Measurement of Photorecombination of Highly Charged Ions at Low Relative Energies

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In the ongoing work on photorecombination (PR) measurements at the electron cooler of the ESR new results have been obtained during the last year. PR is the capture of a free electron under emission of one or more photons. It is usually described as two different processes, radiative recombination (RR) and dielectronic recombination (DR).
The interest in RR, which is the direct path of PR (time-inverse photoeffect), is mainly driven by the puzzling "rate enhancement phenomenon" at very low relative energies between electrons and ions. On the other hand in resonant DR, the free electron is captured radiationless by the ion (inverse to autoionisation), and a doubly excited compound system is formed. If the intermediate state decays under emission of a photon DR is completed. Therefore, investigations of DR provide insight into the atomic structure of the very heavy highly charged ions under study at the GSI.

RR measurements of U^{92+}

For relative energies between electrons and ions above 0.01-0.1 eV up to very high energies the measured rate coefficient for RR can be described by the dipole approximation within a non-relativistic treatment. However, at very low energies recombination rates exceed the predictions by factors of 1.6 for light ions and up to a factor of 5.2 for heavier bare species. For multicharged complex ions even higher enhancement factors have been found, which could partly be explained by low energy DR-resonances. Of course, for bare ions recombination can not proceed via DR. As a measure for the enhancement an excess rate $\Delta\alpha = \alpha_{exp} - \alpha_{theo}$ is defined. While the enhancement turns out not to be influenced by the electron target density, $\Delta\alpha$ is found to scale with the temperatures of the electron beam like $T_{\perp}^{-1/2}$ and $T_{||}^{-1/2}$. The dependence of the rate enhancement on the strength of the magnetic field used to guide the electron beam inside the cooler is even more puzzling than the enhancement itself: An increase of the enhancement with increasing magnetic field is commonly found at all storage rings. In addition, for very heavy ions at high ion energies, and hence at high electron energies, nearly periodic oscillations of the RR rate coefficient in dependence of the magnetic field strength have been observed at the ESR [1, 2]. So far, for very heavy bare ions ($Z > 18$) detailed investigations of the enhancement have only been performed with Bi^{83+} [2]. Recently, measurements with 297.1 MeV/u U^{92+} ions have been carried out at the ESR. The recombined ions have been detected with a position sensitive counter. This additional diagnostics allows one to monitor the ion beam properties during the measurement. It turned out that the size of the ion beam changes in the horizontal (x-) direction while for the size in the vertical direction no changes under variation of the guiding field could be observed. This decrease of ion beam quality is in accordance with previous findings at the ESR, where the transversal temperature $T_{\perp}$ has been found to vary with magnetic field strength [2]. Hence, the oscillations in the recombination rate seem to be closely connected with changes of the ion beam properties in the transversal direction, which are introduced by small variations of the guiding field. However, the reason for this peculiar behaviour is not known yet. Apart from the oscillations an overall increase of the rate enhancement with increasing magnetic field is found.
For less heavy bare ions ($Z < 18$) a $Z^{2.8}$ scaling of the scaled excess rate $kT_{\perp}^{0.5} kT_{||}^{0.5} \Delta\alpha$ has been reported [3]. When the two measurements for Bi^{83+} and U^{92+} are included this behaviour slightly changes to a $Z^{2.6}$ scaling.

