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Experimental O VI dielectronic recombination rate coefficient and its enhancement by external electric fields

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Abstract. The dielectronic recombination rate coefficient of O VI ions has been measured at the heavy ion storage ring CRYRING. The electron energy range covered all dielectronic recombination resonances attached to 2s → 2p ($\Delta n = 0$) core excitations. The rate coefficient in a plasma has been derived. It is compared to theoretical data. In addition the influence of external electric fields on the dielectronic recombination has been investigated. When increasing the electric field strength to 340 V/cm the experimental recombination rate coefficient is found to increase by up to a factor of 2.

Key words. atomic data – atomic processes – line: formation – plasmas – radiation mechanisms: general

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. In this situation benchmarking experiments are vitally needed to guide the development of the theoretical methods and to provide accurate DR rate coefficients for plasma modelers.

In the past decade electron coolers at heavy-ion storage-rings have become the most successful tool for electron-ion recombination studies (Schuch 1993; Müller & Wolf 1997). Comprehensive bibliographic compilations on DR measurements at storage rings have been published, e.g., by Müller (1995) and Schippers (1999). The basic approach for deriving plasma rate coefficients from storage-ring measurements has been summarized by Müller (1999). Recent experimental work on plasma rate coefficients for astrophysical and other plasma applications has been published by Savin et al. (1997, 1999, 2002a,b) on DR of Fe XVIII, Fe XIX, and Fe XX and by Schippers et al. (1998, 2000, 2001) on DR of Ti V, Ni XXVI, and C IV.

DR of lithiumlike oxygen ions can be represented as

$$\begin{aligned} e^- \;+\; O^{5+}(1s^2 2s) &\rightarrow O^{4+}(1s^2 2p\, nl) \\ &\rightarrow \begin{cases} O^{4+}(1s^2 2s\, nl) + h\nu & \text{(type I)} \\ O^{4+}(1s^2 2p\, n'l') + h\nu' & \text{(type II).} \end{cases} \end{aligned} \quad (1)$$

The 2s → 2p ($\Delta n = 0$) excitation energy is ≈12 eV. Higher excitations such as 2s → 3l ($\Delta n = 1$) are not investigated in the context of the present work.

The DR rate coefficient is sensitive to the presence of electromagnetic fields. DR in the presence of external electromagnetic fields (DRF) was studied first theoretically by Burgess & Summers (1969), Jacobs et al. (1976) and Jacobs & Davis (1979). It was recognized that an external electric field mixes states with different orbital quantum numbers. The resulting enhancement of the DR cross section has been verified experimentally for the first time by Müller et al. (1986). DRF experiments providing evidence for the influence of additional magnetic fields as predicted by Robicheaux & Pindzola (1997) have been carried out for example by Bartsch et al. (1999).

In this paper we present the measured O VI recombination rate coefficient with and without electric field present in the interaction region. The experimental procedure is outlined in Sect. 2. In Sect. 3 the experimental results are presented and compared to theory in Sect. 4. The influence of electromagnetic fields on the DR rate coefficient is described in Sect. 5. A summary is provided in Sect. 6.

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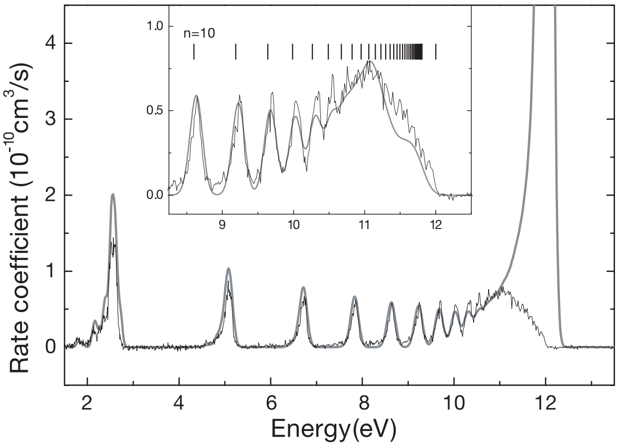

