Recent dielectronic recombination experiments

A. Müller [a,*], T. Bartsch [a], C. Brandau [a], A. Hoffknecht [a], H. Knopp [a], S. Schippers [a], O. Uwira [a], J. Linkemann [b], A.A. Saghiri [b], M. Schmitt [b], D. Schwalm [b], A. Wolf [b], F. Bosch [c], B. Franzke [c], C. Kozhuharov [c], P.H. Mokler [c], F. Nolden [c], M. Steck [c], T. Stöhlker [c], T. Winkler [c], H. Danared [d], D.R. DeWitt [e], H. Gao [e], H. Lebius [e], R. Schuch [e], W. Spies [e], W. Zong [e], G.H. Dunn [f], W.G. Graham [g], J.A. Tanis [h], J. Doerfert [i], D. Savin [j] and Z. Stachura [k]

[a] *Institut für Kernphysik, Strahlenzentrum, Universität Giessen, D-35392 Giessen, Germany*
[b] *Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany*
[c] *Gesellschaft für Schwerionenforschung (GSI), D-64291 Darmstadt, Germany*
[d] *Manne Siegbahn Laboratory, S-104 05 Stockholm, Sweden*
[e] *Physics Department, Stockholm University, S-104 05 Stockholm, Sweden*
[f] *JILA, Boulder, CO 80309-0440, USA*
[g] *Department of Pure and Applied Physics, The Queen's University, Belfast BT7 1NN, UK*
[h] *Department of Physics, W.-Michigan State University, Kalamazoo, MI 49008, USA*
[i] *Institut für Experimentalphysik III, Universität Bochum, D-44780 Bochum, Germany*
[j] *Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA*
[k] *Institute for Nuclear Physics, 31-342 Krakow, Poland*

New recombination experiments with merged cold beams of electrons and atomic ions have been carried out at the storage ring facilities TSR in Heidelberg, ESR in Darmstadt, and CRYRING in Stockholm. A brief overview is given on the recent activities in which the Giessen group was engaged. Topics of this research were dielectronic recombination (DR) of astrophysically relevant ions, recombination of highly charged ions with respect to cooling losses in storage rings, field effects on DR, search for interference effects in photorecombination of ions, correlation effects in DR of low-Z ions, spectroscopy of high-Z ions by DR, and lifetimes of metastable states deduced from DR experiments.

1. Introductory remarks

Recombination of electrons with atomic ions [1] is of lively interest because of the attractive possibilities of high resolution measurements [2] at heavy ion storage rings [3], and because of the long-standing atomic data needs in astrophysical and plasma research [4]. The processes that have received most interest so far are dielectronic recombination (DR)

$$e + A^{q+} \longrightarrow \left[A^{(q-1)+}\right]^{**} \longrightarrow A^{(q-1)+} + \text{photons}, \tag{1}$$

* E-mail: Alfred.Müller@strz.uni-giessen.de.

and radiative recombination (RR)

$$e + A^{q+} \longrightarrow A^{(q-1)+} + \text{photons}. \tag{2}$$

DR involves two successive steps and is thus subject to the influence of external fields and collisions, which act on the intermediate doubly excited state. The first step of DR is the time-reverted Auger process, i.e., the free electron is resonantly captured by the ion with simultaneous excitation of a second electron bound to the ion. In the second step the new charge state of the ion is stabilized by photoemission. Different from that, RR is a direct process in which the energy liberated by the binding of the initially free electron is instantly carried away by a photon.

2. Interference effects

In particular cases, RR and DR can by no means be distinguished by experiments, because initial and final states of the interaction process including the photons may be identical. This situation can lead to interference of the amplitudes for both pathways of the recombination process. Unified photorecombination theory predicts distortions of the DR resonance profiles as a result of such interference [5] and also for overlapping resonances of equal symmetry [6]. An experimental observation of interference of RR and DR has been reported previously for differential cross section measurements carried out at an ion trap [7].

Recent predictions by Gorczyca et al. [8,9] suggested easy observability of interference effects in the recombination of Sc^{3+} and Ti^{4+} ions, both argon-like with the lowest excitation channels associated with 3p → 3d and 3p → 4s core transitions. In experiments at the TSR an effort was made to measure recombination of these ions and to find interference effects [10,11]. Partially due to experimental difficulties with high backgrounds and low cross sections, however, no clear-cut evidence for the predicted effects could be found so far.

