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 hydrogenlike ions, isotope shift measurements of DR resonances, and the experimental determination of hyperfine induced decay rates in divalent ions utilizing DR.

Key words: dielectronic recombination, hyperfine splitting, isotope shift, Breit interaction, heavy-ion storage-ring
PACS: 34.80.Lx, 31.30.Gs, 31.30.J-, 32.70.Cs

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. Refs. [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$^{8+}$ [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 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.

Figure 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. 2a). 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. 2b, $^{45}$Sc has a nuclear spin of $I = 7/2$).
The electron-target measurement reduced the uncertainty of the experimental \((2p_{1/2} \, 10d_{3/2})_{J=3}\) 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 the 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 10d 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 \((2p_{1/2} \, 10d_{3/2})_{J=3}\) 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 \(2s \to 2p\) transition energies in highly charged ions.

3. KLL DR of hydrogenlike 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. Ref. \([16]\)).

A novel approach was taken for measuring high-energy KLL DR resonances of hydrogenlike \(\text{Xe}^{53+}\) 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. Figure 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 hydrogenlike \(\text{U}^{91+}\) 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 \(\text{U}^{91+}\) 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 Ref. \([18]\) is under way \([19]\) aiming at unraveling the contribution of the Breit interaction to the KLL DR resonance strengths (see e.g. Ref. \([20]\)).

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 increases for heavier ions. Isotope shifts of \(2s \to 2p\) transition energies in few-electron highly charged ions have been observed at electron-beam ion traps (EBIT) using optical spectroscopy \([21,22]\).

As discussed above, the \(2s \to 2p\) transition energy can also be extracted from DR measurements at storage rings. The isotope dependence of the \(2s \to 2p\) transition energy is reflected in an isotope shift of DR resonances. This has been investigated theoretically \([23]\) and more recently also been ob-
Fig. 4. Low-energy Nd$^{57+}$ (1$s^2$2$s$) DR resonances for two different neodymium isotopes [24]. Clearly the positions of all resonances shift (by about 40 meV) when going from the isotope with mass number 150 (dark curve) to the one with mass number 142 (light curve).

5. Hyperfine induced decay of the 1$s^2$2$s$2$p$ $^3P_0$ state in berylliumlike ions

Besides the nuclear charge distribution also the magnetic moment of the nucleus has an influence of the DR resonance structure. The hyperfine splitting of DR resonances has already been discussed (Fig. 2b) and also observations of the hyperfine shift [26] and the hyperfine quenching [27,28] of DR resonances have been reported.

The observed hyperfine quenching of DR resonances in experiments with Zn-like Pt$^{48+}$ [27] and Be-like Ti$^{18+}$ [28] is associated with the hyperfine induced $ns\,np\,^3P_0 \rightarrow ns^2\,^1S_0$ transition in divalent atoms and ions. These transitions are presently discussed in connection with optical atomic clocks and also play a role in the determination of isotope abundances from astrophysical observations.

From a fundamental point of view hyperfine induced transitions are very sensitive probes for electron correlation effects. Theoretical treatments of the hyperfine-dominated decay rates in berylliumlike ions differ by factors of up to $\sim 5$ [29,30]. This difference is largely due to different treatments of electron correlation effects which are particularly influential in berylliumlike ions.

Experimentally, hyperfine-induced decay rates for berylliumlike ions were so far only inferred for N$^{3+}$ [31] using astronomical observations of a planetary nebula and yielding an uncertainty of 33%. Even at this limited precision, this result allows one to discriminate between the lifetimes predicted by atomic structure calculations [29,30] that differ by a factor of almost 4 (the result of Ref. [29] is outside the experimental error bar).

The first laboratory measurement of a hyperfine induced lifetime in a highly charged berylliumlike ion has been performed only recently [32]. The experiment make use of fast moving ion beams in the Heidelberg heavy-ion storage ring TSR. The population of the Ti$^{18+}$ (1$s^2$2$s$2$p$ $^3P_0$) state was monitored as a function of storage time by observing the dielectronic recombination signal from a hyperfine quenched DR resonance associated with the excitation of the $^3P_0$ state (Fig. 5, left panel). Recombined Ti$^{17+}$ ions were detected with nearly 100%
of the hyperfine induced exhibits a fast decaying component which is the signature cally predicted lifetime of produced decay (Fig. 5, right panel) with a theoreti-
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The comparison of the measured decay curves for the isotopes with atomic mass numbers A = 48 and A = 47 clearly reveals the hyperfine induced decay (Fig. 5, right panel) with a theoretically predicted lifetime of \( \sim 2.8 \text{ s} \). A careful analysis of the experimental results which takes collision processes with residual gas particles and other competing decay processes into account arrives at a value of 1.8±0.1 s \[32\] which is 57% lower than the only available theoretical result. This difference is attributed to electron correlation effects that were included only approximately in the theoretical calculation. A new calculation \[33\] arrives at a value of 1.49 s in better agreement with the experimental value.

The new laboratory value for Ti\(^{18+}\) is almost an order of magnitude more precise than the only previous experimental value for isoelectronic N\(^{3+}\) \[31\] that was obtained from astrophysical observations and modeling. An essential feature of the storage ring method is the comparison of measured results from different isotopes with zero and nonzero nuclear spin. As compared to optical detection of the fluorescence photon the DR method offers the advantage of a much higher detection efficiency. Moreover, it is readily applicable to a wide range of ions and has the potential for yielding results that are even more accurate than the Ti\(^{18+}\) value.