Fig. 1. Experimental zero-field O^{5+} DR spectrum for an ion energy of 9.4 MeV/u (thin solid line). The resonances are due to the excitation of $1s^22p\,nl$ intermediate states with $n \geq 6$. The thick grey line shows an AUTOSTRUCTURE (Badnell 1986) calculation including Rydberg states up to $n = 1000$. For the comparison the theoretical cross section has been convoluted with the experimental electron energy distribution function. The inset shows the high energy part of the experimental spectrum together with an AUTOSTRUCTURE calculation to which the field ionization model of Schippers et al. (2001) has been applied. In both cases the AUTOSTRUCTURE calculation has been shifted by 0.08 eV towards higher energies and multiplied by a factor of 0.8.

2. Experiment

The O VI DR experiment was carried out at the heavy-ion storage-ring CRYRING of the Manne Siegbahn Laboratory in Stockholm. The $^{16}O^{5+}$ ions were produced in a cryogenic electron beam ion source (CRYSIS), preaccelerated by a radio frequency quadrupole structure to about 300 keV/u, injected into the ring and accelerated to their final energy of 9.4 MeV/u. The ion beam was cooled by interaction with a magnetically guided colinear beam of cold electrons in an electron cooler (Danared et al. 2000). During the recombination measurements the electron cooler was used as an electron target. The electron energy was varied by changing the voltage at the cooler cathode in order to obtain a DR spectrum. The experimental center of mass energy range of $0 < \hat{E} < 15$ eV covered all DR resonances due to 2s → 2p $\Delta n = 0$ excitations. The recombined ions were detected with 100% efficiency behind the first dipole magnet after the cooler.

On their way to the detector the recombined ions had to pass strong magnetic fields the largest of which was within the charge state analyzing bending dipole magnet. These magnetic fields were perpendicular to the ions' flight direction and caused motional electric fields (of the order of 50 MV/m in the ring dipoles) orders of magnitude larger than any motional electric fields in the interaction region. Since a sizeable fraction of recombined ions was expected to be formed in highly excited and, hence, very fragile states, the survival probability of these states and the efficiency of their detection needed particular consideration. Recombined ions that reached a zone of large motional electric fields while being in sufficiently highly excited $1s^22p\,nl$ states were field ionized and therefore not detected. This effect can be clearly seen in Fig. 1 where the experimental spectrum with a cutoff quantum number $n_c \approx 19$ due to field ionization is compared to an AUTOSTRUCTURE (Badnell 1986) calculation including Rydberg states up to $n = 1000$ (the inclusion of even higher n-states did not change the theoretical curve anymore). In a detailed field ionization model (Schippers et al. 2001) the radiative decay of electrons in high Rydberg states on their way from the cooler to the different field ionization zones has been taken into account by hydrogenic decay rates. This model has been applied to the cross sections obtained from the AUTOSTRUCTURE calculation. From the resulting agreement with the experiment (inset of Fig. 1) we conclude, that field ionization is sufficiently well understood in our experimental setup.

For the DRF measurements electric fields were introduced in the interaction region with the aid of magnet coils mounted inside the main solenoid for field corrections. The solenoid produced the longitudinal field $B_{\|}$ needed to guide the electrons through the cooler. The correction coils usually serve for optimizing the alignment of the electron beam with respect to the ion beam. In the present experiments they were used to introduce well defined transverse magnetic field components $B_\perp$ which transformed to electric fields $E_\perp = v_i B_\perp$ in the rest frame of an ion moving with velocity v_i. In order to avoid confusion it should be noted that the motional electric field $E_\perp$ in the interaction region, which caused the enhancement of the DR cross section, was different and spatially well separated from the motional electric fields F which caused field ionization of recombined ions in high Rydberg states. More comprehensive descriptions of the DRF experiments at CRYRING were given by Böhm et al. (2001, 2002).