3. Application in astrophysics

DR and RR are fundamental processes with important influence on the charge state balance of the ions in a plasma and on the radiation emitted. As a result, cross section and rate data for these processes are needed for the understanding and modeling as well as the diagnostics of all plasmas, man-made or natural [4]. Many of the data needs can be met by the application of the merged beams technique involving the electron cooler of a heavy ion storage ring. The expected high quality of X-ray spectra from astrophysical objects to be obtained in future satellite experiments [12] has led to a research program at the TSR in which recombination and ionization of the cosmically abundant ions Fe^{q+} with $q = 15, 16, \ldots, 23$ is studied. Recently, the measurement of the recombination spectrum of fluorine-like Fe^{17+} ions provided a significant new result that surprised the astrophysics experts [13]. Different from all previous expectations

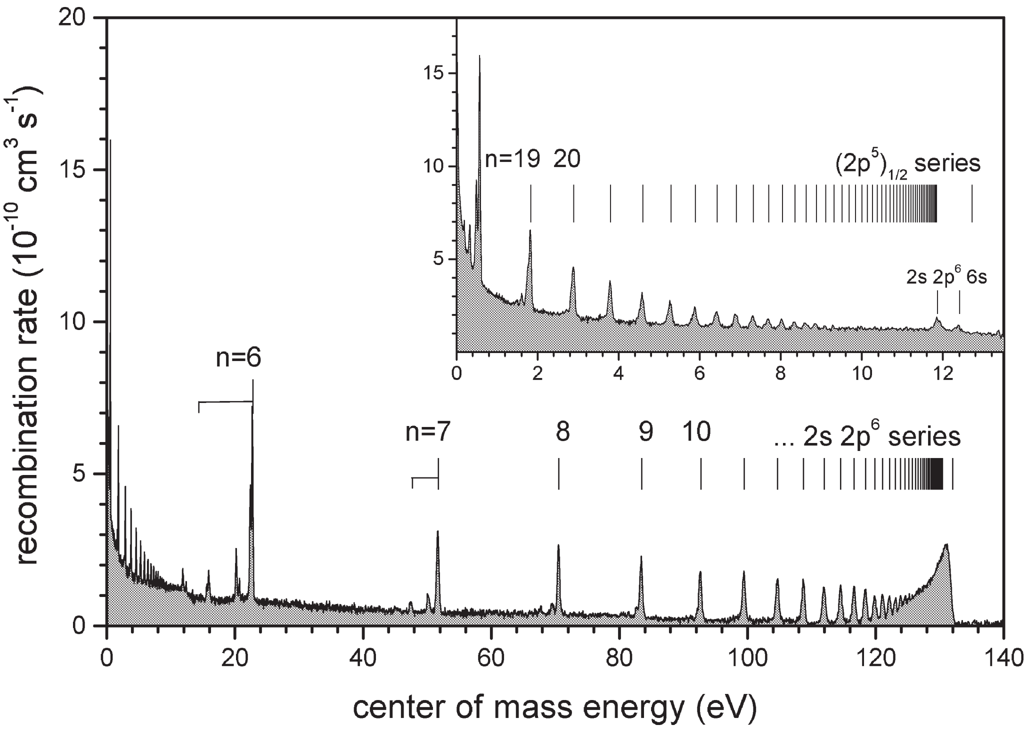

Figure 1. Recombination rates of Fe^{17+} ions measured at the TSR.

the experiment showed the importance of M1 excitations of the $^2P_{3/2}$ core in DR. Hence, in the cold plasma of X-ray driven interstellar nebulae, the recombination rate can be much higher (by two orders of magnitude) than previous calculations. The experimental results from the TSR are shown in figure 1. Experimental data are also available at this time for Fe^{15+} [14,15] and Fe^{18+} [16].

4. Spectroscopy aspects

The development of electron beams with increasingly better energy resolution in connection with the bright cold ion beams available in the rings has paved the way towards a precision spectroscopy of singly and multiply excited states of ions ranging from singly charged low-Z to very highly charged high-Z ions, where Z is the atomic number. With the resolution obtained in previous experiments, QED effects on level energies could already be sensitively probed [17]. A new step towards the best possible precision of energy determinations of states in very highly charged ions and of Lamb shift measurements based on the observation of DR resonances appears to be possible now [18–20]. Few-electron systems studied recently in our collaboration comprise ground-state $Li^+(1s^2\ ^1S)$, metastable $Li^+(1s\,2s\ ^3S)$ [21], as well as lithiumlike Au^{76+} and U^{89+} [20,22]. Details of the latter research are presented elsewhere in these proceedings [23,24].

