

Recombination of Highly Charged Ions with Free Electrons at the ESR

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The series of investigations on dielectronic and radiative recombination (DR and RR) of highly-charged ions with free electrons has been considerably extended in the last year. New measurements with bare, H-like, and Li-like bismuth ions have been performed at the electron cooler of the ESR in pursuing two main objectives: (i) measurement of rate coefficients on an absolute scale at very low center-of-mass energies and (ii) high precision spectroscopy of the intermediate doubly excited states of high- Z systems. In addition, earlier data of recombination measurements with Li-like uranium have been further analyzed.

In the last few years enhanced recombination near zero center-of-mass energy has been reported from nearly all experimental facilities with merged-beam set-ups of ion and electron beams [1]. In some cases these recombination rates exceed the theoretical expectations by more than two orders of magnitude. Some of these excessive enhancements can be attributed to DR-resonances close to the threshold. But even for bare ions, where DR is not possible, discrepancies up to an order of magnitude beyond conventional RR theory are observed and remain unexplained. Experimental parameters such as electron density and electron beam temperatures seem to have a minor influence on the enhancement factor. On the other hand, the enhancement factor is found to increase monotonically with increasing strength of the magnetic guiding field of the electron cooler over a wide range (e.g. between 20 mT to 70 mT in a recent experiment at the TSR in Heidelberg [2]) while the dependence on the nuclear charge or on the ion charge state is still not clear. However, most of these experiments have been carried out at rather low charge states and moderate absolute velocities. At the ESR, an even more striking observation has been made by M. Steck: At higher ion velocities, the recombination rate at cooling conditions changes by up to a factor of five in a nearly periodic manner when varying the magnetic field by only a few mT [3].

These enhancement effects have been studied with bismuth ions of three different charge states. Li-like bismuth has been stored in the ESR at 97.2 MeV/u (corresponding to 53.31 kV cooler voltage), bare and H-like bismuth at 295.3 MeV/u (162 kV cooler voltage). For the bare bismuth, the magnetic guiding field has been varied from 70 mT to 150 mT in 1 mT steps, and the recombination rate at cooling has been recorded. For 22 selected values a complete recombination spectrum in a range from 0 to 125 eV center-of-mass energy has been measured. A first analysis confirmed the findings of M. Steck [3]. A more elaborate analysis of the obtained material, currently being in progress, will provide deeper insight into the problem.

The recombination rates at low energies for both bare and H-like bismuth were measured with good statistics under identical conditions in order to test

whether the spectroscopy of doubly excited states close to or above the autoionization threshold is feasible: In particular, $^{209}\text{Bi}^{82+}$, with its $I=9/2$ nuclear spin, exhibits a large energy splitting between the $F=4$ and $F=5$ hyperfine levels of the ground state ($\Delta E = 5.0835$ eV, see [4]). Pindzola et al. [5] predicted DR associated with hyperfine transitions to occur with quite big resonance strength—barely measurable, however, because of the huge RR background at the relevant energies. Thus, one cannot expect to see single Rydberg resonances ($n \geq 135$). A comparison, however, between the recombination rate spectra of the H-like bismuth, where both RR and DR occur, and of the bare bismuth, where only RR contributes, could yield information both on the hyperfine DR-process and on a possible rate enhancement effect near zero energy. The data analysis is not yet completed.

For Li-like bismuth the lowest lying resonance groups belong to the excitations $2s_{1/2} \rightarrow 2p_{1/2}$ and $2s_{1/2} \rightarrow 2p_{3/2}$. In contrast to Li-like gold [6], the main part of the $(1s^2 2p_{3/2} 6\ell_j)$ resonances (fig. 1) except for two minor $(1s^2 2p_{3/2} 6\ell_{1/2})$ peaks at $\approx 210 - 220$ eV (not shown here) lie above the series limit of the $(1s^2 2p_{1/2} n\ell_j)$ Rydberg resonances. The observation of these high n levels is, thus, nearly undisturbed, fine structure components for $n = 20$ to $n = 24$ could be resolved (fig. 2), and individual Rydberg peaks beyond $n = 50$ have been seen in the online analysis. This will greatly help in the precise determination of the $2s_{1/2} - 2p_{1/2}$ energy splitting (Lamb-shift) in Li-like systems. A detailed description of the method, the main idea of which is the extrapolation of a manifold of Rydberg resonances to the series limit $n = \infty$, can be found in [6,7].

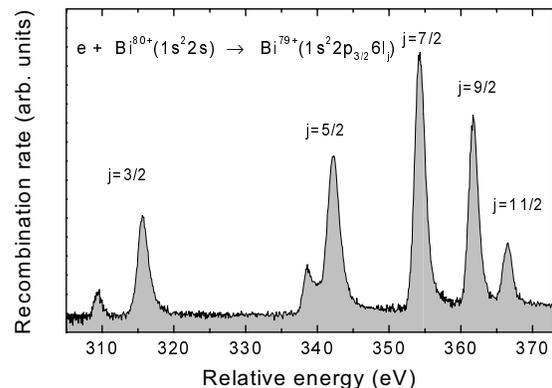


Figure 1: Recombination of Li-like bismuth (preliminary results). Shown are the $1s^2 2s_{1/2} \rightarrow 1s^2 2p_{3/2} 6\ell_j$ DR-resonances.

