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Dielectronic recombination experiments at the storage rings: From the present CSR to the future HIAF

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ABSTRACT

Dielectronic recombination (DR) experiments of highly charged ions at the storage rings have been developed as a precision spectroscopic tool to investigate the atomic structure as well as nuclear properties of stable and unstable nuclei. The DR experiment on lithium-like argon ions was successfully performed at main Cooler Storage Ring (CSRm) at Heavy Ion Research Facility in Lanzhou (HIRFL) accelerator complex. The DR experiments on heavy highly charged ions and even radioactive ions are currently under preparation at the experimental Cooler Storage Ring (CSRe) at HIRFL. The current status of DR experiments at the CSRm and the preparation of the DR experiments at the CSRe are presented. In addition, an overview of DR experiments by employing an electron cooler and a separated ultra-cold electron target at the upcoming High Intensity heavy ion Accelerator Facility (HIAF) will be given.

1. Introduction

Dielectronic recombination (DR) is a fundamental electron-ion collision process, and the precision determination of the absolute rate coefficients of electron-ion recombination is demanded to understand the astrophysical and other natural as well as man-made plasmas [1]. The DR experiments of highly charged ion (HCI) by employing the electron-ion merged beams technique have been developed for more than two decades at heavy ion storage rings, i.e., the Test Storage Ring at MPIK in Heidelberg [2], the Experimental Storage Ring at GSI in Darmstadt [3], Germany, and also the CRYRING at MSL in Stockholm, Sweden [4]. The research topics of DR experiments at these storage rings are very broad, covering from atomic structure, relativistic effect and strong field QED [5], to the interface of atomic and nuclear physics [6]. In the last few years, the DR precision spectroscopy has been extended to the investigation of the hyperfine induced transition rates [7], the nuclear properties of the HCI by measuring the isotope shift [8–10] and hyperfine splitting [5]. Moreover, DR spectroscopy of uranium and protactinium radionuclides produced in-flight has been demonstrated for the first time at the ESR [9,11,12]. More details of the DR experiments at storage rings can be found in the review literatures [1–3,6] and the references cited therein. Very recently, the TSR is planned to be installed at IMP in China and the CRYRING is presently being set up downstream of the ESR at GSI in Darmstadt [14,15]. The motivation and the physics cases of DR spectroscopy at these two storage rings can be found in [6,13–15].

The Cooler Storage Rings (CSR) at HIRFL were installed in 2007 at Institute of Modern Physics (IMP), in Lanzhou, China. The installations of electron coolers at the main Cooler Storage Ring (CSRm, EC35) and the experimental Cooler Storage Ring (CSRe, EC300) provide ideal research platforms for DR experiments of highly charged stable ions and radioisotopes. Until now, the electron-ion recombination experiments of multi-electron ions $^{58}Ni^{19+}$ and $^{112}Sn^{35+}$ were performed at the CSRm [16,17]. In order to fully understand the DR experimental system, an experiment by employing lithium-like $^{36}Ar^{15+}$ions was successfully performed to calibrate the electron energy detuning system at the CSRm [18]. The upgrading of the electron-cooler at the CSRe to perform DR experiments is

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in progress, and will be finished in the summer of 2017. Meanwhile, the DR experiments to study highly charged heavy ions and even radioisotopes are currently in preparation at the CSRe at HIRFL. In addition, an accelerator facility HIAF is being designed and will be constructed by the IMP [19]. The DR spectroscopy of HCI by employing an electron cooler and a separated ultra-cold electron target is listed as the main motivation of atomics physics at HIAF.

In the following sections, we will give a brief review about the status of DR experiments at the CSRm. The upgrading of the electron energy detuning system of e-cooler EC-300 and further research topic of DR experiments at the CSRe will also be introduced. In addition, the perspectives for future DR experiments at the upcoming HIAF will be discussed.

2. DR experiments at the HIRFL-CSR storage rings

Electron-ion collision includes three basic processes of electron-ion recombination, electron impact ionization, and electron impact excitation. Radiative recombination (RR) and DR are the most representative mechanisms in electron-ion recombination. RR is a direct non-resonant process, it can be represented as

$$e + A^{q+} \rightarrow A^{(q-1)+} + h\nu \tag{1}$$

i.e., a free electron is captured by an ion A^{q+} with emission of a photon simultaneously. While the DR can be regarded as a two-step processes and can be expressed as

$$e + A^{q+} \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + n \cdot h\nu \tag{2}$$

i.e., in the first step, a free electron is radiationlessly captured by an ion A^{q+}, the excess energy is used to excite a bound electron in the ion core, by which a doubly excited intermediate state of the ion is formed. In the second step, the intermedia state stabilizes via photoemission. Here, we will only focus on the DR experiments at the heavy ion storage ring.

