Dielectronic recombination of Be-like argon at the CSRm

Z K Huang, W Q Wen, X Xu, S X Wang, H B Wang, L J Dou, S Mahmood, N Khan, W Q Xu, T H Xu, K Yao, X Y Chuai, X L Zhu, D M Zhao, L J Mao, J C Yang, Y J Yuan, L F. Zhu and X Ma

1 Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China
2 Department of Modern Physics, University of Science and Technology of China, Hefei, 230026, China.
3 University of Chinese Academy of Sciences, Beijing 100049, China.
4 School of Science, Bengbu University, Bengbu 233030, China.
5 Institute of Modern Physics, Fudan University, Shanghai 200433, China

E-mail: x.ma@impcas.ac.cn

Abstract. Electron-ion recombination of Be-like 40Ar14+ has been measured for the first time at the main Cooler Storage Ring (CSRm) at Heavy Ion Research Facility in Lanzhou (HIRFL), China. The absolute rate coefficients over 0-60 eV electron-ion energy were obtained and all the resonances associated with the $\Delta n=0$ dielectronic recombination channel ($2s^2 \rightarrow 2s2p$) were studied. In addition to radiative and dielectronic recombination, the recombination spectrum also shows strong contributions from trielectronic recombination channel ($2s^2 \rightarrow 2p^2$). The experimental method and preliminary results are presented.

1. Introduction

The radiative recombination (RR) and dielectronic recombination (DR) are important electron-ion recombination processes in naturally occurring and man-made plasmas [1]. In RR process, a free electron is captured into a bound state of the ion and directly decays by emitting a photon. However, DR is a two-step process in which a doubly excited intermediate state is formed through a resonant process involving capture of a free electron and simultaneously excitation of a bound electron, then the doubly excited intermediate state stabilizes into a stable state against autoionization via photoemission. In last two decades, electron-ion recombination experiments have already been intensively investigated on many heavy ion storage rings. i.e., the Test Storage Ring (TSR) at MPIK in Heidelberg [2], the Experimental Storage Ring (ESR) at GSI in Darmstadt [3], Germany, and the CRYRING at MSL in Stockholm, Sweden [4]. In addition, the electron beam ion traps (EBITs) are also employed to study electron-ion recombination and play a crucial role in understanding fundamental electron-ion collision processes. i.e., DR measurements at LLNL EBIT [5], NIST-EBIT [6], Tokyo-EBIT [7], Stockholm-EBIT [8], interference between resonant and nonresonant photorecombination at Shanghai-EBIT [9], and observation of trielectronic recombination at Heidelberg-EBIT [10].

For Be-like ions, apart from RR and DR, the electronic recombination is feasible to proceed through another resonant pathway, involving the simultaneously excitation of both $2s$ core electrons into a $2p^2$ triply excited state during attachment of a free electron to an $nl$ Rydberg state, called trielectronic recombination (TR). The TR was observed for the first time from electron-ion recombination experiment of Be-like Cl13+ at storage ring TSR [11]. Afterwards, the following electron-ion
recombination of Be-like ions have been investigated at above mentioned three storage rings. For instance, astrophysics related measurements for C2+, N3+, O4+ [12], F5+ [13], Ne6+ [14], Mg8+ [15], Si10+ [16], Cl13+ [11], Fe22+ [17], hyperfine induced transition investigations on Be like S 12+ [18] and Ti 18+ [19] ions, and precision measurements on Ge28+ [20] and Xe50+ [21] ions to test the quantum electrodynamics (QED) theory and investigate electron-electron correlation effect.

The HIRFL facility have two heavy ion storage rings, the main Cooler Storage Ring (CSRm) and the experimental Cooler Storage Ring (CSRe). The storage rings CSRm and CSRe are equipped with electron coolers EC-35 and EC-300 respectively and provide an ideal research platforms for DR experiments of highly charged stable ions as well as radioisotopes. Argon is the 11th abundant element in the solar system and Be-like argon has been observed in hot solar plasmas where the temperature is ~10^6 K [22]. The intensity ratios of the emission lines from Ar^{14+} can be used to diagnose coronal plasmas [23]. Based on the calibrated DR experiment of Li-like Ar^{15+} at the CSRm [24, 25], we performed the DR experiment of Ar^{14+} with nuclear spin I=0 recently. A feature-rich DR resonance spectrum was obtained in the collision energy from 0 to 60 eV, which covers four (2s^2→2s2p) \Delta n=0 DR series and five (2s^2→2p^2) \Delta n=0 TR series. In the following sections, a short introduction about the experimental measurement and preliminary result of electron-ion recombination spectrum is presented. A brief outlook for upcoming DR experiments at the CSRe and future DR precision spectroscopy at the High Intensity heavy ion Accelerator Facility (HIAF) facility will be discussed.

