the heavy-ion storage ring TSR of the Max-Planck-Institut für Kernphysik in Heidelberg. Electron cooling is the transfer of the ion beam's internal kinetic energy to a heat bath consisting of cold electrons. It is most effective when the electrons move with nearly the same average velocity as the ions. This condition is achieved in the collinear part of the interaction region inside the electron cooler, inserted into one of the straight sections of the storage ring (see Fig. 1). In the electron cooler an electron beam is merged with the ion beam, guided along the ion beam and finally demerged by toroidal and axial

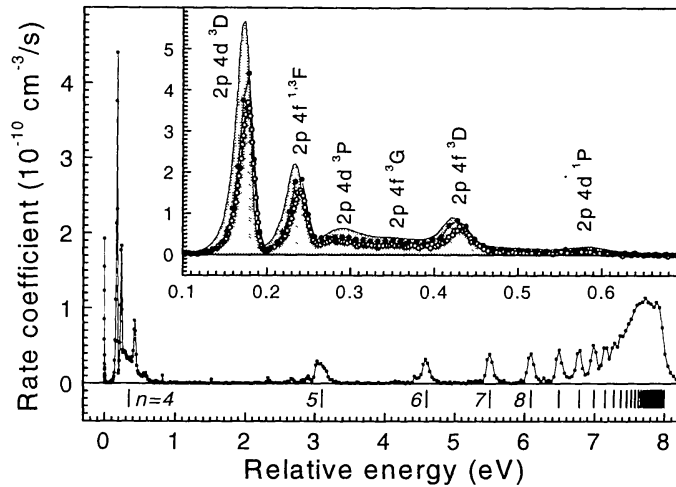


Figure 2. Experimental CIV merged-beams rate coefficient (full circles, Schippers et al. 2001). The vertical dashes denote the $2pnl$ resonance positions according to a Rydberg formula. The inset shows the CIV DR spectrum in the region of the $2p4l$ resonances, the experimental CRYRING data (open circles), and the theoretical results (shaded curve) of Mannervik et al. (1998). Their peak designations are given for the most prominent DR resonances.

magnetic fields. Since the stored ions move with typically 10% of the speed of light electron energies of about 3 keV are required in order to reach the cooling condition.

As a result of electron cooling the ion beam shrinks to a diameter of typically 2 mm and its internal velocity spread is reduced to below 0.01%. Moreover, after the cooling period of typically a few seconds, any metastable states that initially might have been present in the ion beam have vanished. The resulting extremely well defined ion beam is subsequently used for recombination experiments where the electron cooler is used as an electron target. Non-zero relative energies E_{rel} between electrons and ions are introduced by detuning the electron energy from its value required for cooling. In order to prevent internal ion beam heating from becoming effective, the detuning periods only last a few milliseconds, after which cooling is restored. Absolute ($\pm 15\%$ uncertainty) merged-beams recombination rate coefficients as a function of E_{rel} are obtained from the measured recombination count rate on the single-particle recombination detector (Fig. 1) by appropriate normalization on the simultaneously measured ion and electron currents.

3. Results and Discussion

As an example Fig. 2 shows the CIV merged-beams recombination rate coefficient as a function of E_{rel} (Schippers et al. 2001). Due to the low experimental energy spread, which is mainly determined by the electron beam temperature (here 0.15 meV and 10 meV in the longitudinal and transverse degrees of free-

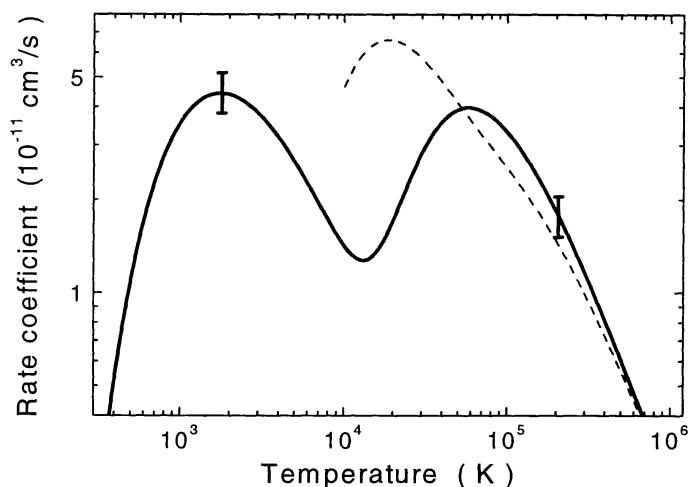


Figure 3. C IV DR rate coefficients in a plasma. Thick full line: experimentally derived result of Schippers et al. (2001, systematic uncertainty $\pm 15\%$), thin dashed line: recommendation by Mazzotta et al. (1998).

