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# Experimental N V and Ne VIII low-temperature dielectronic recombination rate coefficients

S. Böhm[1], A. Müller[1], S. Schippers[1], W. Shi[1], M. Fogle[2,⋆], P. Glans[2], R. Schuch[2], and H. Danared[3]

[1] Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Giessen, Leihgesterner Weg 217, 35392 Giessen, Germany
e-mail: Sebastian.G.Boehm@physik.uni-giessen.de
[2] Atomic physics, Fysikum, Stockholm University, AlbaNova, 10691 Stockholm, Sweden
[3] Manne Siegbahn Laboratory, 10405 Stockholm, Sweden

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**Abstract.** The dielectronic recombination rate coefficients of N V and Ne VIII ions have been measured at a heavy-ion storage ring. The investigated energy ranges covered all dielectronic recombination resonances attached to 2s → 2p ($\Delta n = 0$) core excitations. The rate coefficients in a plasma were derived and parameterized by using a convenient fit formula. The experimentally derived rate coefficients were then compared to theoretical data. In addition the influence of external electric fields with field strengths up to 1300 V/cm on the dielectronic recombination rate coefficient was investigated.

**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 obtained from astrophysical observations (Ferland 2003). In order to be able to infer a reliable description of the plasma properties, such as element abundances and temperatures, 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 modelling stem from theoretical calculations. A recent compilation of DR data for dynamic finite density plasmas can be found in the Atomic Data and Analysis Structure Database (ADAS) which can be accessed under http://www-cfadc.phys.ornl.gov/data_and_codes (Badnell et al. 2003). The resolution and precision of this data is tuned to spectral analysis and are sufficient to predict the DR contributions to individual spectral line emissivities. Calculating DR-rate coefficients is a challenging task since an infinite number of states is involved in this process. Approximations and computational simplifications are applied in order to make DR calculations tractable; hence, experimental benchmarks are required for testing and improving the theoretical methods. Here we present experimentally derived N V and Ne VIII DR-rate coefficients.

⋆ *Present Address*: Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6372.

In the storage ring measurements the ensembles of colliding particles have a well-defined average relative velocity. As a consequence, high resolution is obtained in the whole range of accessible energies such that, cross sections can be measured in great detail. In contrast to that, convolution of the measured data with the plasma temperature leads to broad smooth dependences of plasma rate coefficients $\alpha(T)$, where most details in the cross sections are washed out. Nevertheless, the details of the cross sections at low energies have a strong influence on the size of the plasma rate coefficient at low temperatures. It is difficult to predict such low-lying DR resonances with sufficient accuracy by theoretical calculations. An example has been given recently by Schippers et al. (2004) who studied DR of berylliumlike Mg IX. This ion exhibits strong DR resonances at electron-ion collision energies below 100 meV. All theoretical calculations show good agreement with experiment at high temperatures, but show significant discrepancies at low temperatures.

Low-energy DR of lithiumlike ions can be represented as

$$\begin{aligned} e^- \; + \; A^{q+}\left(1s^2 2s\right) &\rightarrow A^{(q-1)+}\left(1s^2 2p\, nl\right) \\ &\rightarrow \begin{cases} A^{(q-1)+}\left(1s^2 2s\, nl\right) + h\nu & \text{(type I)} \\ A^{(q-1)+}\left(1s^2 2p\, n'l'\right) + h\nu' & \text{(type II).} \end{cases} \end{aligned} \tag{1}$$

The 2s → 2p ($\Delta n = 0$) excitation energy is ≈10 eV for $N^{4+}$ and ≈16 eV for $Ne^{7+}$, respectively. DR resonances that are associated with higher excitations such as 2s → 3$l$ ($\Delta n = 1$) that occur at higher energies have not been measured.

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 and thereby changes the autoionization rates that are relevant for the DR process. The resulting enhancement of the DR cross section was verified experimentally for the first time by Müller et al. (1986, 1987). DRF experiments providing evidence for the influence of additional magnetic fields as predicted by Robicheaux & Pindzola (1997) were carried out by Bartsch et al. (1999, 2000) and Böhm et al. (2001).