2. Experimental setup

The schematic view of HIRFL-CSR facility combined with the DR experimental setup at the CSRm is shown in Figure 1. The detailed experimental setup and method for DR experiment at CSRm has already been described in details in reference [24]. Here we give a very brief introduction to electron-ion recombination experiments of Be-like Ar^{14+} at CSRm. The ions were firstly produced in an Electron Cyclotron Resonance Ion Source (ECRIS), accelerated by the Sector Focused Cyclotron (SFC), and then injected into the CSRm with an energy of 6.928 MeV/u. Electron cooler EC-35 was employed to cool the ion beam and also used as an electron target for the electron-ion recombination experiments. The ion beam was always kept at the same mean velocity with electron beam under the electron cooling condition. In order to obtain the nonzero relative energy between electron and ion beams in the center-of-mass (c.m.) frame, a bias voltage produced by electron energy detuning system was directly applied on the cathode of the cooler to change the electron beam energy according to a pre-set timing sequence [24, 26]. The main parameters for this experiment are listed in Table 1.
Figure 1. The schematic view of HIRFL-CSR facility combined with DR experimental setup at the CSRm. The DR experimental setup is located at the electron cooler section.

Table 1. The main parameters of DR experiment of Be-like argon

| Parameters                  | Value |
|-----------------------------|-------|
| Circumference of CSRm (m)   | 161.0 |
| Interaction length (m)      | 4.0   |
| The radius of beam tube (cm)| 12.5  |
| Beam energy (MeV/u)         | 6.928 |
| The max beam current (μA)   | 50    |
| Beam momentum spread (δp/p) | 2.2×10^{-4} |
| Beam life time (s)          | 50    |
| Cooling point (kV)          | -3.760|
| Electron beam current (mA)  | 118.4 |
| The radius of electron beam (cm)| 2.6  |
| Magnetic field at cooling section (GS)| 390 |
| Magnetic field at gun section (GS)| 1250 |

A DC current transformer (DCCT) was used to monitor the ion beam current and life time in real time during the experiment. Two independent beam position monitors (BPM) were utilized to monitor the relative position of the ion beam and electron beam in the cooling section. In addition, a Tektronix RSA3408 Schottky noise signals spectrum analyzer was employed to diagnose the longitudinal beam dynamics and correct the experimental data analysis off-line. In each measurement cycle, the ion beam was electron cooled for 3~5 seconds after injection and reached an equilibrium distribution with an longitudinal momentum spread of ~2×10^{-4}. The recombined ions, formed at the merge section, were separated from the primary ion beam in the first bending magnet downstream of electron cooler, and detected by a movable scintillator particle detector (YAP: Ce + PMT) with 100% detection efficiency [27]. The absolute recombination rate coefficients $\alpha$ can be deduced from background subtracted count rate R with the following formula,

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

where $N_i$ is the number of stored ions in the ring, $n_e$ is the density of electron beam, $L$ is the length of effective interaction section, $C$ is the circumference of the storage ring, $\beta_e$ and $\beta_i$ are the relativistic factors of electron and ion beams, respectively.