The main uncertainties of the measured rate coefficient arise from the measurement of the ion current with a current transformer (≈10%) and the uncertainty of the interaction length (≈5%). All uncertainties in quadrature add up to ±11% uncertainty of the absolute rate coefficient.

3. Results

Our experimental O VI DR rate coefficient is displayed in Fig. 1. It contains all $1s^22p\,nl$ resonances associated with 2s → 2p transitions ranging from $n = 6$, which is the lowest energetically allowed resonance, up to $n \approx 20$. Individual resonances can be resolved up to $n \approx 15$. For $n = 6$, even the l substates are partially resolved. Background subtraction (here radiative recombination is regarded as background) was achieved by fitting an empirical formula with five fit parameters P_i,

$$\alpha_b(E) = \frac{P_1}{1 + P_2E + P_3E^2} + P_4 + P_5E \tag{2}$$

to those parts of the measured spectra where no DR resonances occurred.

For the derivation of a meaningful plasma rate coefficient from our experimental data we have to estimate how much DR strength was not measured due to the field ionization cutoff discussed above. Following the procedure of Schippers et al. (2001) we have extrapolated the measured DR spectrum by the scaled AUTOSTRUCTURE result. For the scaling a constant energy shift of 0.08 eV towards higher energies and a constant

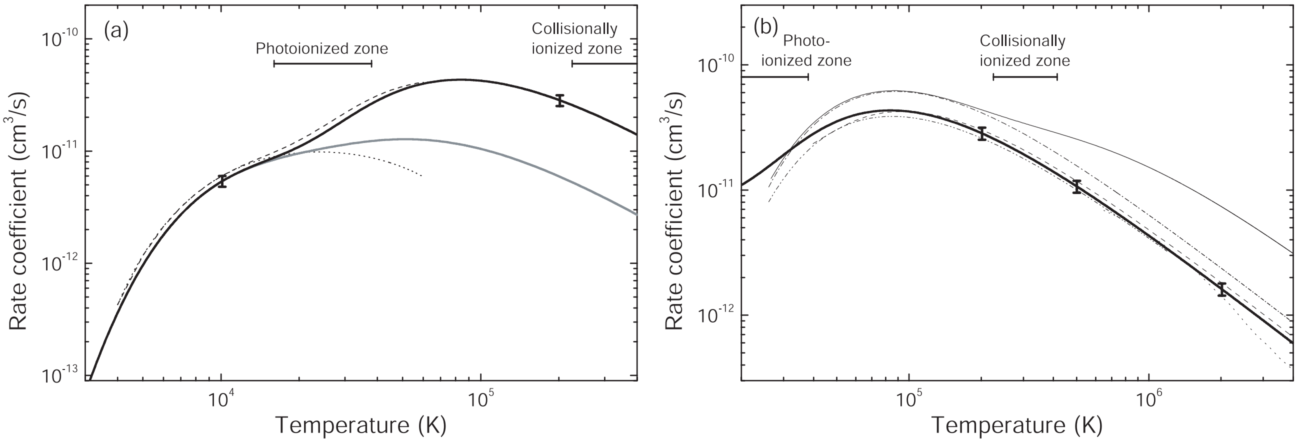

Fig. 2. The O VI $\Delta n = 0$ DR rate coefficient in a plasma is shown for temperatures below 4×10^5 K **a)** and for temperatures above 20 000 K **b)**. The thick full line represents the experimentally derived rate coefficient with an systematic uncertainty of ±11%. **a)** The thick grey curve results from our measured rate coefficient without the AUTOSTRUCTURE extrapolation (see text). Also shown is the theoretical DR rate coefficient of Nussbaumer & Storey (1983) (dotted line) and the recommended DR rate coefficient of Arnaud & Rothenflug (1985) (dashed line) who combined the calculations of Nussbaumer & Storey (1983) for low energies and calculations of Jacobs et al. (1978) as fitted by Shull & van Steenberg (1982) for higher energies. **b)** The theoretical results of Badnell & Pindzola (1989) (dashed line), McLaughlin & Hahn (1984) ($>6.5 \times 10^5$ K, dotted line), Burgess (1965) (dash-dotted line) and the fit of Shull & van Steenberg (1982) to data of Jacobs et al. (1978) (dash-dot-dotted line) are shown. The rate coefficient of Aldrovandi & Péquignot (1973) (thin solid line) includes $\Delta n \neq 0$ DR.