dom, respectively), individual $2pnl$ DR resonances associated with $2s \rightarrow 2p$ core excitations are resolved for $n \leq 9$. Toward the series limit overlapping high- n resonances produce the prominent structure around $E_{\text{rel}} \approx 7.5$ eV. As discussed explicitly by Schippers et al. (2001) one experimental limitation is the cut off of high Rydberg resonances in the motional electric field generated in the charge analyzing dipole magnet (cf., Fig. 1). In the C IV experiment the associated experimental cut off has been around the quantum number $n_{\text{cut}} = 19$ and the unmeasured DR resonance strength accumulated in resonances with $n > n_{\text{cut}}$ has been substantial. This issue is much less severe for more highly charged ions such as Fe XVIII (Savin et al. 1997; 1999) where due to the higher nuclear charge the DR resonance strengths decrease more rapidly with increasing n and, moreover, the experimental cut off occurs at a much higher n_{cut} typically larger than 100.

The inset of Fig. 2 enlarges the region of the $2p4l$ resonances where other experimental results measured at the Stockholm heavy ion storage ring CRYRING (Mannervik et al. 1998) are also available. The agreement between the two experimental data sets is within the experimental uncertainties. Mannervik et al. (1998) also performed theoretical calculations of the recombination rate coefficient within the framework of relativistic many-body perturbation theory. From these calculations it became clear that relativistic effects decisively determine the DR resonance strength even for such a light ion as C IV. Conclusively, it can be stated that accurate theoretical recombination rate coefficients can probably only be obtained from relativistic fine structure calculations and that simpler LS-coupling calculations are bound to be in error.

For the derivation of the C IV plasma recombination rate coefficient the measured merged-beams recombination rate coefficient was first extrapolated to high n by a theoretical calculation in order to account for the unmeasured

high- n DR resonance strength. In a second step the combined measured and extrapolated rate coefficient was convoluted by a Maxwellian electron energy distribution characterized by the plasma electron temperature T_e . The resulting experimentally derived C IV plasma DR rate coefficient (Schippers et al. 2001) is plotted in Fig. 3 (thick full line) as a function of T_e . Also shown in Fig. 3 is the recommended C IV DR rate coefficient by Mazzotta et al. (1998, thin dashed line). At temperatures below 50 000 K it deviates by factors of up to 5 from our experimental result. When comparing with all available theoretical C IV DR rate coefficients we find that none of them agrees with the experimentally derived rate coefficient over the entire relevant temperature range (Schippers et al. 2001).

In conclusion, heavy-ion storage rings are the tools of choice for the experimental determination of absolute recombination rate coefficients. By comparison with the experimental results we find that theoretical DR rate coefficients currently used in plasma modeling can be in serious error. In view of these deficiencies we are presently carrying out an experimental program for the determination of low temperature recombination rate coefficients of the iron L-shell ions Fe XVII to Fe XIV (Savin et al. 1997; 1999; 2001). In the future we plan to extend these measurements to higher excitation energies that are relevant for high temperature DR occurring in the solar as well as in stellar coronae.

References

- Mannervik, S., deWitt, D., Engström, L., Lidberg, J., Lindroth, E., Schuch, R., & Zong, W. 1998, *Phys.Rev.Lett*, 81, 313
- Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, *A&A*, 133, 403
- Müller, A. 1999, *Int. J. Mass Spectr.* 192, 9
- Müller, A., & Wolf, A. 1999, in *Accelerator-based atomic physics techniques and applications*, ed. J. C. Austin & S. M. Shafroth (Woodbury, New York: AIP Press), 147
- Müller A., & Schippers S. 2001, in *ASP Conf. Ser.*, 247, *The challenge of high resolution X-ray and IR spectroscopy*, ed. G. Ferland & D. W. Savin (Provo, Utah: Astronomical Society of the Pacific), in press
- Savin, D. W., et al. 1997, *ApJ*, 489, L115
- Savin, D. W., et al. 1999, *ApJS*, 123, 687
- Savin, D. W., et al. 2001, *ApJS*, in print
- Schippers, S. 1999, *Phys. Scr.*, T80, 158
- Schippers, S., Gwinner, G., Bartsch T., Hoffknecht, A., Müller, A., Schwalm, D., and Wolf, A. 2000, in *AIP Conf. Proc.*, 500, *The Physics of Electronic and Atomic Collisions*, ed. Itikawa, Y., Okuno, K., Tanaka, H., Yagishita, A., & Matsuzawa, M. (Meville, New York: American Institute of Physics), 400
- Schippers, S., Müller, A., Gwinner, G., Linkemann, J., Saghiri, A. A., & Wolf, A. 2001, *ApJ*, 555, 1027



Everyone was smiling with the thought of enjoying the next day's sessions