5. Enhanced recombination at meV and sub-meV energies

New and unexpected effects on the recombination of ions were found at very low electron–ion collision energies [25–27]. Recombination rate enhancements far beyond the expectations for RR led to enormous intensity losses during electron cooling of ion beams [28], with beam lifetimes as low as 2 s. Again, measurements at storage rings provide a suitable experimental approach to the understanding of this exciting and important phenomenon. Previous measurements on the sequence of Au^{q+} ions with $q = 49$, 50 and 51 are now finally analyzed [29]. Measurements carried out at a high-density electron target with Au^{25+} showed the record high enhancement factor of 365 of the measured recombination rate above theoretical expectations for RR [30]. As in the TSR experiments with the more highly charged gold ions this huge enhancement is probably due to DR resonances at very low energies. An increase of the electron density in the Au^{25+} experiment from 3.3×10^8 cm^{-3} to 3.7×10^9 cm^{-3} had no significant effect on the measured recombination rate [31]. Measurements of similar nature with variation of experimental parameters were also carried out with Cl^{17+}, U^{89+} and Au^{76+} ions. Recombination rate enhancements are observed in all three cases although no DR resonances can be expected for these ions at low energies (and are impossible for the completely stripped Cl^{17+} ions). The results of that work are still being analyzed. Negligible effects of electron density variations in accordance with previous observations at CRYRING [32] seem to contradict the expectations based on molecular dynamics calculations [33] simulating the plasma conditions in the electron cooler.

6. Field effects

While electric fields were experimentally demonstrated to influence the size of DR cross sections for singly charged ions [34], there were discrepancies between theory and experiment and inconsistencies in the understanding of these effects particularly also for multiply charged ions. First quantitative measurements covering a wide range of controlled electric and magnetic fields have been reported for Si^{11+} ions [35] showing that further detailed studies of field effects on DR will be necessary. The analysis of the previous measurements was finalized [36,37]. Remaining discrepancies with state-of-the-art theory sparked the prediction of a new mechanism of DR rate enhancement in the presence of an additional magnetic field perpendicular to the electric field [38]. Such magnetic fields have been involved in all but one previous DR measurements. Qualitatively, the assumption of additional m-mixing by magnetic fields on top of the ℓ-mixing caused by electric fields and the resulting enhancement of DR cross sections is in accordance with the experimental observations. A clear-cut experimental proof of magnetic field effects in crossed E- and B-fields, however, remains to be found.

7. Lifetimes of excited states

Storage rings have been extensively used for lifetime measurements of excited atomic, molecular and nuclear states [3]. The observation of DR starting from excited long-lived parent states has provided high precision data for transition probabilities in few-electron atomic ions [39]. The technique used in such experiments promises to be widely applicable. Experiments were carried out at the TSR to determine the lifetime of metastable 2^3S helium-like Li^+ [21]. The preliminary result of the analysis is (47.3 $\pm$ 2.9) s. Test experiments were also carried out towards lifetime studies with Cu^{25+} ions.

8. Summary

The recombination of an ion with a free electron is an important fundamental collision process. It plays a significant role in all kinds of plasmas and therefore has vast applications in plasma diagnostics and plasma modeling. Due to its fundamental character it provides an ideal testing ground for our understanding of atomic structures, transition probabilities and collision dynamics. Dielectronic recombination in particular can be employed for a collisional spectroscopy of multiply excited states. Extrapolation of Rydberg resonance energies to their series limit can even provide precise excitation thresholds for singly excited states and thus opens new pathways towards high precision tests of QED calculations of level energies in very highly charged few-electron systems. The physics of electron–ion recombination also involves unique interesting phenomena, such as interference of different recombination channels or different, but overlapping resonances of equal symmetry. Effects of external fields on DR provide an intriguing field of research. Surprising results are obtained at the very low relative energies which can now be accessed by the merged beams technique in storage rings using the cold electron beams. At least for energies up to about 1 keV the storage cooler rings provide the method of choice for studies of electron–ion recombination. These studies will be further extended in the near future. The ongoing technical improvements of the storage rings and of their operation provide increasingly better conditions for recombination measurements. A big step in the quality of the measurements will be possible when additional, dedicated electron targets in the rings will become available.

Acknowledgements

The authors thank the staff at the different storage ring facilities for their invaluable help. Fruitful interaction with numerous colleagues in theoretical physics has been stimulating and illuminating for the present research program. Support by the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, by the Max-Planck-Institut für Kernphysik, Heidelberg, by the German Ministry of Education, Science, Research and Technology (BMBF), and by the Human Capital and Mobility Programme of the European Community is gratefully acknowledged.

