Article ID: 1007－4627(2002)02－0136－04

High Resolution Studies of Ion Recombination with Cold Electrons

R. Schuch[1], N. Eklöw, M. Fogle, E. Lindroth,
S. Madzunkov, T. Mohamed, D. Nikolic
(*Department of Atomic Physics*, SCFAB, *Stockholm University*, *S*-10691 *Stockholm*, *Sweden*)

P. Glans
(*Physics Department*, *Mid-Swedish University*, *Sundsvall*, *Sweden*)

H. Danared, A. Källberg, A. Paal
(*MSL*, *Stockholm University*, *S*-10405 *Stockholm*, *Sweden*)

Abstract: We present our latest results on recombination of electrons with ions at very low energies obtained at the CRYRING heavy-ion storage ring. New data on the enhanced rate coefficient are shown. Then we concentrate on recent measurements of dielectronic recombination resonances with Li-like, Na-like, and Cu-like ions, where from the spectra of resonances very accurate values for energy splittings are derived for crucial tests of relativistic, correlation, and QED effects.

Key words: recombination rate coefficient; dielectronic recombination resonance; QED effect; cooler storage ring

CLC number: O562 **Document code**: A

Cooler storage rings are excellent tools to study recombination of electrons with ions. This process has several important applications, besides being of fundamental interest. Astrophysical objects are studied through their radiation spectra emitted from electron-ion recombination; plasma modeling and diagnostics are based on the knowledge of recombination cross sections. It is the proposed mechanism for antihydrogen production in a trap filled with antiprotons and positrons. The most fundamental process is radiative recombination (RR): $Z^{q+} + e \rightarrow Z^{(q-1)+} + h\nu$.

Recombination can also proceed via exciting an initially bound electron to form a doubly excited state in the $Z^{(q-1)+}$ intermediate system, in so-called dielectronic recombination (DR). Then the cross sections show strong resonant-like structure. Accurate measurements of these resonances in scattering of electrons at ions can be used for critical tests of calculations. The experiments presented here have both aspects in their motivations.

We will present measurements of the recombination rate coefficients in absolute scale both in energy and height. The experiments are done with the electron cooler of the CRYRING storage ring at the Manne Siegbahn Laboratory (MSL) in Stockholm. This electron cooler has an adiabatically expanded electron beam that gives electrons with mean transversal velocity component of 1 meV and longitudinal velocity component of 0.1 meV.

The highly charged ions are created in an electron-beam ion source, injected into the ring, and

Received date: 5 Mar. 2002; **Corrected date**: 5 Mar. 2002

1) **Contact**: Schuch@ Physto. Se.

accelerated to several MeV/u After electron cooling of the ion beam for a few (1—3) seconds, the recombination rates as function of relative energy between electrons and ions are measured (Fig. 1). Here we show the example of the count rate for Ni^{16+} (Ref. [7]). This is achieved by ramping the electron energy up and down from cooling to a maximum energy in the center-of-mass frame so that recombination spectra are obtained both with the electrons being slower and faster than the ions (see Fig. 1). With these scans, as displayed in Fig. 1, we can check the correction for dragging the ions when detuning the electron beam energy as well as for the space charge of the electron beam. These corrections are important in order to get accurate energy scales in the spectra[1]. For the low relative velocities scanned in these experiments (energies around 0—1 eV) it is possible to take full advantage of the low energy spread of the adiabatically expanded electron beam and a resolution in the order of meV is obtained. But data is also taken for an extended energy range of up to 100 eV. From fits to the resonances we confirm the longitudinal and transversal temperatures of the expanded electron beam to be less than 0. 1 and 1—3 meV, respectively.

In measurements using bare ions, where only RR can occur, there is a consistent disagreement between the measured rates and the theoretical RR descriptions at very low relative energy[1—3]. It could be shown that this deviation depends on the weak magnetic field in the interaction region[4,5]. This effect will be elucidated by a new experiment where the transverse velocity component is varied instead of the longitudinal one.

Recently, highly accurate measurements of atomic energy levels in few-electron ions, such as Cu-like Pb^{53+}[6], Na-like Ni^{17+}[7], and Li-like Kr^{33+}[8] and Be^{+}[10], have been done by recombination at CRYRING. The key points of the method are i. that the inner-shell energy splitting is balanced to a large part by the recombination energy in a Rydberg state, and ii. with a good calculation, the Rydberg state can be calculated to almost any given accuracy, plus iii. that we developed a method to calibrate the experimental energies to a high absolute accuracy. The energy calibration is done by measuring with the Schottky frequency the velocities of electrons and ions, and by a determination of the ring circumference[9].