6. Conclusion

One aspect of electron-ion recombination at heavy-ion storage rings is its use for spectroscopy of highly charged ions. Two recent developments of the experimental instrumentation have significantly increased the sensitivity and thereby the relevance of this electron-collision spectroscopy, namely the high-resolution electron target at the TSR in Heidelberg and the use of stochastic cooling in DR experiments at the ESR in Darmstadt. For the 2s – 2p\(_{3/2}\) splitting in Li-like ions electron-collision spectroscopy currently outperforms optical measurements on highly charged ions. Work with exotic nuclei will hopefully flourish at the new storage ring NESR at the FAIR. The DR isotope-shift method will develop its full potential especially when a separate electron target will be made available in addition to the NESR electron cooler.

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Figure 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. 2a). 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. 2b, $^{45}$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 the 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 10d 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.

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As discussed above, the \(2s \rightarrow 2p\) transition energy can also be extracted from DR measurements at storage rings. The isotope dependence of the \(2s \rightarrow 2p\) transition energy is reflected in an isotope shift of DR resonances. This has been investigated theoretically [23] and more recently also been ob-
observed experimentally with DR of Li-like Nd$^{57+}$ ions [24] (Fig. 4). In this work isotope shifts of DR resonances of about 40 meV were measured with uncertainties below 1 meV. Moreover, the difference between the nuclear charge radii of the isotopes with mass numbers 142 and 150 was derived with an accuracy that is competitive with that of other methods.

The determination of isotope shifts from few-electron ions offers some advantages as compared to optical methods that use neutral atoms. Because of the simplicity of the atomic configuration, the interpretation of the data is clear and without ambiguity. For the $2s \rightarrow 2p$ transitions of Li-like ions the electronic part can be treated theoretically with high accuracy. Many-body and mass effects are small and can be reliably accounted for.

The novel storage-ring DR isotope-shift method can be easily extended to unstable isotopes or long-lived nuclear isomers provided that such species can be produced in sufficiently large quantities. High production yields of radioactive ions are predicted for the upcoming Facility for Antiproton and Ion Research (FAIR) [25] and the DR isotope-shift method may develop into a standard tool for probing nuclear matter.

5. Hyperfine induced decay of the $1s^2 2s 2p \, ^3P_0$ state in berylliumlike ions

Besides the nuclear charge distribution also the magnetic moment of the nucleus has an influence of the DR resonance structure. The hyperfine splitting of DR resonances has already been discussed (Fig. 2b) and also observations of the hyperfine shift [26] and the hyperfine quenching [27,28] of DR resonances have been reported.

The observed hyperfine quenching of DR resonances in experiments with Zn-like Pt$^{48+}$ [27] and Be-like Ti$^{18+}$ [28] is associated with the hyperfine induced $ns \, np \, ^3P_0 \rightarrow ns^2 \, ^1S_0$ transition in divalent atoms and ions. These transitions are presently discussed in connection with optical atomic clocks and also play a role in the determination of isotope abundances from astrophysical observations.

From a fundamental point of view hyperfine induced transitions are very sensitive probes for electron correlation effects. Theoretical treatments of the hyperfine-dominated decay rates in beryllium-like ions differ by factors of up to $\sim 5$ [29,30]. This difference is largely due to different treatments of electron correlation effects which are particularly influential in beryllium-like ions.

Experimentally, hyperfine-induced decay rates for beryllium-like ions were so far only inferred for N$^{3+}$ [31] using astronomical observations of a planetary nebula and yielding an uncertainty of 33%. Even at this limited precision, this result allows one to discriminate between the lifetimes predicted by atomic structure calculations [29,30] that differ by a factor of almost 4 (the result of Ref. [29] is outside the experimental error bar).

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exhibits a fast decaying component which is the signature predicted lifetime of 48 and A for the isotopes with atomic mass numbers a value of 1 s in better agreement with the experimental results which takes collision processes with residual gas particles and other analysis of the experimental results that was obtained from astrophysical observations and modeling. An essential feature of the storage
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The comparison of the measured decay curves for the isotopes with atomic mass numbers A = 48 and A = 47 clearly reveals the hyperfine induced decay (Fig. 5, right panel) with a theoretically predicted lifetime of ~2.8 s. A careful analysis of the experimental results which takes collision processes with residual gas particles and other competing decay processes into account arrives at a value of 1.8 ± 0.1 s [32] which is 57% lower than the only available theoretical result. This difference is attributed to electron correlation effects that were included only approximately in the theoretical calculation. A new calculation [33] arrives at a value of 1.49 s in better agreement with the experimental value.

The new laboratory value for Ti$^{18+}$ is almost an order of magnitude more precise than the only previous experimental value for isoelectronic N$^{3+}$ [31] that was obtained from astrophysical observations and modeling. An essential feature of the storage

6. Conclusion

One aspect of electron-ion recombination at heavy-ion storage rings is its use for spectroscopy of highly charged ions. Two recent developments of the experimental instrumentation have significantly increased the sensitivity and thereby the relevance of this electron-collision spectroscopy, namely the high-resolution electron target at the TSR in Heidelberg and the use of stochastic cooling in DR experiments at the ESR in Darmstadt. For the $2s - 2p_3/2$ splitting in Li-like ions electron-collision spectroscopy currently outperforms optical measurements on highly charged ions. Work with exotic nuclei will hopefully flourish at the new storage ring NESR at the FAIR. The DR isotope-shift method will develop its full potential especially when a separate electron target will be made available in addition to the NESR electron cooler.

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