The present paper is organized as follows. The experimental procedure is outlined in Sect. 2. In Sect. 3 the experimental results are presented and compared to theoretical results in Sect. 4. The influence of electromagnetic fields on the DR-rate coefficient is discussed in Sect. 5, and summary provided in Sect. 6

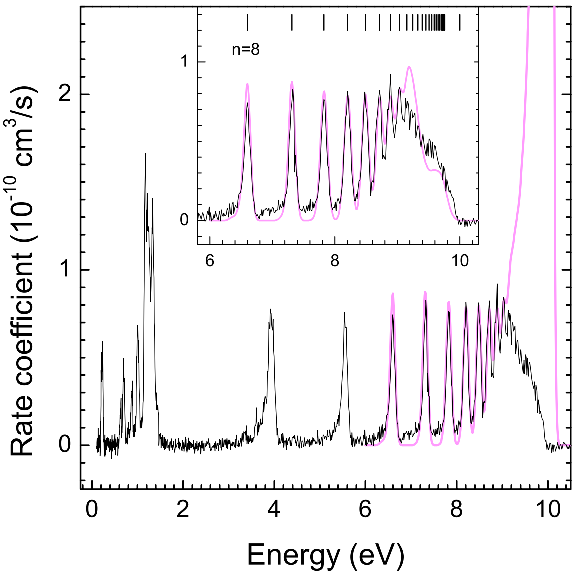


**Fig. 1.** Experimental zero-field $N^{4+}$ DR spectrum for an ion energy of 7.5 MeV/u (thin solid line). The resonances are due to the excitation of $1s^22p\,nl$ intermediate states with $n \geq 5$. The thick line beginning at 6 eV ($n \geq 8$) shows the extrapolation function obtained by adjusting an AUTOSTRUCTURE calculation to the experimental high-$n$ spectrum. It includes Rydberg states up to $n = 1000$. The inset shows the high energy part of the experimental spectrum together with the extrapolation function to which the field ionization model of Schippers et al. (2001) has been applied.

## 2. Experiment

The N V and Ne VIII DR experiments were carried out at the heavy-ion storage-ring CRYRING of the Manne Siegbahn Laboratory in Stockholm. The $^{14}N^{4+}$ and $^{20}Ne^{7+}$ 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 a few 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 (Zong et al. 1998). The experimental center of mass energy range of $0 < \hat{E} < 11$ eV for $^{14}N^{4+}$ and $0 < \hat{E} < 20$ eV for $^{20}Ne^{7+}$, respectively, covered all DR resonances due to $2s \rightarrow 2p$ ($\Delta n = 0$) excitations. The recombined ions were detected with 100% efficiency behind the first dipole magnet following the cooler.

On their way to the detector the recombined ions had to pass strong magnetic fields. The largest field was that of the charge-state analyzing bending dipole magnet. These magnetic fields were perpendicular to the ions' flight direction and caused motional electric fields (on 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 need particular consideration. Recombined ions that reached a zone of large motional electric fields while 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 N V spectrum is compared with two different calculations, one including basically all Rydberg states that contribute to the DR cross section and one where the field-ionization cut-off caused by the experimental conditions has been modeled. The straight field ionization cut-off quantum-number resulting from the simple over-the-barrier treatment is $n_c \approx 17$. The detailed field ionization model (Müller et al. 1987; Schippers et al. 2001) accounts for the radiative decay of electrons in high Rydberg states on their way from the cooler to the different field ionization zones. The model uses hydrogenic decay probabilities and field ionization rates in a hydrogenic approach for all the individual Stark states developing in the external fields. Compared with a simple step function at $n_c = 17$ the model provides a realistic survival pattern of DR contributions from a band of Rydberg states around $n_c$. From the good agreement of the model calculations with the experiment (insets of Figs. 1 and 2) we conclude that field ionization has been 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 of the cooler for field corrections. The solenoid produced the longitudinal field $B_{\parallel}$ 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 those motional electric fields $F$ that 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).

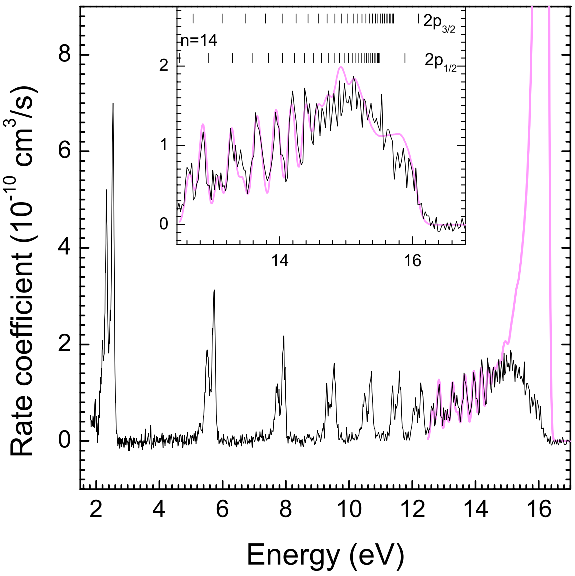


**Fig. 2.** Experimental zero-field $Ne^{7+}$ DR spectrum for an ion energy of 11.4 MeV/u (thin solid line). The resonances are due to the excitation of $1s^22p\,nl$ intermediate states with $n \geq 7$. The thick line beginning at 12.45 eV ($n \geq 14$) shows the extrapolation function obtained by adjusting an AUTOSTRUCTURE calculation to the experimental high-$n$ spectrum. It includes Rydberg states up to $n = 1000$. The inset shows the high energy part of the experimental spectrum together with the extrapolation to which the field ionization model of Schippers et al. (2001) has been applied.