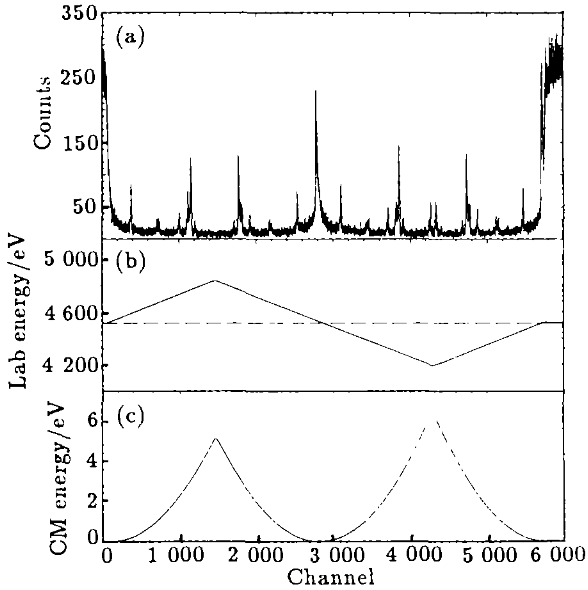

Fig. 1 (a) Time spectrum of the recombination count rate for Ni^{16+} obtained by the zig-zag energy scan of the electrons as shown in (b). The spectrum consists of 4 complete data sets. Note that the high peak at the center, which is from the non-resonant recombinations, defines precisely the time and electron energy at which the electron velocity equals the ion velocity. For reference, the approximate interaction energy is show in (c).

All the ions considered here have one valence electron in an s state. The lowest energy resonances are thus most likely formed by exciting the ns electron to np_j and bind the free electron to high n, for the example of Pb^{53+} it is a $4s_{1/2}$ to $4p_{1/2}$ excitation and simultaneous capture in a $18l_j$-state, with $j=21/2$. Quantum Electrodynamical (QED) effects, such as self energy and vacuum polarization, are substantial in this highly charged ion and contribute to the $4p_{1/2}$-$4s_{1/2}$ splitting with 2 eV. In

Fig. 2 we show the rate coefficient for the case of Pb^{53+} and Pb^{54+}. Thus adding one electron in 4s makes the recombination rate around a factor 100 higher. A quantitative analysis of this experiment shows, that the DR-resonances can be determined with a precision of 1 meV and one is thus sensitive to the $4s_{1/2}$ to $4p_{1/2}$ splitting with the same precision[6]. This splitting is around 120 eV, which gives a relative accuracy in the 10^{-6} regime. It is clear that in cases where resonances are only a few meV above threshold, their position is determined by QED; and, the present-day ability to calculate the QED contribution to such a resonance energy is much larger than the experimental uncertainty.

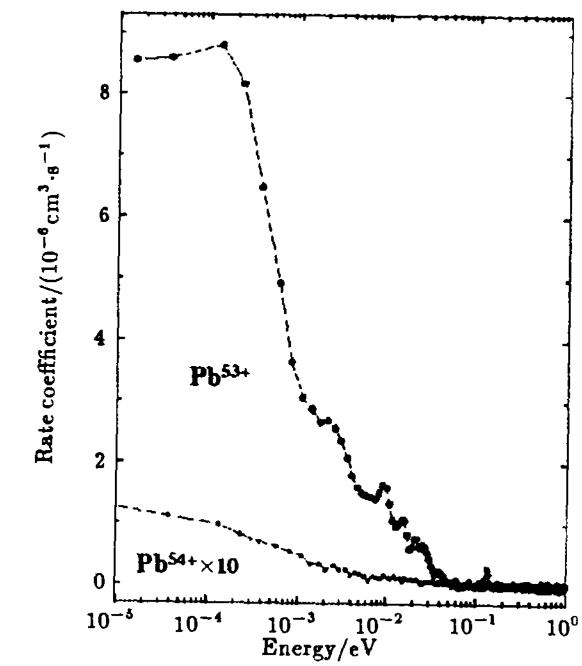

Fig. 2 The recombination rate coefficient for the cases of Pb^{53+} and Pb^{54+}. The coefficient for Pb^{54+} are multiplied by 10.

An accurate method to calculate the resonance energies is based on relativistic many-body theory and is capable of meV accuracy for few electron systems (except for the QED effects)[5—10]. This method uses complex rotation to handle autoionizing states.

Another prominent example is our determination of the $2p_{1/2}$-$2s_{1/2}$ splitting in Kr^{33+} where the $2s_{1/2}$ Lamb shift was determined to within 0.1%, which is so far its most precise determination[8]. In Li-like Kr, having just three electrons, correlation and QED effects can indeed be treated *ab initio* and they are also substantial due to the high nuclear charge; the self-energy exceeds correlation effects by one order of magnitude in the $2p_{1/2}$-$2s_{1/2}$ splitting.