factor of 0.8 has been applied to the calculated DR cross section such that the theoretical DR spectrum matches the experimental one in the energy range of 2–11 eV. At higher energies where the experimental result is influenced by field ionization of high Rydberg states, it is simply substituted by the scaled AUTOSTRUCTURE calculation. Schippers et al. (2001) used the same factor of 0.8 to achieve agreement between the AUTOSTRUCTURE calculation and their experimental C IV data. From a theoretical point of view, the approximations inherent in AUTOSTRUCTURE (independent processes, isolated resonances and distorted wave) become more accurate at higher charge states for astrophysically important ions. For Cu^{26+} (Kilgus et al. 1992) the AUTOSTRUCTURE calculation agrees well with the experiment for the $2\mathrm{p}_{1/2}$ series and is 10–20% too large for the $2\mathrm{p}_{3/2}$ series.

The O VI plasma rate coefficient has been derived by convoluting the extrapolated experimental DR cross section $\sigma(\hat{E})$ with an isotropic Maxwellian electron energy distribution yielding

$$\alpha(T_\mathrm{e}) = (k_\mathrm{B}T_\mathrm{e})^{-3/2}\frac{4}{\sqrt{2m_\mathrm{e}\pi}} \times \int_0^\infty \mathrm{d}\hat{E}\,\sigma\left(\hat{E}\right)\hat{E}\exp\left(-\hat{E}/k_\mathrm{B}T_\mathrm{e}\right) \tag{3}$$

with the plasma electron temperature T_e, the electron rest mass m_e, and Boltzmann's constant k_B. This procedure is applicable as long as the relative energy $\hat{E}$ is larger than the experimental energy spread , i.e., for $T_\mathrm{e} \gg 40$ K in the present case.

The experimentally derived DR rate coefficients with (thick black line) and without (thick grey line) the extrapolation are shown in Fig. 2a. Above 20 000 K the rate coefficient is significantly influenced by the contributions of high Rydberg states $n > 19$ restored by the extrapolation.

Table 1. The fit parameters of the experimentally inferred O VI $\Delta n = 0$ rate coefficient using Eq. (4) are listed. Units are $\mathrm{cm^3 s^{-1} K^{1.5}}$ for c_i, and eV for E_i. The systematic error of the rate coefficient $\alpha(T_\mathrm{e})$ from Eq. (4) is ±11%.

i	c_i	E_i
1....	3.21E–3	11.92
2....	1.15E–3	11.98
3....	4.2E–4	8.96
4....	8E–5	4.178
5....	6E–5	2.28
6....	2.89E–6	1.84
7....	7.03E–7	3.5

A convenient representation of the plasma DR rate coefficient is provided by the following fit formula

$$\alpha(T_\mathrm{e}) = T_\mathrm{e}^{-3/2}\sum_i c_i \exp\left(-E_i/k_\mathrm{B}T_\mathrm{e}\right). \tag{4}$$

It has the same functional dependence on the plasma electron temperature as the Burgess (1965) formula, where the coefficients c_i and E_i are related to oscillator strengths and excitation energies, respectively. The results for the fit to the experimental O VI $\Delta n = 0$ DR rate coefficient in a plasma are summarized in Table 1. The fit deviates from the thick full line in Fig. 2 by no more than 0.2% for $T_\mathrm{e} \geq 7500$ K and by no more than 4% for $3000 \text{ K} \leq T_\mathrm{e} < 7500$ K. Below 3000 K the DR rate coefficient decreases to zero and radiative recombination dominates the recombination rate coefficient.