At higher nuclear charges the $2p_{3/2}$ -states are shifted to even higher energies so that for the lowest

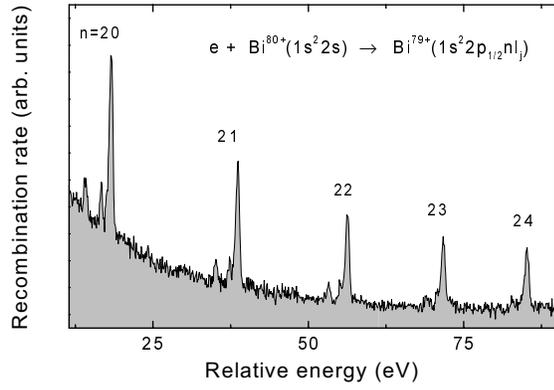


Figure 2: Recombination of Li-like bismuth (preliminary results). Shown are RR and DR-Rydberg series of $1s^2 2s_{1/2} \rightarrow 1s^2 2p_{1/2} n l_j$ DR-resonances with $n=20-24$. Individual fine structure components have been resolved.

lying resonances of Li-like uranium the $2s_{1/2} \rightarrow 2p_{3/2}$ excitation is associated with a capture of the free electron into $n = 5$ instead of $n = 6$ shell. As a consequence, the lifetimes of the intermediate doubly excited states are usually shorter, and the resulting bigger natural linewidths (0.3 - 1.0 eV) provide a particularly easy experimental access to the investigation of DR-line shapes.

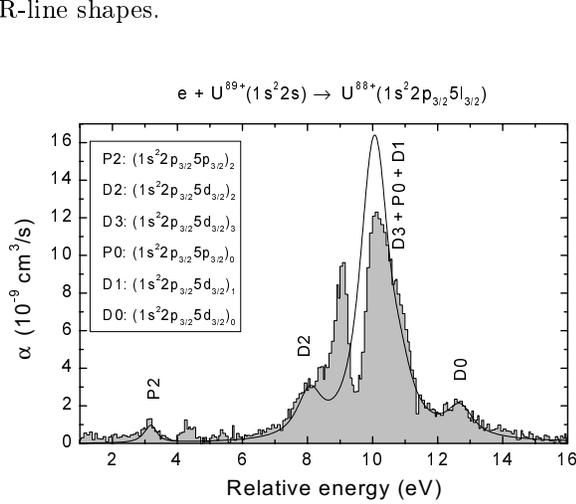


Figure 3: Experimental data (shaded area) and theoretical calculations [8] (solid line) for the $1s^2 2p_{3/2} 5l_{3/2}$ DR-resonance group in Li-like uranium. The RR contribution and the background have been subtracted.

In figs. 3 and 4 experimental data for the center-of-mass energy intervals from 1 eV to 16 eV and from 64 eV to 85 eV, resp. are compared with fully relativistic calculations [8], convoluted with an anisotropic two parameter Maxwellian velocity distribution. The transverse temperature, kT_{\perp} , of the electron beam is taken to be 120 meV according to the temperature of the cooler cathode. An upper limit of 0.5 meV for the longitudinal electron temperature, kT_{\parallel} , is extracted from the fit to the isolated resonance $(1s^2 2p_{3/2} 5d_{5/2})_4$ at 72.9 eV. The corresponding experimental resolution is close to 0.3 eV which is the calculated natural width. In the energy range of the $j=3/2$ manifold around 10

eV the contribution from this convolution is small—the calculated natural line widths are much broader than the experimental resolution. The resonance energies, however, have to be shifted to slightly lower values. At higher energies the resolution decreases roughly proportional to $\sqrt{kT_{\parallel} \cdot E_{cm}}$, hence the experimental energy spread gains more and more influence. At around 75 eV, where the $j=5/2$ manifold is located, experimental and natural widths are of the same order.

In the calculations, a Fermi distribution with a rms radius of 5.86 fm [9] for the nucleus has been assumed. The MCDF calculations turned out to be very sensitive to the choice of this parameter. Changes of the rms radius by 1% yield (measurable) shifts of resonance energies of up to 1 eV. For the $j=5/2$ resonance group (fig.4) there is a very good agreement between theory and experiment. The peak structure as well as resonance strengths, relative and absolute heights are well reproduced. However, experiment and theory are slightly shifted in energy with respect to each other. The situation for the $j=3/2$ peaks (fig. 3) is not as clear yet: The peak at 8.5 eV finds no calculated equivalent while the triple peak at 10.5 eV is overestimated. The reason for these discrepancies is currently being sought. On the other hand, this is an illustrative example for the advantages of the DR measurements, characterized by more than one observable quantity, i.e. by the rates, the energies, the widths, as well as by the pattern in the multitude of peaks.

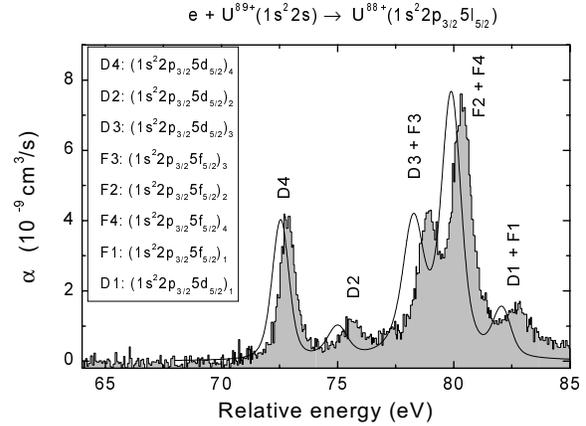


Figure 4: Experimental data (shaded area) and theoretical calculations [8] (solid line) for the $1s^2 2p_{3/2} 5l_{5/2}$ resonance group in Li-like uranium. The RR contribution and the background have been subtracted. The peaks are assigned according to the theory.

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