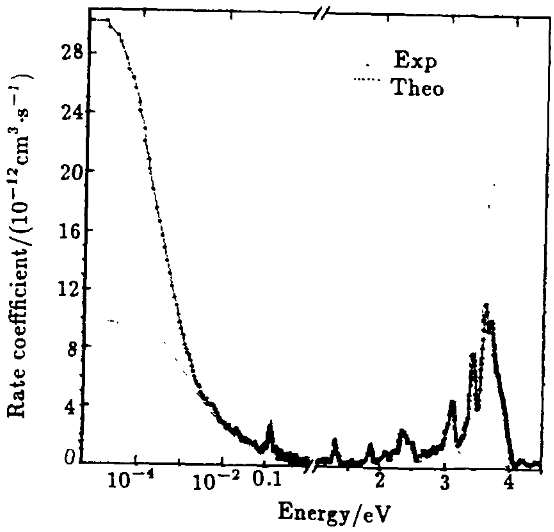

Fig. 3 Comparison of the experimental recombination rate coefficient for Be^+ with a calculation[10] in relativistic many-body perturbation theory.

With the present level of accuracy, the DR spectra can only be reproduced by the most refined calculations; fully relativistic, highly correlated and accounting for QED corrections. The accuracy is even high enough that the results call for a development of improved methods to treat QED in a many-electron environment. Surprisingly even very light ions, as Be^+[10], can be dominated by relativistic effects although the ions in other respects are well described non-relativistically. Fig. 3 shows the example of the lightest Li-like ion Be^+. In this case we see a $2s_{1/2}$ to $2p_{1/2}$ excitation and simultaneous capture into $2l_j$ and $3l_j$-states. QED effects are small in the $2s_{1/2}$ of this light ion, and are easily corrected for. But, some of the resonances only appear when relativistic effects are included.

With the resolution and accuracy reached we were recently able to resolve and measure the hyperfine splitting in a very highly-charged ion by dielectronic resonances. Although it would hardly have been anticipated a few years ago, resonances in collision cross sections provide today an alternative to photon spectroscopy to obtain highly accurate information on atomic energy levels and now even on nuclear effects.

The measured rate coefficients are also of interest to plasma or astrophysical applications. For many of the interesting ions such as Be, C, N, O, Ne, Ar, Fe, and Ni in several charge states, accurate experimental data on temperature dependent rate coefficients is now available.

Acknowledgement We acknowledge the collaboration with the CRYRING crew in the experiments and the financial support by the Swedish research council (VR).

References:

[1] Schuch R, W Zong, Badnell N. Int Journ of Mass Spectrometry, 1999, **192**: 225.

[2] Gao H, De Witt D, Schuch R, *et al*. Phys Rev Lett, 1995, **75**: 4 381.

[3] Gao H, Schuch R, Justiniano E. J Phys B Lett, 1997, **30**: L499.

[4] Gwinner G, *et al*. Phys Rev Lett, 2000, **84**: 4 822.

[5] Eklow N, Glans P, W Zong, *et al*. Hyperfine Interactions, 2000, **127**: 251.

[6] Lindroth H, Tokman M, Glans P, *et al*. Phys Rev Lett, 2001, **86**: 5 027.

[7] Fogle M, *et al*. submitted to J Phys B.

[8] Madzunkov S, Lindroth E, Eklöw N, *et al*. Phys Rev, 2002, **A65**: 032505.

[9] W Zong, Schuch R, Lindroth E, *et al*. Phys Rev, 1997, **A56**: 386.

[10] Mohamed T, *et al*. submitted to P. R. A.

离子和冷却电子重组的高分辨谱研究

R. Schuch*, N. Eklöw, M. Fogle, E. Lindroth, S. Madzunkov, T. Mohamed, D. Nikolic
(*Department of Atomic Physics*, *SCFAB*, *Stockholm University*, S-10691 *Stockholm*, *Sweden*)

P. Glans
(*Physics department*, *Mid-Swedish University*, *Sundsvall*, *Sweden*)

H. Danared, A. Källberg, A. Paal
(*MSL*, *Stockholm University*, S-10405 *Stockholm*, *Sweden*)

摘　要：给出了在 CRYRING 重离子储存环上测量到的在很低能量下电子与离子重组的最新实验结果和有关速率系数增强的新的数据. 主要讨论类锂、类钠和类铜离子的共振双电子重组的新近测量结果，以及从这些共振谱中所导出的非常精确的离子能级劈裂值，从而将严格检验相对论效应、电子关联效应和量子电动力学效应. 其中，对类锂 Kr^{33+} 离子 $2s_{1/2}$ 能级 Lamb 移位的确定精度达到了 0.1%.

关 键 词：重组速率系数；共振双电子重组；量子电动力学效应；冷却存储环