4. Comparison with theoretical results

Our experimental O VI DR plasma rate coefficient is compared to theoretical results in Figs. 2, 3.

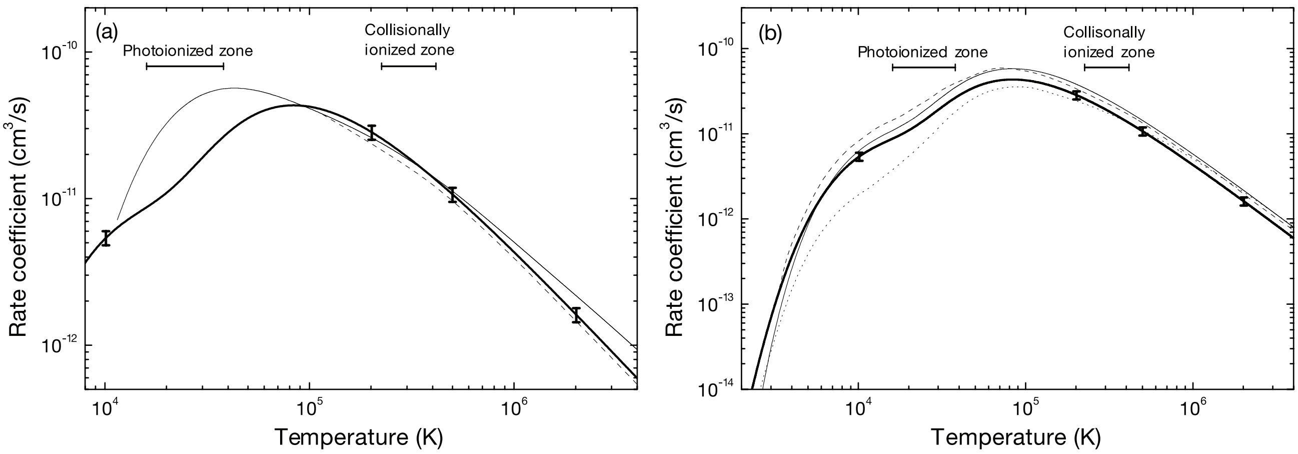

Fig. 3. The experimental O VI $\Delta n = 0$ DR rate coefficient in a plasma (thick full line, systematic uncertainty ±11%) is shown. **a)** The relativistic calculations of Chen (1991) (dashed line) and data of Mazzotta et al. (1998) (thin solid line) obtained by a fit to the work of Chen (1991) are compared to the experiment. **b)** The calculations of Krylstedt et al. (1990) (dashed line), Romanik (1988) (thin solid line), and Roszman (1989) (dotted line) cover the entire range of the experimental data.

In Fig. 2a the data of Nussbaumer & Storey (1983) reproduces the experimental result very well for low energies but strongly deviates above 19 500 K because only low lying resonance states were included in the calculation. Arnaud & Rothenflug (1985) combined the calculations of Nussbaumer & Storey (1983) and data presented by Shull & van Steenberg (1982). The combined data matches the experiment very well over the entire range of validity and is no more than 15% larger than the experimental data. This deviation is almost within the experimental uncertainty.

The other calculations (Fig. 2b) are only valid for temperatures above ≈26 500 K. The Burgess (1965) general formula (GFI) overestimates the rate coefficient by ≈60%. The data of Shull & van Steenberg (1982) is based on results of Jacobs et al. (1978) and is within the experimental uncertainty above $\approx 10^5$ K. McLaughlin & Hahn (1984) calculated the DR rate coefficient for temperatures above 6.5×10^5 K. At 4×10^6 K it underestimates the experimentally derived rate coefficient by ≈35%. The results of Aldrovandi & Péquignot (1973) have been calculated using the GFI including $\Delta n \neq 0$ DR which is the reason for the additional difference between theory and experiment above 2×10^5 K.

