Recombination of Highly Charged Ions with Free Electrons at the ESR

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During the last year the studies on dielectronic and radiative recombination (DR and RR) with free electrons at the ESR have been intensified. Beside new measurements with bare and Li-like uranium and the further analysis of previous beamtimes the first final results on RR with bare bismuth ions have been obtained. They provide new insights into the phenomenon of rate enhancement at very low energies [1] and show a very good agreement between the measured rate coefficient and RR theory [2] over a wide energy range beyond 10^{-2} eV. It was the first experiment of this kind with a bare ion heavier than Argon.
In order to study RR of a bare heavy ion 295.3 MeV/u Bi^{83+}-ions were produced by using the GSI accelerator facility and injected into the ESR. In the storage ring the circulating Bi^{83+}-ions were merged with the cold electron beam of the electron cooler allowing recombination processes to happen along the 2.5 m long interaction length. Recombined Bi^{82+} ions were counted as a function of the electron energy on a scintillator detector located behind the first dipole magnet downstream of the electron cooler. Fig. 1 shows the measured absolute rate coefficient as a function of the relative energy between electrons and ions from $E_{rel} = 0$ eV to 125 eV. The spectrum shows the typical shape of a RR rate coefficient with a maximum at $E_{rel} = 0$ eV and a continuous decrease for increasing relative energies. The solid line represents a calculated RR curve which has been obtained using a cut-off principal quantum number n_{max} = 116 and electron temperatures $kT_{||} = 0.1$ meV and $kT_{\perp} = 120$ meV. There is a very good agreement with the experimental data for relative energies from $E_{rel} =$ 15 meV to 125 eV. For $E_{rel} \leq 15$ meV an additional increase of the measured rate towards lower energies appears which can be seen in the inset of Fig. 1. This shape of the spectrum is typical for low energy recombination experiments and has been observed at several different facilities [3,4,5]. At $E_{rel} = 0$ eV we obtained a maximum rate coefficient of 1.5×10^{-7} $\mathrm{cm^3s^{-1}}$ exceeding the theoretical rate of 2.9×10^{-8} $\mathrm{cm^3s^{-1}}$ by a factor of 5.2. The origin of this so-called rate enhancement is still unknown.

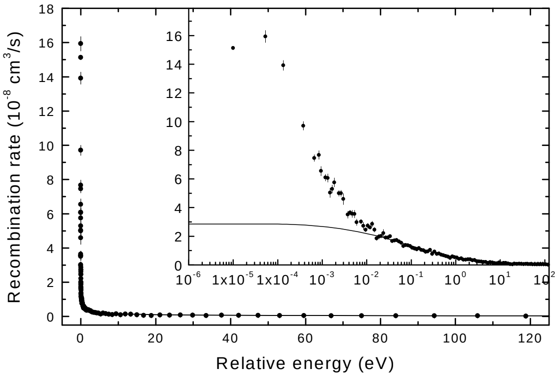

Figure 1: Measured absolute (circles) and calculated (solid line) recombination rate of Bi^{83+} plotted against the relative energy between electrons and ions. In the inset a logarithmic energy scale is used in order to focus on a comparison at very low energies.

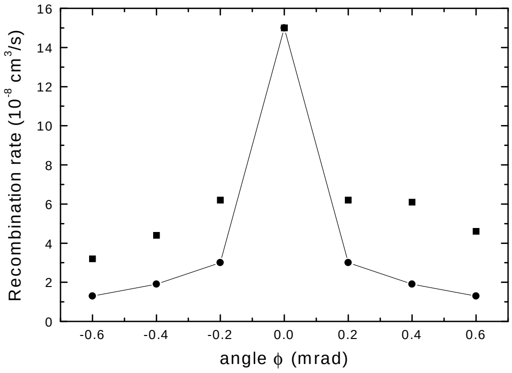

Figure 2: Maximum recombination rates of Bi^{83+} at $E_{rel} = 0$ eV for different angles ϕ set between electron and ion beam. The circles denote the expected values whereas the measured rate coefficients are represented by the squares.

In order to investigate the influence of experimental parameters on the recombination rate we performed controlled changes of electron density, magnetic guiding field and angle between the two interacting beams. Fig. 2 shows the maximum recombination rate rate at $E_{rel} = 0$ eV for different interaction angles ϕ from -0.6 mrad to 0.6 mrad. It turns out that for $\phi \neq 0$ mrad the measured rate coefficients (squares) are above the expected values (circles). Such a behaviour is already known from other experiments performed by the ESR group. Apparently the ion beam reacts on the introduction of the angle, Lorentz and cooling forces appear to minimize the effect of the change. In any case, the distribution shows a rather symmetric progression with the maximum at $\phi = 0$ mrad confirming the accurate adjustment of the cooler.

Whereas measurements at three different electron densities $n_e = 1.6 \times 10^6$ $\mathrm{cm^{-3}}$, $n_e = 3.2 \times 10^6$ $\mathrm{cm^{-3}}$ and 4.7×10^6 $\mathrm{cm^{-3}}$ show no significant influence on the recombination rate, changes of the magnetic guiding field in the interaction region from 70 mT to 150 mT in steps of 1 mT revealed strong effects on the recombination rate. According to an earlier experiment of the ESR group with 310 MeV/u U^{92+} ions [6] no other cooler setting beside the magnetic field strength was changed. Using this procedure oscillations of the recombination rate at cooling have been found in the previous U^{92+} measurement. As one can see in Fig. 3 where the maximum recombination rate at $E_{rel} = 0$ eV is plotted versus the magnetic field strength $B_{||}$ we obtained similar re-