The main uncertainties of the measured rate coefficient arise from measurement of the ion current with a current transformer (≈10%) and the uncertainty of the interaction length (≈5%). All uncertainties add up to ±15% uncertainty of the absolute rate coefficients obtained with the narrow electron energy distribution of the storage-ring experiment.

## 3. Results

Our experimental N V and Ne VIII DR-rate coefficients $\alpha(\hat{E})$ are displayed in Figs. 1 and 2, respectively. They contain all $1s^22p\,nl$ resonances associated with $2s \to 2p$ transitions up to $n \approx n_c$ ($n_c \approx 17$ for N V and $n_c \approx 28$ for Ne VIII). For the lowest $n$, even the $l$ substates are partially resolved. Background subtraction (here radiative recombination is regarded as background) was achieved by fitting an empirical formula to those parts of the measured spectra where no DR resonances occurred (Eq. (2) in Böhm et al. 2003b).

For derivation of a meaningful plasma rate coefficient from our experimental data we had to estimate how much DR strength was not observable in the experiment due to the field ionization cut-off discussed above. Following the procedure described by Schippers et al. (2001) we had extrapolated the measured DR spectrum to high-$n$ Rydberg states. We took advantage of the fact that for these high Rydberg states, which are to be restored by the extrapolation, simple scaling laws can be used to calculate the DR cross section. The AUTOSTRUCTURE code (Badnell 1986) is a convenient tool to make such an extrapolation. The AUTOSTRUCTURE extrapolation function, including Rydberg states up to $n = 1000$ (states with $n > 1000$ do not contribute significantly anymore), is matched to the high-$n$ Rydberg region of the experimental spectrum by applying a constant energy shift of 0.05 eV towards higher energies and a scaling factor of 1.15 to the calculated DR cross section for N V. The resulting function that is based on the AUTOSTRUCTURE calculation and used for extrapolating the experimental rate coefficients is shown in Fig. 1 from the region just above $n = 8$ to the high-$n$ Rydberg contributions together with the experimental data. We do not intend to compare theory to experiment in this context but will do so later in this paper in connection with the discussion of plasma rate coefficients. For Ne VIII the experiment and extrapolation function could be matched for $n \geq 14$ by applying a correction factor of 1.63 to the radiative rate of the inner shell transitions $2p_j \to 2s_{1/2}$ and an energy shift of 0.04 eV towards higher energies. Again, this manipulation does not imply an attempt to correct the AUTOSTRUCTURE calculation, but instead is just meant as a way to adjust a meaningful function to the experimental data. This function is then used for the required extrapolation and the result obtained for the extrapolation function is shown in Fig. 2. While the measured rate coefficients have an uncertainty of ±15%, the possible error of the extrapolated cross sections is difficult to quantify. We estimate an uncertainty of 25% for the combined error of the resulting plasma rate coefficients.

Plasma rate coefficients were derived by convoluting the experimental DR cross section $\sigma(\hat{E}) = \alpha(\hat{E}) \times \sqrt{m_e/2\hat{E}}$ including the high-$n$ extrapolation with a Maxwellian electron energy distribution yielding

$$\alpha(T_e) = (k_B T_e)^{-3/2} \frac{4}{\sqrt{2 m_e \pi}} \times \int_0^\infty d\hat{E}\, \sigma(\hat{E}) \hat{E} \exp\left(-\hat{E}/k_B T_e\right) \quad (2)$$

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 relative energy $\hat{E}$ is larger than the experimental energy spread, i.e., for $T_e \gg 70$ 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. 3 for N V and in Fig. 4 for Ne VIII. Above ≈20 000 K the rate coefficient for N V and Ne VIII is significantly influenced by the contributions of high Rydberg states $n > 17$ and $n > 28$, respectively, restored by the extrapolation.