References

[1] W.G. Graham et al. (eds.), *Recombination of Atomic Ions*, NATO ASI Series B: Physics, Vol. 296 (Plenum, New York, 1992).

[2] A. Müller, Comments At. Mol. Phys. 32 (1996) 143.

[3] A. Müller and A. Wolf, in: *Accelerator-Based Atomic Physics Techniques and Applications*, eds. S. Shafroth and J. Austin (American Institute of Physics, Woodbury, NY, 1997) pp. 147.

[4] M. Inokuti (ed.), Adv. At. Mol. Opt. Phys. 33 (1994).

[5] N.R. Badnell and M.S. Pindzola, Phys. Rev. A 45 (1992) 2820.

[6] V.V. Karasiov, L.N. Labzowsky, A.V. Nefiodov and V.M. Shabaev, Phys. Lett. A 161 (1992) 453.

[7] D.A. Knapp, P. Beiersdorfer, M.H. Chen, J.H. Scofield and D. Schneider, Phys. Rev. Lett. 74 (1995) 54.

[8] T.W. Gorczyca, M.S. Pindzola, F. Robicheaux and N.R. Badnell, Phys. Rev. A 56 (1997) in press.

[9] T.W. Gorczyca, Private communication (July 1997).

[10] S. Schippers, T. Bartsch, C. Brandau, J. Linkemann, A. Müller, A. Saghiri and A. Wolf, this issue.

[11] S. Schippers, T. Bartsch, C. Brandau, A. Müller, G. Gwinner, A. Saghiri and A. Wolf, submitted to J. Phys. B.

[12] R.S. Warwick, in: *Proc. of the Workshop: The Next Generation of X-ray Observatories*, Leicester X-ray Astronomy Group Special Report XRA97/02, eds. M.J.L. Turner and M.G. Watson (University of Leicester, 1997) p. 7.

[13] D.W. Savin, T. Bartsch, M.H. Chen, S.M. Kahn, D.A. Liedahl, J. Linkemann, A. Müller, M. Schmitt, D. Schwalm and A. Wolf, Astrophys. J. Lett. 489 (1997) L115.

[14] J. Linkemann, J. Kenntner, A. Müller, A. Wolf, D. Habs, D. Schwalm, W. Spies, O. Uwira, A. Frank, A. Liedtke, G. Hofmann, E. Salzborn, N.R. Badnell and M.S. Pindzola, Nucl. Instrum. Methods Phys. Res. B 98 (1995) 154.

[15] J. Linkemann, A. Müller, J. Kenntner, D. Habs, D. Schwalm, A. Wolf, N.R. Badnell and M.S. Pindzola, Phys. Rev. Lett. 74 (1995) 4173.

[16] D.W. Savin, A.A. Saghiri, T. Bartsch, M.H. Chen, S.M. Kahn, J. Linkemann, A. Müller, S. Schippers, M. Schmitt and A. Wolf, in: *Proc. of the 20th Internat. Conf. on the Physics of Electronic and Atomic Collisions*, Abstracts of Contributed Papers, Vienna, Austria (23.07–29.07.1997) TU 145.

[17] W. Spies, A. Müller, J. Linkemann, A. Frank, M. Wagner, C. Kozhuharov, B. Franzke, K. Beckert, F. Bosch, H. Eickhoff, M. Jung, O. Klepper, W. König, P.H. Mokler, R. Moshammer, F. Nolden, U. Schaaf, P. Spädtke, M. Steck, P. Zimmerer, N. Grün, W. Scheid, M.S. Pindzola and N.R. Badnell, Phys. Rev. Lett. 69 (1992) 2768.

[18] W. Spies, O. Uwira, A. Müller, J. Linkemann, L. Empacher, A. Frank, C. Kozhuharov, P.H. Mokler, F. Bosch, O. Klepper, B. Franzke and M. Steck, Nucl. Instrum. Methods Phys. Res. B 98 (1995) 158.

[19] S. Mannervik, S. Asp, L. Broström, D.R. DeWitt, J. Lidberg and R. Schuch, Phys. Rev. A 55 (1997) 1810.

[20] C. Brandau, F. Bosch, G. Dunn, B. Franzke, A. Hoffknecht, C. Kozhuharov, P.H. Mokler, A. Müller, F. Nolden, S. Schippers, Z. Stachura, M. Steck, T. Stöhlker, T. Winkler and A. Wolf, in: *Proc. of the 20th Internat. Conf. on the Physics of Electronic and Atomic Collisions*, Abstracts of Contributed Papers, Vienna, Austria (23.07–29.07.1997) TU 147.