Relativistic intermediate coupling calculations have been carried out by Chen (1991) for temperatures beyond 10^5 K. The result is shown in Fig. 3a. It can almost not be distinguished from the data of this work. The data of Mazzotta et al. (1998) are based on Chen's calculations and are also included in Fig. 3. For temperatures between 11 600 and 85 000 K the data of Mazzotta et al. does not match the experimental data.

Theoretical rate coefficients which are close to the experimental data over the entire temperature range are shown in Fig. 3b. Above 2×10^6 K they are all ≈50% above the experiment. In the case of Romanik (1988) and Roszman (1989) this is due to the fact, that they additionally included $\Delta n \neq 0$ DR.

The theoretical results of Nussbaumer & Storey (1983), Krylstedt et al. (1990), Romanik (1988), and the DR rate coefficient recommended by Arnaud & Rothenflug (1985), show a very good agreement with the experimental data at low temperatures. For other ions, e. g. C IV (Schippers et al. 2001) no standard theory was found to match the experiment at low temperatures. In the case of O VI the first DR resonances are at ≈2 eV whereas for C IV the first resonances are at ≈0.1 eV. These resonances at low energies are far more difficult to describe theoretically. It has been shown by Mannervik et al. (1998) that even for the low charged C IV only a fully relativistic many body perturbation treatment reproduces the experimental results. More recent calculations along these lines have been carried out by Tokman et al. (2002) for F VII. This suggests that calculations using pure LS-coupling are not appropriate for the description of the recombination process. Generally a reliable theoretical treatment of DR should be based at least on Multiconfiguration Breit-Pauli or Multiconfiguration Dirac-Fock calculations (Savin et al. 2002b). At energies below 2 eV, however, more detailed theoretical treatment e.g. by many–body perturbation theory (MBPT) becomes necessary.

The maximum abundance of O VI is calculated to occur at $\approx 3 \times 10^5$ K by Mazzotta et al. (1998) for electron ionized plasmas. Most of the theories reproduce the experimental result very well in that temperature range. From the data of Aldrovandi & Péquignot (1973) (Fig. 2b) we conclude that $\Delta n \neq 0$ DR has to be taken into account in that temperature range.

For photoionized plasmas Kallman & Bautista (2001) calculated the maximum abundance of O VI to occur at ≈25 000 K. In that temperature range the data compiled by Arnaud & Rothenflug (1985) reproduces the experiment almost within the experimental uncertainty.

4.1. *Total recombination rate coefficient*

A unified treatment of total recombination including DR and radiative recombination (RR) has been performed by Nahar (1999). Such a calculation in principle also accounts for interference between RR and DR. In order to compare these data to our experiment (see Fig. 4) we have added the RR rate coefficient as obtained by Péquignot et al. (1991) to our experimental

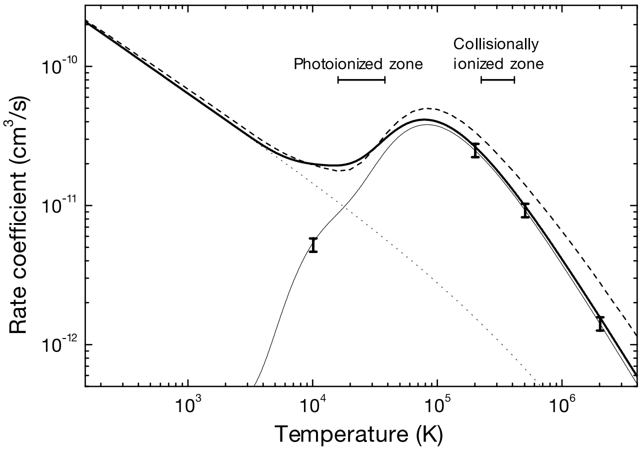

Fig. 4. Total O VI recombination rate coefficients in a plasma: this work (thick full line, systematic error ±11%) and theoretical unified calculation of Nahar (1999) (dashed line). Our total recombination rate coefficient is obtained as the sum of the RR rate coefficient of Péquignot et al. (1991, dotted line) and our DR rate coefficient (thin full line). Nahar's data includes $\Delta n \neq 0$ transitions.