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

$$\alpha(T_e) = T_e^{-3/2} \sum_i c_i \exp\left(-E_i/k_B T_e\right). \quad (3)$$

It has the same functional dependence on the plasma electron temperature as the Burgess (1965) formula, where coefficients $c_i$ and $E_i$ are related to oscillator strengths and excitation energies, respectively. The results for the fit to the experimental N V $\Delta n = 0$ DR-rate coefficient in a plasma are summarized in Table 1. The fit deviates from the thick full line in Fig. 3 by no more than 0.2% for $T_e \geq 5000$ K and by no more than 1% for 2500 K $\leq T_e <$ 5000 K. Below 2500 K the DR-rate coefficient

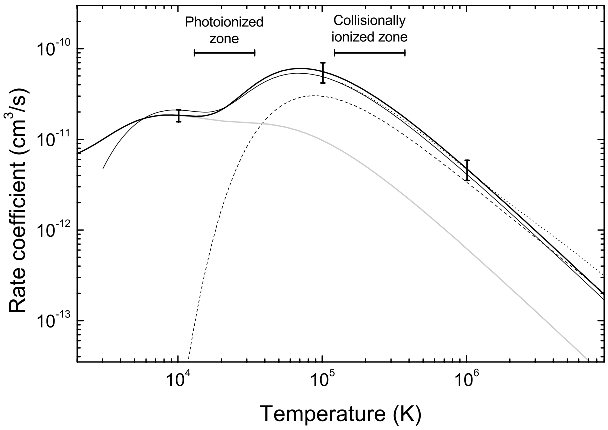


**Fig. 3.** The experimental N V $\Delta n = 0$ DR-rate coefficient in a plasma shown (thick solid line) with a systematic uncertainty of ±15% below 20 000 K and ±25% above. The thick grey line represents our measured rate coefficient without the AUTOSTRUCTURE extrapolation (see text). The theoretical rate coefficient as calculated by Colgan et al. (2004) is shown for $\Delta n = 0$ DR alone (thin solid line) and with inclusion of $\Delta n = 1$ DR (dotted line). Also included is the theoretical rate coefficient of Mazzotta et al. (1998, dashed line).

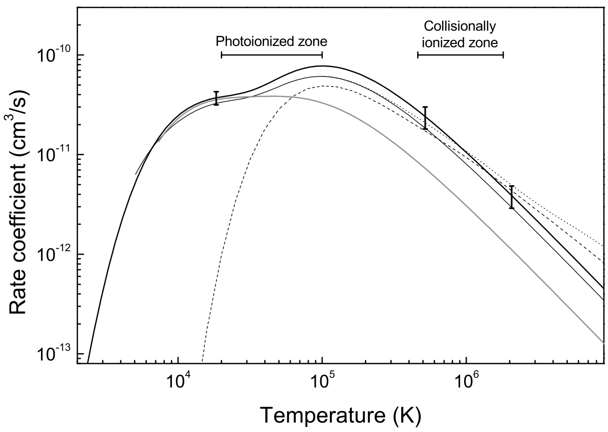


**Fig. 4.** The experimental Ne VIII $\Delta n = 0$ DR-rate coefficient in a plasma shown (thick solid line) with a systematic uncertainty of ±15% below 40 000 K and ±25% above. The thick grey line represents our measured rate coefficient without the AUTOSTRUCTURE extrapolation (see text). The theoretical rate coefficient as calculated by Colgan et al. (2004) is shown for $\Delta n = 0$ DR alone (thin solid line) and with inclusion of $\Delta n = 1$ DR (dotted line). Also included is the theory-based rate coefficient inferred by Mazzotta et al. (1998, dashed line).

decreases rapidly, and radiative recombination dominates the recombination rate coefficient. The result for Ne VIII is given in Table 2. The fit deviates from the thick full line in Fig. 4 by no more than 0.3% for $T_e \geq 11\,000$ K and by no more than 2% for 3000 K $\leq T_e < 11\,000$ K.

## 4. Comparison with theoretical results

### 4.1. N V

Our experimental N V DR plasma rate coefficient is compared to theoretical results in Fig. 3. The theoretical calculation of Colgan et al. (2004) reproduces the experimental result very

**Table 1.** Fit parameters of the experimentally inferred N V $\Delta n = 0$ DR-rate coefficient using Eq. (3). Units are cm$^3$ s$^{-1}$ K$^{1.5}$ for $c_i$ and eV for $E_i$. The systematic error of the rate coefficient $\alpha(T_e)$ from Eq. (3) is ±15%.