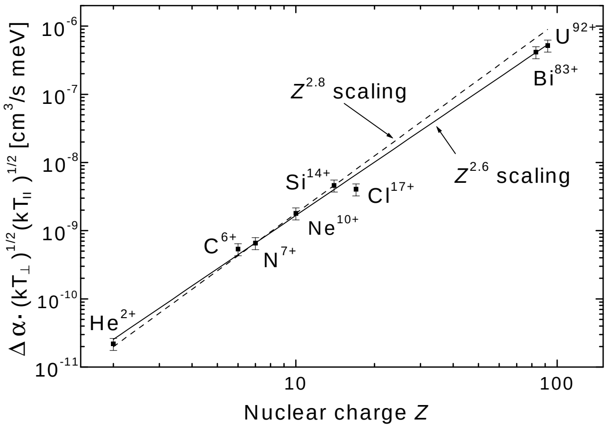

Figure 1: Dependence of the scaled excess rate $kT_{\perp}^{0.5} \cdot kT_{||}^{0.5} \cdot \Delta\alpha$ at 0 eV on the nuclear charge Z. The measurements have been performed at different storage rings (TSR, CRYRING, ESR). The excess rates have not been normalized to the same magnetic field strength. The dashed line is a $Z^{2.8}$ scaling according to [3]. The full line is the new $Z^{2.6}$ scaling with inclusion of the Bi^{83+} and U^{92+} data.

Determination of $2s_{1/2} - 2p_{1/2}$ energy splitting of Li-like heavy-ions by means of DR

Li-like ions are the simplest ions in which $\Delta n = 0$ excitations ($2s_{1/2} \rightarrow 2p_{1/2}$ and $2s_{1/2} \rightarrow 2p_{3/2}$) are possible from the ground-state, thus providing $1s^2 2p_{1/2,3/2} n\ell_j$-DR-resonances in the low-energy domain. For a comprehensive theoretical description of the measured DR features of the heavy ions under investigation (Au^{76+}, Pb^{79+}, Bi^{80+} and U^{89+}) a fully relativistic treatment is needed. In addition, radiative (QED) corrections scale approximately with Z^4 and therefore become increasingly important. The same is true for corrections caused by the finite size of the atomic nucleus and by relativis-

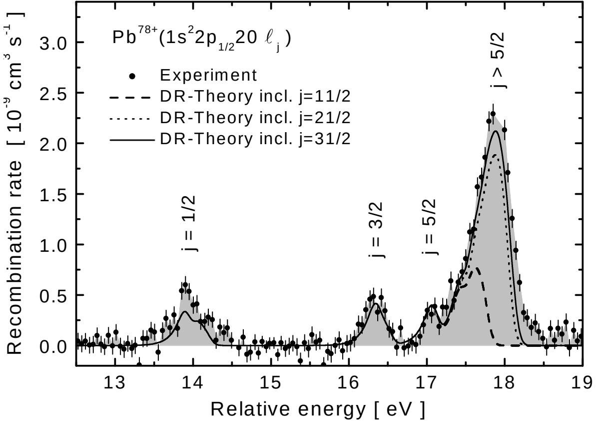

Figure 2: Measured Pb^{79+} recombination rate coefficient compared with our fully relativistic theoretical calculation (full line). The theory has been shifted by -0.65 eV (see text) .

tic effects. Up to now for DR in Li-like very heavy ions there are no strict QED calculations which allow for a direct comparison with the experiment and hence a testing of QED in strong fields. On the other hand a large number of QED calculations for the $2s-2p$ splitting in Li-like ions are available, mainly triggered by the accurate measurements of Schweppe et al. for U^{89+} [4]. We have developed a novel method which allows to extract excitation energies of the projectile ions from the DR resonance positions of the doubly excited recombined ion. For every excitation channel of the dielectronic capture an infinite number of dielectronic resonances converging to the associated series limit may be observed. The main idea is to extrapolate the energies of individual Rydberg resonances to the associated series limit. For increasing values of n and there especially for high angular momenta j the mutual influence of core and Rydberg electrons can be neglected and the excitation energy E_∞ can be described by

$$E_\infty(Z) = E_{Res}(Z,n,j) + E_B(Z,n,j), \qquad (1)$$

where $E_{Res}(Z,n,j)$ is the resonance energy and $E_B(Z,n,j)$ the binding energy of the Rydberg electron, e.g. in a H-like approximation (Dirac energies). Therewith, one deals with a multitude of resonances the energy dependence of which is well known. Beside the series limit as one fitting parameter, additonal free parameters can be introduced to improve the energy calibration.