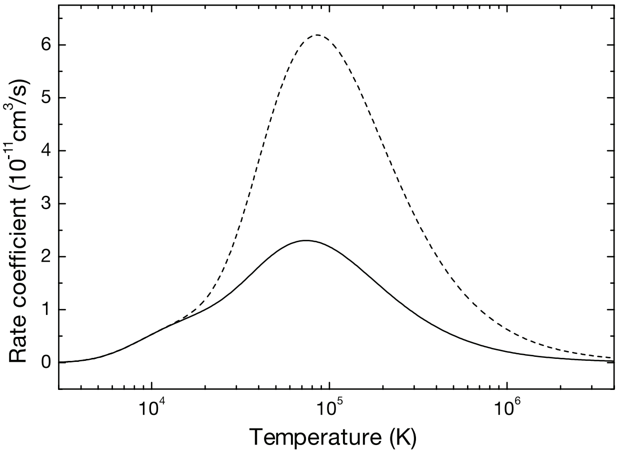

Fig. 5. The solid line shows the plasma rate coefficient for the case of zero electric field as obtained in the experiment including the extrapolation to high *n*. The dashed curve shows the plasma rate coefficient as obtained by a model calculation (Böhm et al. 2002) including maximum mixing of the *l* substates by an external electric field.

DR rate coefficient. Experiment and theory do not deviate more than 10% from each other below $\approx 5 \times 10^4$ K. This suggests that similarly to DR of C IV ions (Schippers et al. 2001) interference effects do not play a significant role in the recombination of O VI ions, either. The calculation of Nahar (1999) includes $\Delta n \neq 0$ transitions which is the reason for the difference between theory and experiment at high temperatures.

5. Field effects

The DR rate coefficient can be strongly influenced by the presence of electromagnetic fields. On the one hand electric fields ionize electrons in high Rydberg states which reduces the recombination rate coefficient. On the other hand electric fields mix *l*-substates and thus increase the recombination rate coefficient (Jacobs et al. 1976). This is demonstrated in Fig. 5 where field-free and full-mixing results are compared to one another. The thick full line shows the zero field plasma rate coefficient as obtained in the experiment including the extrapolation to high *n*. The dashed curve shows the plasma rate coefficient as obtained by a model calculation (Böhm et al. 2002) that includes maximum mixing of the *l* substates by an external electric field but does not include any magnetic fields. The predicted enhancement sets in at $\approx 10^4$ K and reaches its maximum at $\approx 10^5$ K where the field enhanced rate coefficient obtained by the model calculation is a factor of ≈ 3 higher than the experimentally derived zero-field rate coefficient.

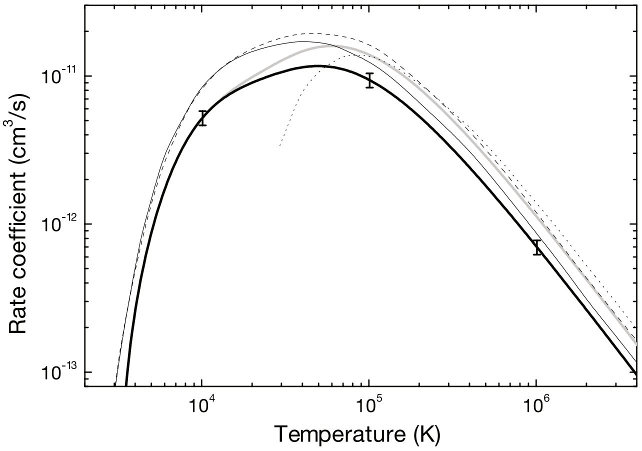

Fig. 6. Experimental DR plasma rate coefficient (ion energy of 9.4 MeV/u; including Rydberg states up to $n_c = 19$) for the field free case (black thick line) and in the presence of an electric field of 340 V/cm (grey thick line). The theoretical calculation of Krylstedt et al. (1990) included Rydberg states up to $n = 20$ once for the field free case (black thin line) and for the presence of an electric field (dashed line). The result obtained by the generalized Burgess formula GFII (see text) including electric field effects is also shown (dotted line).