| $i$ | $c_i$ | $E_i$ |
|---|---|---|
| 1.... | 2.410E−3 | 9.907 |
| 2.... | 1.710E−3 | 9.734 |
| 3.... | 2.835E−4 | 11.11 |
| 4.... | 7.197E−4 | 9.287 |
| 5.... | 1.356E−4 | 4.712 |
| 6.... | 6.171E−5 | 1.180 |
| 7.... | 2.945E−6 | 0.2815 |

**Table 2.** Fit parameters of the experimentally inferred Ne VIII $\Delta n = 0$ DR-rate coefficient using Eq. (3). Units are cm$^3$ s$^{-1}$ K$^{1.5}$ for $c_i$ and eV for $E_i$. The systematic error of the rate coefficient $\alpha(T_e)$ from Eq. (3) is ±15%.

| $i$ | $c_i$ | $E_i$ |
|---|---|---|
| 1.... | 5.992E−3 | 16.41 |
| 2.... | 5.492E−3 | 14.68 |
| 3.... | 6.338E−4 | 6.714 |
| 4.... | 3.394E−4 | 2.354 |
| 5.... | 8.214E−6 | 1.601 |
| 6.... | 7.205E−6 | 1.584 |
| 7.... | 2.122E−6 | 82.86 |

well down to about 5000 K, well below the temperature range where N V is expected to form in photoionized or in a collisionally ionized plasma. These temperature ranges are also indicated in Fig. 3. They were estimated from the model calculations of Kallman & Bautista (2001) as described by Schippers et al. (2004). Also included is the result of Colgan et al. (2004) obtained with the inclusion of $\Delta n = 1$ DR, which gives a significant contribution above 50 000 K.

Mazzotta et al. (1998) compiled DR-rate coefficients and condensed this compilation into a set of recommended DR-rate coefficients. For the lithiumlike ions they adopted the DR calculations of Chen (1991), who calculated total DR-rate coefficients for 11 ions (carbon, oxygen, neon, ..., xenon). For the remaining ions, such as N V, Mazzotta et al. (1998) interpolated along the iso-electronic sequence. This result is also included in Fig. 3, and is close to the experimental result above $2\times10^5$ K. However, it has to be pointed out that Mazzotta et al. (1998) included $\Delta n \geq 1$ DR, which has not been measured in the present experiment. At lower temperatures the plasma rate coefficient of Mazzotta et al. (1998) deviates strongly from the present experimental result. The deviation can almost be removed by excluding the $n = 5$ DR resonance from the experimental data as can be seen in Fig. 5. This leads us to the conclusion that the result of Mazzotta et al. (1998) misses including the $n = 5$ DR resonance located between ≈0−1.5 eV. The interpolation along isoelectronic sequences seems to give sufficiently good results at high temperatures but can deviate by orders of magnitude at low temperatures due to the uncertainty in the inclusion

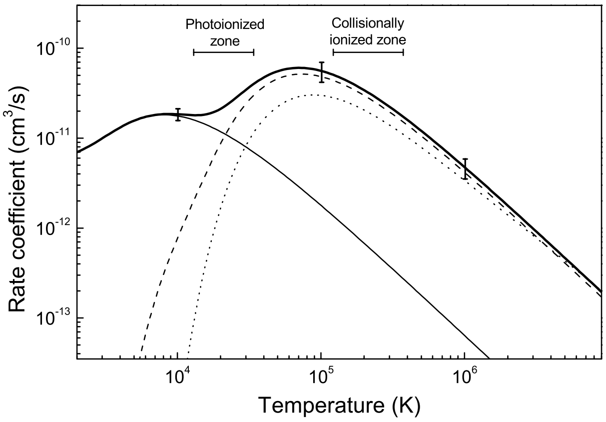


**Fig. 5.** The experimental N V $\Delta n = 0$ DR-rate coefficient in a plasma (thick solid line) shown (including the AUTOSTRUCTURE extrapolation) with a systematic uncertainty of ±15% below 20 000 K and ±25% above. The thin solid line shows our measured rate coefficient for the $n = 5$ DR resonance only. The dashed line shows our measured rate coefficient excluding the $n = 5$ DR resonance. Also included is the theoretical rate coefficient of Mazzotta et al. (1998, dotted line).

