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Relativistic, QED and nuclear effects in highly charged ions revealed by resonant electron–ion recombination in storage rings

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ABSTRACT

Dielectronic recombination (DR) of few-electron ions has evolved into a sensitive spectroscopic tool for highly charged ions. This is due to technological advances in electron-beam preparation and ion beam cooling techniques at heavy-ion storage rings. Recent experiments prove unambiguously that DR collision spectroscopy has become sensitive to 2nd order QED and to nuclear effects. This review discusses the most recent developments in high-resolution spectroscopy of low-energy DR resonances, experimental studies of KLL DR of very heavy hydrogen like ions, isotope shift measurements of DR resonances, and the experimental determination of hyperfine induced decay rates in divalent ions utilizing DR.

1. Introduction

Merged electron–ion beams arrangements at heavy-ion storage rings equipped with electron coolers have evolved into powerful spectroscopic tools for studies of highly charged ions. The experiments combine high detection efficiencies associated with fast moving ion beams with cold electron and ion beams. Especially resonant electron–ion recombination, also termed dielectronic recombination (DR), provides access to the electronic structure of highly charged ions over a wide range of energies from below 1 meV up to several 10 keV where the K-shells of the heaviest ions can be excited.

The aim of this paper is to review the most recent experimental electron–ion recombination work with an emphasis on the spectroscopy of highly charged ions. For more extensive reviews that also cover further aspects of electron–ion recombination experiments see e.g. [1] (general overview over experimental work on electron–ion collisions), [2] (overview over recent atomic collision experiments at storage rings including DR), [3] (X-ray spectroscopy with few-electron highly charged ions), [4] (DR in external electromagnetic fields), [5] (DR measurements for applications in astrophysics) and [6] (summary of DR work at storage rings until 1999).

2. High-resolution spectroscopy of low-energy DR resonances

The experimental energy spread in electron–ion merged-beam arrangements with an electron-cooled ion beam is mainly determined by the internal energy spread of the electron-beam. It is smallest at very low relative electron–ion collision energies due to the merged-beams kinematics. Therefore, highest resolving powers in DR experiments require (i) a very cold electron-beam and (ii) an atomic system that supports DR resonances at low relative energies, preferably below 100 meV. Such systems are e.g. the lithium-like ions F^{6+} [7], Na^{8+} [8] and Sc^{18+} [9].

A very cold electron-beam has been developed for the heavy-ion storage ring TSR (Fig. 1) at the Heidelberg Max-Planck-Institute for Nuclear Physics. This high-resolution electron target [10] uses magnetic adiabatic electron-beam expansion, adiabatic beam acceleration and, optionally, a photocathode [11] which is operated at LN_2 temperatures. Thus, the electrons are already created at a much lower temperature as compared to a conventional thermal cathode. A separate electron target offers the additional advantage that the electron cooler can be used to cool the ion beam continuously during a measurement with the target. In the previous

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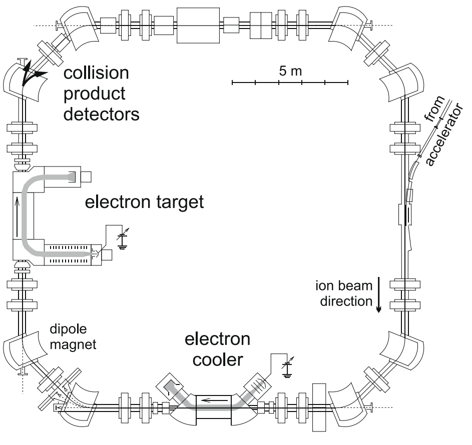

Fig. 1. The heavy-ion storage ring TSR at the Heidelberg Max-Planck-Institute for Nuclear Physics is equipped with two co-propagating electron-beams, the electron cooler and the high-resolution electron target. Recombined (or ionized) ions which are produced by electron–ion collisions in the electron-beams are intercepted by single-particle detectors which are located behind the first dipole magnets following the electron cooler and electron target.

arrangement without the electron target the cooler was alternatingly switched between cooling mode and measurement mode. In comparison, the newly available twin-electron-beam technique leads to a colder ion beam with a much better defined mean velocity.

Fig. 2 demonstrates the progress that has been achieved with the installation of the high-resolution electron target. The displayed low-energy DR spectrum of Sc^{18+} is dominated by the three narrow resonance terms $(2p_{3/2}\ 10d_{5/2})_{J=4}$, $(2p_{3/2}\ 10d_{3/2})_{J=2}$ and $(2p_{3/2}\ 10d_{3/2})_{J=3}$ predicted at 28.9, 33.7 and 67.8 meV, respectively [9]. The cooler measurement does not resolve the two low-energy resonances individually (Fig. 2(a)). In contrast, the measurement with the high-resolution electron target even resolves the hyperfine structure of the $1s^2\ 2s_{1/2}$ initial state (Fig. 2(b), $^{45}\mathrm{Sc}$ has a nuclear spin of $I = 7/2$).