In our experimental setup there is always an additional magnetic field perpendicular to the electric field in the interaction region which further influences the recombination rate coefficient but has not been considered in the theoretical investigations discussed below (Robicheaux & Pindzola 1997; Bartsch et al. 1999).

External electric fields have been included in the calculations of Krylstedt et al. (1990) (Fig. 6). Their result is shown for the field free case (thin solid line) and for maximum field enhancement (thin dashed line). In the calculation $1s^2 2p\,nl$ Rydberg states only up to $n_{\max} = 20$ have been included. This almost coincides with our experimental field ionization cut-off (Sect. 2). Therefore the data of Krylstedt et al. can directly be compared with our corresponding experimental results. The largest discrepancy of the zero field results is at around 3×10^4 K where the theoretical recombination rate coefficient is $\approx 50\%$ larger than the experimental one. However, it has to be pointed out, that a quantitative comparison can only be made for the zero field case where the magnetic field (≈ 100 mT) parallel to the electron and ion beams does not alter the recombination rate coefficient. This changes as electric fields perpendicular to the magnetic field are applied. Now the magnetic field significantly alters the recombination rate coefficient. Since the calculation of Krylstedt et al. (1990) does not include a magnetic field the comparison in this case is only qualitative. Inclusion of the magnetic field significantly complicates the calculations and available theories are still far off the experiment (Böhm et al. 2002). Field effects are also included in the Burgess general formula II (GFII, dotted line, Fig. 6) which is given in Krylstedt et al. (1990) for $n_{\max} = 20$. For temperatures $T \geq 5 \times 10^5$ K the experimental rate coefficient in a plasma in the presence of an electric field $E_\perp = 340$ V/cm and a magnetic field $B_\parallel = 100$ mT for DR including Rydberg states up to $n = 19$ is enhanced by about a factor of 1.8.

The present study of field effects on DR is relevant to low density plasmas subject to large external fields e.g. solar flares. The other major concern of the role of fields on DR in plasmas is that of the intrinsic plasma microfield. Here the effect is density dependent; at high plasma densities enhancement due to field mixing is reduced by continuum lowering i.e. by collisions driving high-*n* states into local thermal equilibrium (LTE). Such conditions suppress the high-*n* states, that would otherwise contribute to enhanced DR (see Badnell et al. 1993).

6. Conclusions

The recombination rate coefficient of O VI has been measured for $n < 20$ and plasma rate coefficients were obtained from the data. For higher *n* ($20 < n < 1000$) an extrapolation was obtained by scaling an AUTOSTRUCTURE calculation to the experiment for $n < 20$. The results were compared to theoretical plasma rate coefficients. The data of Krylstedt et al. (1990) and Romanik (1988) are not too far off from our experimental data over the whole temperature range. The discrepancies at low temperatures for these two calculations are below 70%. At high temperatures discrepancies of ≈50% can be ascribed to the inclusion of $\Delta n \neq 0$ DR in the data of Romanik (1988) and Roszman (1989), while the present work only considers $\Delta n = 0$ DR.

The influence of electric and magnetic fields on DR has been investigated experimentally for $n \leq 20$ and a significant enhancement was observed. A direct comparison with existing theoretical data is not possible because the theory does not include the magnetic field which was present in the experiment. Extrapolations of the DRF results to $n > 20$ by a model calculation yields total DR rate coefficient enhancement factors of up to 3 for maximum mixing of the *l* substates by an external electric field. In the experiment (Böhm et al. 2002) the enhancement saturated for electric fields above 500 V/cm.

Our results bear important implications for the modelling of cosmic plasmas where external fields are ubiquitous (Widrow 2002). In solar flares, e.g., electric fields up to 1.3 kV/cm have been observed (Zhang & Smartt 1986).

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