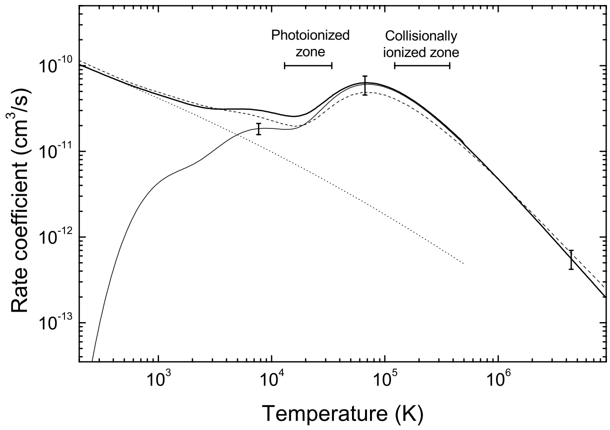


**Fig. 6.** Total N V recombination rate coefficients in a plasma: this work (thick full line, systematic error ±15% below 20 000 K and ±25% above) and theoretical unified calculation of Nahar & Pradhan (1997, dashed line). Our total recombination rate coefficient is obtained as the sum of the RR rate coefficient of Péquignot et al. (1991, dotted line) and our DR-rate coefficient (thin full line).

of the lowest-energy resonance contributions. The positions of resonances at small energies strongly influence the plasma rate coefficients at low temperatures.

### 4.2. Ne VIII

The experimental Ne VIII plasma rate coefficient is compared with theoretical results in Fig. 4. The data of Colgan et al. (2004) reproduces the experimental result very well over the entire relevant temperature range. Also shown in Fig. 4 is the result of Colgan et al. (2004) including $\Delta n = 1$ DR, which gives a significant contribution above 300 000 K. The recommended rate coefficient of Mazzotta et al. (1998) reproduces the experimental data well beyond $10^5$ K. Above $1.2 \times 10^6$ K the result of Mazzotta et al. (1998) is above the experimental result. This is due to the fact that they included $\Delta n \geq 1$ DR, which has not been measured in the present experiment. At temperatures where Ne VIII is expected to form in photoionized plasmas, the recommendation of Mazzotta et al. (1998) deviates from the experimental result by orders of magnitude. A plausible reason for this is again in the sensitivity of low-temperature plasma rate coefficients to the exact resonance positions at low electron-ion energies.

### 4.3. Total recombination rate coefficient

A unified treatment of total recombination, including DR and radiative recombination (RR), has been performed by Nahar & Pradhan (1997). Such a calculation also accounts for interference between RR and DR. In order to compare these data with our experiment (see Fig. 6), we added the theoretical RR rate coefficient by Péquignot et al. (1991) to our experimental DR-rate coefficient. The maximum deviation of theory from experiment is less than 30%. It is found at temperatures near $2 \times 10^4$ K emphasizing again the crucial role of exact resonance positions at low energies. The calculation of

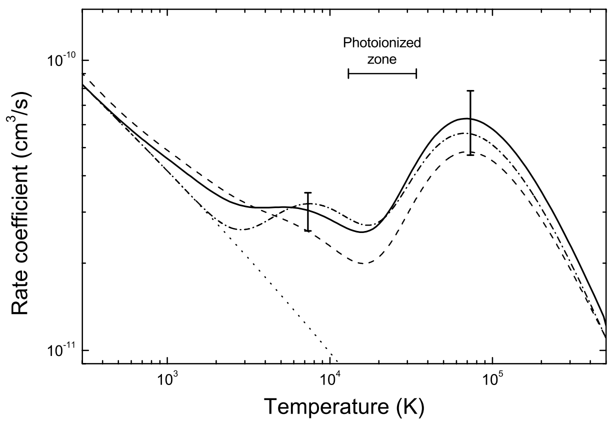


**Fig. 7.** Total N V recombination rate coefficients in a plasma: this work (thick full line, systematic error ±15% below 20 000 K and ±25% above), the calculation by Colgan et al. (2004) (dash-dotted line), and the unified theoretical calculation of Nahar & Pradhan (1997, dashed line). The total recombination rate coefficients based on the experiment and on the Colgan et al. (2004) calculation are obtained by just adding the RR rate coefficient as obtained by Péquignot et al. (1991, dotted line) to the DR data displayed in the previous figures.

Nahar & Pradhan (1997) includes $\Delta n \geq 1$ transitions, which is the reason for the slight difference between theory and experiment at high temperatures.

Figure 7 shows an enlarged part of the plasma rate coefficient for N V. In addition to the data presented in Fig. 6, the calculation of Colgan et al. (2004) is now included with the RR rate coefficient by Péquignot et al. (1991) added to it. The agreement with the experiment is well inside the experimental uncertainty, although this calculation does not include any interference effects at all. This finding, together with the observed agreement between the different theoretical approaches, suggests that similar to DR of C IV ions (Schippers et al. 2001) and O VI ions (Böhm et al. 2003b) interference effects do not play a significant role in the recombination of N V ions, either.