The electron-target measurement reduced the uncertainty of the experimental $(2p_{3/2}\ 10d_{3/2})_{J=3}$ DR resonance position at 0.06861(10) eV [13] by more than an order of magnitude as compared to the cooler measurement [9]. This is mainly due to fact that the ion energy is much better defined when the twin-electron-beam technique is applied. In combination with an accurate theoretical value for the binding energy of the 10*d* Rydberg electron from relativistic many-body perturbation theory (RMBPT) a value for the $2s_{1/2}$—$2p_{3/2}$ energy splitting in Sc^{18+} was derived from the experimental $(2p_{3/2}\ 10d_{3/2})_{J=3}$ DR resonance position with an uncertainty of only 4.6 ppm [13] which is less than 1% of the few-body effects on radiative corrections [14]. It is a factor of ~3 lower than the relative uncertainty of the best optical measurements of $2s \rightarrow 2p$ transition energies in highly charged ions.

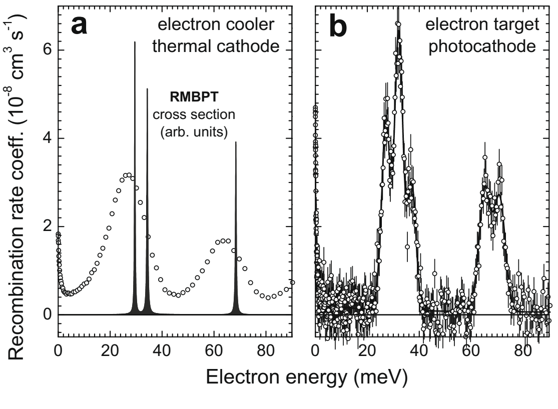

Fig. 2. Comparison of the low-energy $\mathrm{Sc}^{18+}(1s^2 2s)$ DR spectrum measured (symbols) with the TSR electron cooler (a) [9] and the TSR electron target (b) [12,13]. Clearly, the experimental energy spread is much lower with the electron target (~1 meV instead of 7.2 meV), such that features from the hyperfine structure of the $1s^2\ 2s_{1/2}$ state could be resolved. The full curve (b) is a fitted rate coefficient (see [12] for details) based on the RMBPT cross section of Kieslich et al. [9] (a, full shaded curve, without hyperfine splitting).

3. KLL DR of hydrogen like heavy ions

At the other end of the experimentally accessible energy range KLL DR resonances of heavy ions can be observed which occur at relative electron–ion energies of several 10 keV (Fig. 3). Very heavy highly charged ions are routinely stored in the experimental storage ring (ESR) at GSI in Darmstadt, Germany. At the ESR the twin-electron-beam technique is not available and the electron cooler is used as a target for recombination experiments. Since electron cooling of the ion beam requires zero relative electron–ion energy previous DR measurements with electron-cooled ion beams at the ESR were limited to low relative energies of up to a few 100 eV (see e.g. [16]).

A novel approach was taken for measuring high-energy KLL DR resonances of hydrogen like Xe^{53+} ions. Stochastic cooling was used to reduce the internal energy spread of the ion beam and the electron cooler was exclusively used as a target for DR measurements. Fig. 3 [15] shows that the experimental energy spread was almost as narrow as the natural linewidths of the DR resonances.

In a more recent experiment KLL DR of hydrogen like U^{91+} has been investigated at the ESR. Because of the scaling of the natural linewidths with nuclear charge a more favorable relation between experimental energy spread and natural linewidths is expected for heavier ions. However, the U^{91+} experiment did not yet come up to this expectation due to other experimental limitations [17] which may be overcome in future work. Nevertheless, a detailed comparison with theoretical calculations along the lines described in [18] is under way [19] aiming at unraveling the contribution of the Breit interaction to the KLL DR resonance strengths (see e.g. [20]).

4. Isotope shifts of dielectronic recombination resonances

With increasing nuclear charge the overlap of the electronic wave functions with the atomic nucleus becomes larger. Consequently, the influence of the nuclear structure on the electron shell

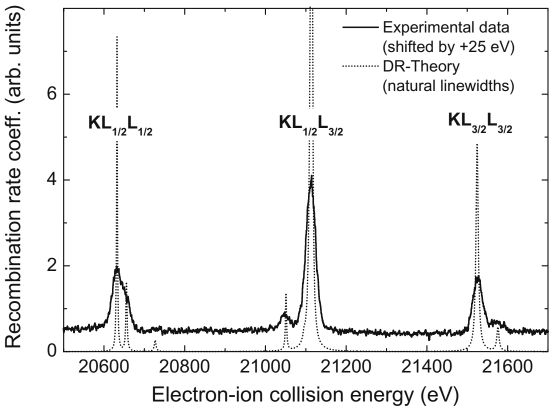

Fig. 3. Preliminary comparison between experimental (full line) and calculated (dotted line) KLL DR spectra of hydrogen like Xe^{53+} [15].