[21] A. Saghiri, J. Linkemann, M. Schmitt, D. Schwalm, A. Wolf, T. Bartsch, A. Hoffknecht, A. Müller, W.G. Graham, J. Tanis, N. Badnell and A. Price, in: *Proc. of the 20th Internat. Conf. on the Physics of Electronic and Atomic Collisions*, Abstracts of Contributed Papers, Vienna, Austria (23.07–29.07.1997) TU 143.

[22] C. Brandau, A. Hoffknecht, H. Knopp, A. Müller, C. Kozhuharov, B. Franzke, M. Steck, T. Winkler, L. Groening, F. Bosch, T. Stöhlker, P.H. Mokler and Z. Stachura, in: *Proc. of the 20th Internat. Conf. on the Physics of Electronic and Atomic Collisions*, Abstracts of Contributed Papers, Vienna, Austria (23.07–29.07.1997) TU 146.

[23] C. Brandau et al., this issue.
[24] C. Brandau et al., this issue.
[25] A. Müller, S. Schennach, M. Wagner, J. Haselbauer, O. Uwira, W. Spies, E. Jennewein, R. Becker, M. Kleinod, U. Pröbstel, N. Angert, J. Klabunde, P.H. Mokler, P. Spädtke and B. Wolf, Phys. Scripta 37 (1991) 62.
[26] O. Uwira, A. Müller, W. Spies, J. Linkemann, A. Frank, T. Cramer, L. Empacher, R. Becker, M. Kleinod, P.H. Mokler, J. Kenntner, A. Wolf, U. Schramm, T. Schüssler, D. Schwalm and D. Habs, Hyperfine Interact. 99 (1996) 295.
[27] H. Gao, D.R. DeWitt, R. Schuch, W. Zong, S. Asp and M. Pajek, Phys. Rev. Lett. 75 (1995) 4381.
[28] S. Baird, J. Bosser, C. Carli, M. Chanel, P. Lefèvre, R. Ley, R. Maccaferri, S. Maury, I. Meshkov, D. Möhl, G. Molinari, F. Motsch, H. Mulder, G. Tranquille and F. Varenne, Phys. Lett. B 361 (1995) 184.
[29] O. Uwira, A. Müller, J. Linkemann, T. Bartsch, C. Brandau, M. Schmitt, A. Wolf, D. Schwalm, R. Schuch, W. Zong, H. Lebius, W.G. Graham, J. Doerfert and D.W. Savin, Hyperfine Interact. 108 (1997) 149.
[30] A. Hoffknecht, O. Uwira, S. Schennach, A. Frank, J. Haselbauer, W. Spies, N. Angert, P.H. Mokler, R. Becker, M. Kleinod, S. Schippers and A. Müller, J. Phys. B 31 (1998) 2415.
[31] A. Hoffknecht et al., this issue.
[32] H. Gao, S. Asp, C. Biedermann, D.R. DeWitt, R. Schuch, W. Zong and H. Danared, Hyperfine Interact. 99 (1996) 301.
[33] G. Zwicknagel, Q. Spreiter and C. Toepffer, Hyperfine Interact. 108 (1997) 131.
[34] A. Müller, D.S. Belić, B.D. De Paola, N. Djurić, G.H. Dunn, D.W. Mueller and C. Timmer, Phys. Rev. Lett. 56 (1986) 127; Phys. Rev. A 36 (1987) 599.
[35] T. Bartsch, A. Müller, W. Spies, J. Linkemann, H. Danared, D.R. DeWitt, H. Gao, W. Zong, R. Schuch, A. Wolf and G.H. Dunn, Hyperfine Interact. 108 (1997) 177.
[36] T. Bartsch, A. Müller, W. Spies, J. Linkemann, H. Danared, D.R. De Witt, H. Gao, W. Zong, R. Schuch, A. Wolf, G.H. Dunn, M.S. Pindzola and D.C. Griffin, Phys. Rev. Lett. 79 (1997) 2233.
[37] T. Bartsch et al., this issue.
[38] F. Robicheaux and M.S. Pindzola, Phys. Rev. Lett. 79 (1997) 2237.
[39] H.T. Schmidt, P. Forck, M. Grieser, D. Habs, J. Kenntner, G. Miersch, R. Repnow, U. Schramm, T. Schüßler, D. Schwalm and A. Wolf, Phys. Rev. Lett. 72 (1994) 1616.