The layout of the HIRFL complex is shown in Fig. 1 [20]. HIRFL-CSR is the post-acceleration system of the Heavy Ion Research Facility in Lanzhou, consisting of the Cooler Storage Rings CSRm, CSRe, and a radioactive beam line RIBLL II to connect the two rings. The Sector Focused Cyclotron (SFC) and Separated Sector Cyclotron (SSC) are used as the injector system to provide heavy ion beams with the energy range of 8–30 MeV/u for CSRm. The heavy ion beam injected into the CSRm is accumulated, cooled and accelerated to the high-energy range of 100–400 MeV/u. Then the heavy ion beam can be extracted from the CSRm and be injected into the CSRe directly for internal-target experiments and high-precision spectroscopy with electron-cooled ion beam. The combination of the CSRm and the RIBLL II could also be used to produce radioactive ion beams and then to separate and inject radioactive ions into the CSRe for DR experiments. The relevant parameters for DR experiments at HIRFL-CSR are listed in Table 1.

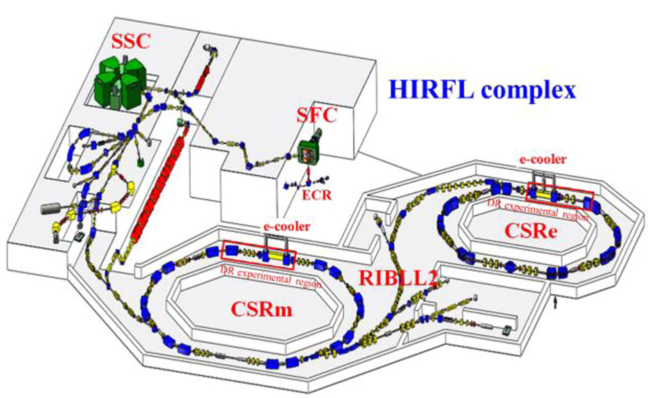

Fig. 1. Layout of HIRFL facility. The DR experiments were performed at the electron-coolers at the CSRm and the CSRe, as marked by the red rectangles.

Several DR experiments of heavy ions have been performed at the CSRm, and a detailed description of the DR experiments of Lithium-like $^{36}Ar^{15+}$ at the CSRm is presented in [18]. Here, we will only briefly overview the DR experiment of argon ions at the CSRm to show the specific experimental technique and method. The lithium-like argon ions, produced from an Electron Cyclotron Resonance (ECR) ion source, are accelerated by the SFC, and then injected into the CSRm with an beam energy of 8.37 MeV/u. The EC-35 was employed to cool the ion beam and was also used as an free electron target in the measurements. During the experiment, the ion beam was merged with the electron beam over an effective interaction length of L = 3.4 m in the cooler section. A schematic view of the DR experimental setup at the CSRm is shown in Fig. 2. In the measurement cycle, the ion beam was injected into the CSRm and electron-cooled for several seconds until the high quality ion beam was obtained. Then the electron energy detuning system started to work, and applied a bias voltage on the electron cooler cathode to scan the electron beam energy according to a preset timing sequence [21]. Downstream of electron cooler EC-35, the recombined ions were separated from the primary ion beam in the first bending magnet and detected by a movable scintillator particle detector (YAP: Ce + PMT) with 100% detection efficiency [22]. During the measurement, a DC current transformer (DCCT) was used to monitor the ion beam current in real time and the lifetime of $^{36}Ar^{15+}$ beam in the CSRm was about 120 s. Ion beam position monitor (BPM) and electron BPM were utilized to monitor the relative position of the ion beam and electron beam in the cooling section. All of the DR measurements were performed under the condition of keeping the electron beam and ion beam parallel along the central line of the cooler. In addition, the Schottky noise signals, recorded and analyzed by a Tektronix RSA3408 spectrum analyzer, were also used to diagnose the ion beams dynamics and to correct the experimental data analysis off-line.

In the DR experiments at heavy ion storage rings, the recombination rate coefficients α can be deduced from the background subtracted recombination counting rate R at a relative energy E_{rel} between electron and ion by the formula [23]:

$$\alpha = \frac{R}{N_i n_e (1 - \beta_e \beta_i)} \frac{C}{L} \tag{3}$$

where N_i is the number of stored ions, n_e is the density of electron beam, L is the effective interaction section, C is the circumference of the storage ring. The DR spectrum of Lithium like argon $^{36}Ar^{15+}$ obtained from the DR experiment at the CSRm is shown in Fig. 3. The measured spectrum covers the whole energy range of $\Delta n = 0$ excitations $2s \rightarrow 2p_{1/2}$ and $2s \rightarrow 2p_{3/2}$. Associated Rydberg resonance series of the doubly excited intermediate states $2p_{1/2}\ nl_j$ and $2p_{3/2}\ nl_j$ are indicated by vertical bars. From the DR resonance

Table 1
The relevant parameters of DR experiments at HIRFL-CSR.

Parameters (Unit)	CSRm	CSRe
Circumference (m)	161.0	128.8
Ion beam energy (MeV/u)	6–50	25–400
Electron beam energy (keV)	4–35	10–300
Cathode radius (cm)	1.25	1.25
Magnetic expansion factors	1–4	1–10
Max. magnetic field in gun region (Gs)	1200	5000
Magnetic field at cooling section (Gs)	600–1500	500–1500
Effective cooling section length (m)	3.4	3.4
Transverse temperature $k_B T_{\perp}$(meV)	30	200
Longitudinal temperature $k_B T_{//}$ (meV)	0.1	1