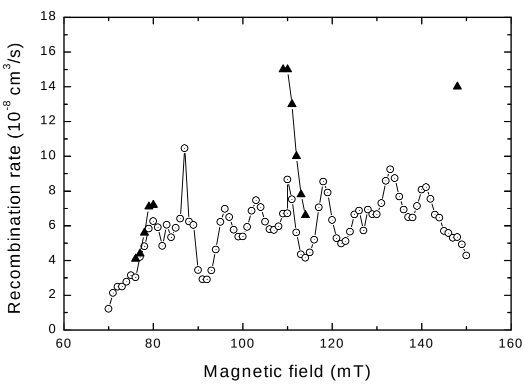

Figure 3: Measured maximum recombination rate of Bi^{83+} at $E_{rel} = 0$ eV versus the magnetic field. The open circles represent the uncorrected recombination rate. Complete absolute recombination measurements with all corrections and normalizations were performed for 12 selected field strengths indicated by the full triangles.

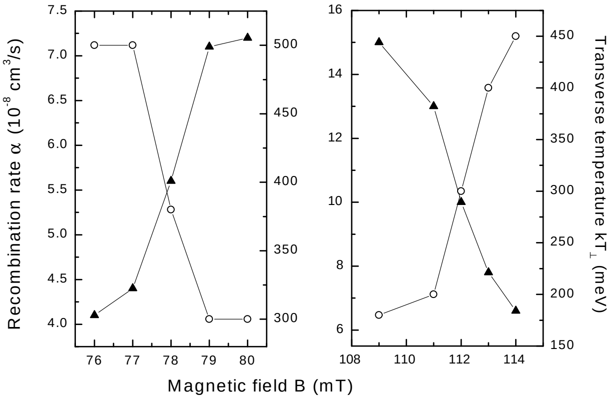

Figure 4: Comparison of the measured maximum rate coefficients of Bi^{83+} (full triangles) for different magnetic fields and the transverse electron temperatures (open circles) inferred from fits to the corresponding recombination spectra at energies beyond 0.1 eV

sults for Bi^{83+} (open circles). Since the measurement of a complete recombination spectrum is very time-consuming only the recombination rate at cooling has been recorded for each magnetic field. For these data points corrections such as background subtraction were not possible. Therefore these recombination rates represented by the open circles in Fig. 3 can only display the qualitative dependence on the magnetic field. However, for selected magnetic fields complete recombination measurements have been performed (full triangles) showing the same progression.

Recently the ESR cooler group found out in experiments with 300 MeV/u Kr$^{36+,35+}$-ions that the "oscillation period" between two maxima of the recombination rate can be influenced by a variation of the magnetic fields of the toroids before and after the cooling section of the cooler. It turned out that the "period" corresponds to the change of the magnetic field allowing the electrons one more turn on their helical trajectory through the cooler. Nevertheless this observation does not explain the physical origin of the oscillations.

Analyzing all the complete recombination spectra measured for different magnetic fields a connection between the maximum rate coefficient at $E_{rel} = 0$ eV and the adapted transverse electron temperature obtained from fits of RR theory to the experimental data becomes obvious (Fig. 4). For magnetic fields between 76 mT and 80 mT (left panel) one can see that with increasing magnetic field the measured maximum rate coefficient increases while the corresponding transverse temperature decreases. In the region between 109 mT and 114 mT (right panel) the corresponding behaviour has been observed. Therefore there seems to be a relationship between the rate coefficient and the transverse electron temperature (or: the electron beam quality). Nevertheless it should be pointed out that this interpretation is only one way to describe the experimental data. At first sight a change of the electron beam temperature by more than a factor of 3 induced by a small variation of the magnetic guiding field in the solenoidal section does not seem to be a realistic scenario. A further theoretical analysis should especially focus on the possible influence of the electron energy since in experiments with lithium-like 97.2 MeV/u Bi^{80+} ions (corresponding to 53.31 kV cooling voltage instead of 162 kV) and also in experiments at low ion energies at other storage rings the oscillations did not appear.

Besides these results discussed above only very recently new RR and DR experiments have been carried out at the ESR with bare (291.7 MeV/u) and Li-like (92.3 MeV/u) uranium. While the measurements with the U^{92+} extend the investigation of the 'RR rate enhancement effect', the interest in the Li-like U^{89+} is of a more spectroscopic nature: Low lying DR resonances belonging to $2s_{1/2} \rightarrow 2p_{1/2}$ and $2s_{1/2} \rightarrow 2p_{3/2}$ excitations provide an excellent testing ground for relativistic atomic structure and QED calculations. In particular U^{89+}, the heaviest element which can be routinely accelerated at the GSI, is known from previous test runs [7] as well as from theoretical predictions [8] to provide interesting physical (and measurerable !) features: (a) The natural linewidths of the $1s^22p_{3/2}5l_j$ resonances are supposed to be in the order of few tenths up to 1 eV. (b) In MCDF calculations [8] the peak positions of the $1s^22p_{3/2}5l_j$ resonances show a strong influence on the charge distribution used to model the nucleus. (c) Some of the peaks (e.g. the $(1s^22p_{3/2}5l_{3/2})_2$ resonance) can only be explained if one takes into account strong relativistic and 'dynamic QED' effects like the Breit interaction.

Special care has been taken to measure the $1s^22p_{1/2}nl_j$ ($n > 20$) Rydberg resonances with good resolution and statistics, because the extrapolation of these resonances to the series limit allows for the determination of the underlying $2s_{1/2} - 2p_{1/2}$ excitation energy ('Lamb shift'). And, in the case of U^{89+} this new method cannot only be compared to theory but also to the up to now most accurate high Z 'Lamb shift' experiment of Schweppe et al. [9].

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