## 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, electric fields mix $l$-substates and thereby increase the recombination rate coefficient (Jacobs et al. 1976).

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 (Robicheaux & Pindzola 1997; Bartsch et al. 1999) but has not been considered in the theoretical investigations addressing the ions discussed in this paper.

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 in connection with 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 the rate 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, which would otherwise contribute to enhanced DR (see Badnell et al. 1993). Generally, as the uncertainties in the basic atomic structure decrease, the error in neglecting field effects becomes more significant.

Ne VIII DR spectra are shown in Fig. 8 for the field-free case and for the case of an externally applied electric field of 1300 V/cm. In both cases the longitudinal magnetic guiding field was 180 mT. The large increase in the recombination rate coefficient for high Rydberg states is due to the electric field present in the interaction region that is perpendicular to the longitudinal magnetic guiding field and to the ions' direction of flight. The cut-off quantum number $n_c$ is the same for both spectra ($n_c = 28$), and the observed enhancement is a factor of 2. Unfortunately the number of Rydberg states that could be measured was limited by field ionization as described in Sect. 2. An extrapolation of the measured rate coefficient in the presence of electromagnetic fields is not possible at this time, since the most advanced calculations (Griffin et al. 1998a,b) reproduce the experimental result only qualitatively. For higher Rydberg states the enhancement due to electromagnetic fields in the interaction region grows, as has been shown by $n$-differential measurements (Böhm et al. 2002, 2003a). The enhancement of the DR-rate coefficient due to pure electric fields of Ne VIII has been calculated for individual Rydberg states from $n = 10$–$40$ (Griffin et al. 1998a). For an electric field of 100 V/cm the enhancement factor increases from $\approx 1$ at $n = 10$ to $\approx 5$ at $n = 40$, which shows that under certain circumstances it is essential to account for the effect of electromagnetic fields on the DR-rate coefficient. The experimental plasma-rate coefficient with and without fields for Ne VIII is shown in Fig. 9. Here the maximum enhancement compared to the field-free case is 60% at an electric field of $E = 1300$ V/cm and a magnetic field of $B = 180$ mT. The cut-off quantum number was $n_c = 28$. The measured enhancement of 60% is already well beyond the deviation of experiment and theoretical calculations as described above.

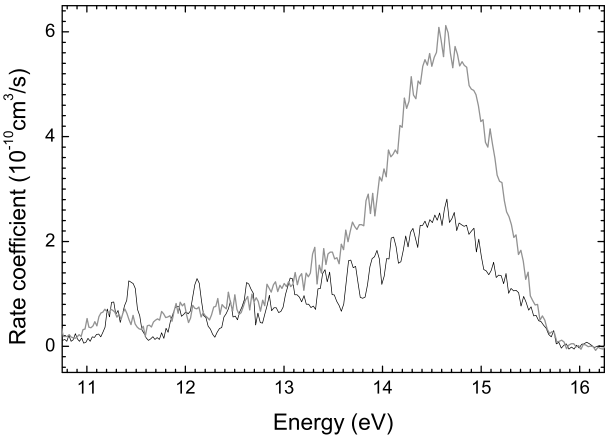


**Fig. 8.** Ne VIII DR spectra are shown for the field free case (black solid line) and for the case of an applied electric field of 1300 V/cm (thick grey line). The longitudinal guiding field was 180 mT in both cases.

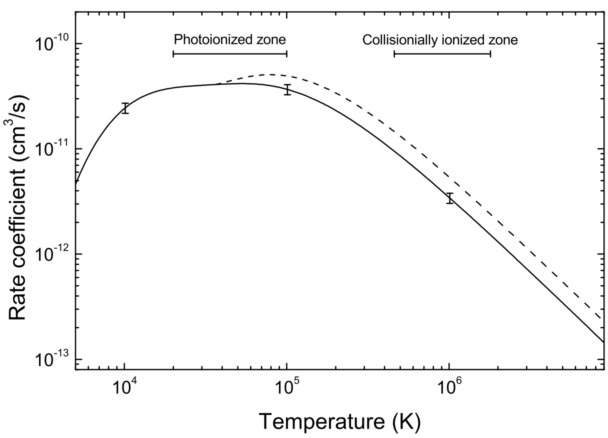


**Fig. 9.** Experimental Ne VIII DR plasma rate coefficient (ion energy of 11.4 MeV/u; including Rydberg states up to $n_c = 28$) for the field free case (solid line) and in the presence of an electric field of 1300 V/cm (dashed line).