In particular, for very heavy Li-like ions all $1s^2 2p_{1/2} n\ell_j$ resonance manifolds with $n \geq 20$ can be found within the energy range (0-400 eV) which is accessible by our present experimental set-up. Individual Rydberg states up to $n \approx 45$ have been observed. For Rydberg states with $n = 20-25$ detailed information about the finestructure and resonance strengths could be obtained (see Fig. 2). As can be seen from the figure a very good agreement between the experiment and fully relativistic calculation (GRASP code) is found as long as the *shapes* and the *resonance strengths* of the DR-resonances are concerned. This agreement is even more striking as the experimental rate coefficient has been measured on an absolute scale, and hence theory and experiment are not normalized with respect to each other. It should be noted that the inclusion of very high angular momentum components ($j_{max} \gtrsim 23/2$) is needed. On the other hand it is known that uncertainties in absolute energies produced by the GRASP code are ≈ 1 eV or even more, which are mainly caused by the approximations used to include QED in the MCDF code. But the additional theory-based knowledge about the shape and the finestructure of the doubly excited Rydberg states can be used to improve the accuracy of the extrapolation significantly.

With the method described above the following values for the $2s_{1/2} - 2p_{1/2}$ splitting have been obtained: $E_\infty(\mathrm{Au}^{76+}) = 216.11(20)$ eV, $E_\infty(\mathrm{Pb}^{79+}) = 230.62(20)$ eV and $E_\infty(\mathrm{U}^{89+}) = 280.56(20)$ eV. These results are sensitive to QED contributions of the order α^2. A further reduction of the error by a factor of ≈ 5 can be expected in the near future as the main source of errors is the available knowledge of the velocity distribution of the cooler electrons. This distribution can be probed with high accuracy with an ion of lower nuclear charge Z. In contrast to the very heavy ions, isolated resonances with small natural linewidth ("δ-like") are expected, so that a measured spectrum reflects the velocity distribution of the target electrons. Details can be found in [5].

Scaling behaviour of DR Rydberg states

As mentioned above, one strength of DR investigations utilizing storage ring coolers is the measurement of *absolute* rate coefficients. This allowed us to determine the scaling behaviour of the resonance strength $S = \int \sigma(E) \mathrm{d}E$ of the Rydberg series of Pb^{79+} (Fig. 3). For the doubly excited Rydberg states a $E^{-1}n^{-3}$ scaling can be expected as $S_{Res} \propto A_a \cdot \omega$, the autoionisation rate $A_a \propto n^{-3}$ and the flourescence yield $\omega \approx$ *const.* for sufficiently high n. A comparison (Fig. 3) between experimental resonance strengths for the DR of Pb^{79+}, reveals a n^{-3} scaling law and DR/MCDF calculations for $n = 20-25$ confirm these predictions.

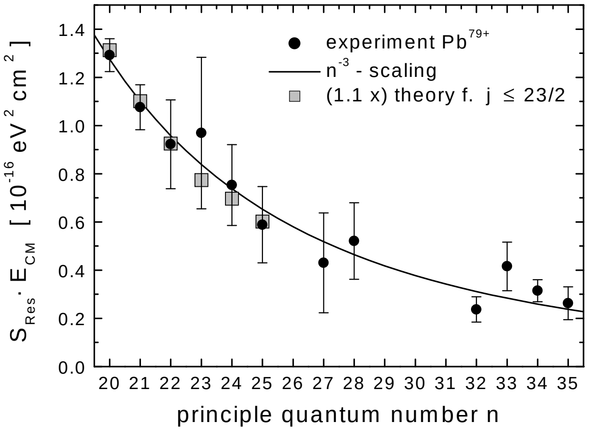

Figure 3: $E^{-1}n^{-3}$ scaling of the DR resonance strength S_{Res} of $\mathrm{Pb}^{78+}(1s^2 2p_{1/2} n\ell_j)$-resonances (DR of Pb^{79+}). The full circles are experimental data, the full line is a scaling according to $E \cdot S_n = E \cdot S_{n=20} \cdot 20^3/n^3$. The grey squares are DR/MCDF calculations (GRASP). Theory has been multiplied by a factor 1.1 in order to take states into account with $j > 23/2$.

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