## 6. Conclusions

The $\Delta n = 0$ DR-rate coefficients of N V and Ne VIII have been measured for $n < 17$ and $n < 28$, respectively. After extrapolation to $n = 1000$, $\Delta n = 0$ DR plasma rate coefficients were obtained from the data. The results were compared with theoretical plasma rate coefficients of Colgan et al. (2004) and Nahar & Pradhan (1997), as well as with the recommended rate coefficient by Mazzotta et al. (1998). The results of Colgan et al. reproduce the experimental results very well for both ions even at low temperatures. The data recommended by Mazzotta et al. do not reproduce the experimental results for temperatures below $10^6$ K. This is a consequence of the sensitivity of low-temperature plasma rate coefficients to the exact position of low energy resonances, which were not accessible to Mazzotta et al. (1998).

The deviation can almost be removed by excluding the $n = 5$ DR resonance from the experimental data. This leads us to the conclusion that the result of Mazzotta et al. (1998) misses the $n = 5$ DR resonance located between $\approx 0$–$1.5$ eV. The interpolation along isoelectronic sequences seems to give sufficiently good results at high temperatures but can deviate by orders of magnitude at low temperatures due to the uncertainty in the inclusion of the lowest-energy resonance contributions.

The influence of electric and magnetic fields on DR was investigated experimentally. A significant enhancement of the DR-rate coefficient was observed. A direct comparison with existing theoretical data is not possible because present-day theory does not include the magnetic field that was present in the experiments besides perpendicular electric field components.

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

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## References

Badnell, N. R. 1986, J. Phys. B, 19, 3827, http://amdpp.phys.strath.ac.uk/autos/
Badnell, N. R., O'Mullane, M. G., Summers, H. P., et al. 2003, A&A, 406, 1151
Badnell, N. R., Pindzola, M. S., Dickson, W. J., et al. 1993, ApJ, 407, L91
Bartsch, T., Schippers, S., Müller, A., et al. 1999, Phys. Rev. Lett., 82, 3779
Bartsch, T., Schippers, S., Beutelspacher, M., et al. 2000, J. Phys. B, 33, L453
Böhm, S., Schippers, S., Shi, W., et al. 2001, Phys. Rev. A, 64, 032707
Böhm, S., Schippers, S., Shi, W., et al. 2002, Phys. Rev. A, 65, 052728
Böhm, S., Danared, H., Djurić, N., et al. 2003a, Nucl. Instrum. Methods B, 205, 370
Böhm, S., Müller, A., Schippers, S., et al. 2003b, A&A, 405, 1157
Burgess, A. 1965, ApJ, 141, 1588
Burgess, A., & Summers, H. P. 1969, ApJ, 157, 1007
Chen, M. H. 1991, Phys. Rev. A, 44, 4215
Colgan, J., Pindzola, M. S., & Badnell, N. R. 2004, A&A, 417, 1183
Danared, H., Källberg, A., Andler, G., et al. 2000, Nucl. Instrum. Methods A, 441, 123
Ferland, G. J. 2003, ARA&A, 41, 517
Griffin, D. C., Mitnik, D., Pindzola, M. S., & Robicheaux, F. 1998a, Phys. Rev. A, 58, 4548
Griffin, D. C., Robicheaux, F., & Pindzola, M. S. 1998b, Phys. Rev. A, 57, 2708
Jacobs, V. L., & Davis, J. 1979, Phys. Rev. A, 19, 776
Jacobs, V. L., Davies, J., & Kepple, P. C. 1976, Phys. Rev. Lett., 37, 1390
Kallman, T., & Bautista, M. 2001, ApJS, 133, 221
Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, A&A, 133, 403
Müller, A., Belić, D. S., DePaola, B. D., et al. 1986, Phys. Rev. Lett., 56, 127
Müller, A., Belić, D. S., DePaola, B. D., et al. 1987, Phys. Rev. A, 36, 599
Nahar, S. N., & Pradhan, A. K. 1997, ApJS, 111, 339
Péquignot, D., Petitjean, P., & Boisson, C. 1991, A&A, 251, 680
Robicheaux, F., & Pindzola, M. S. 1997, Phys. Rev. Lett., 79, 2237
Schippers, S., Müller, A., Gwinner, G., et al. 2001, ApJ, 555, 1027
Schippers, S., Schnell, M., Brandau, C., et al. 2004, A&A, 421, 1185
Widrow, L. M. 2002, Rev. Mod. Phys., 74, 775
Zhang, Z., & Smartt, R. N. 1986, Sol. Phys., 105, 355
Zong, W., Schuch, R., Gao, H., DeWitt, D. R., & Badnell, N. R. 1998, J. Phys. B, 31, 3729