3. Results and discussion

The measured recombination spectrum of Be-like $^{40}\text{Ar}^{14+}$ from 0 to 60 eV is shown in Figure 2. The resonant electron capture in DR and TR processes can be proceeded through the following pathways and leads to series of resonance peaks.

$$\epsilon^- + \text{Ar}^{14+}(2s^2 \ 3S_0) \rightarrow \begin{cases} \text{Ar}^{13+}[2s2p(\frac{1}{2}P_{0,2})n\ell]^+\,, n \geq 10, \text{ DR}; \\ \text{Ar}^{13+}[2s2p(\frac{1}{2}P_{1})n\ell]^+\,, n \geq 7, \text{ DR}; \\ \text{Ar}^{13+}[2p^2(\frac{1}{2}P_{0,1,2}+\frac{1}{2}D_{2,1}+\frac{1}{2}S_{0})n\ell]^+\,, n \geq 6, \text{ TR}; \end{cases}$$
In the recombination spectrum, the resonance positions of each Rydberg state can be well approximated by Rydberg formula:

\[ E_{\text{res}} = E_{\text{exc}} - R \frac{n^2}{q^2} \]

where \( E_{\text{exc}} \) is the core excitation energy of the ions, which is taken from the NIST database. \( R \) is the Rydberg constant, \( q \) is the charge state of the target ion. The energy axis has been scaled up by a factor of 1.06 to achieve agreement with the known \( 2s2p \, ^1P_1 \) series limit at 56 eV. Based on the Eq. (3), all the Rydberg series of the \( \Delta n=0 \) dielectronic recombination channel (\( 2s^2 \rightarrow 2s2p \)) are indicated with vertical bars in different colors as shown in Figure 2. The dielectronic series \( 2s2p \, ^1P_1 \) can be resolved up to \( n = 25 \) under the present energy resolution. The series limit is for \( n_{\text{cut}} = 74 \) due to the field ionization of the bending magnet upstream the detector. The energy position of \( 2s2p \, ^3P_{0,1,2} \) series limits are around 30 eV and mixed with resonances \( 2s2p \, ^1P_1 \) \( 10l \), and could not be resolved.

By fitting the first four resonance peaks at relative energy below 0.5 eV with a flattened Maxwellian profile [28], the obtained electron temperature distributions are \( k_BT_|| = 2.45 \) meV and \( k_BT_\perp = 10.96 \) meV for longitudinal and transverse direction, respectively. As a result, the experimental energy resolution is determined to be 0.07 eV full width at half maximum at the relative energy around 0.2 eV. The resonance peaks around 0.5 eV, 4 eV and 11 eV cannot be fully identified according to the indication of the DR series associated with \( ^3P_{0,1,2} \) and \( ^1P_1 \) as shown in Figure 2. These peaks belong to the contribution from TR process and identified as Rydberg series associated with the transition \( 2s^2 \rightarrow 2p^2 \) (\(^1S_0, ^1D_2, ^3P_{0,1,2}\)). To fully understand the electron-ion recombination spectrum as shown in Figure 2, a theoretical calculation of Be-like argon ion by AUTOSTRUCTURE code is currently in progress. The recombination rate coefficient of Be-like \(^{40}\)Ar\(^{14+}\) including experimental and theoretical results as well as plasma rate coefficients will be described in a paper which is in preparation.

**Figure 2.** The electron-ion recombination spectrum of Be-like argon. The energy axis has been scaled up by a factor of 1.06 to achieve agreement with the known \( ^1P_1 \) series limit at 56 eV. Four \( \Delta n = 0 \) DR series associate with \( 2s^2 \rightarrow 2s2p, \, ^1P_1, \, ^3P_{0,1,2} \) and parts of five \( \Delta n = 0 \) TR series \( 2s^2 \rightarrow 2p^2, \, ^1S_0, \, ^1D_2, \, ^3P_{0,1,2} \) are observed and indicated by vertical bars in different colors.

4. Summary and outlook
In summary, the DR spectrum of Be-like \(^{40}\)Ar\(^{14+}\) was successfully measured for the first time at the CSRm electron-cooler. The \( \Delta n = 0 \) transitions of DR \( (2s^2 \rightarrow 2s2p) \) and parts of TR \( (2s^2 \rightarrow 2p^2) \) were
observed within the measured energy region of 0-60 eV in the c.m. frame. The plasma rate coefficients obtained from the measured DR rate coefficients of Be-like $^{40}$Ar$^{14+}$ will be useful data for astrophysics. Based on the experience from the DR experiments at the CSRm, a new electron energy detuning system for electron-ion recombination experiments at the CSRe is being developed in cooperation with Budker Institute of Nuclear Physics (BINP) in Russia. The detuning range of the high voltage will be increased up to 30 kV at EC-300 in the CSRe, as a result, a relative energy between ion beam and electron beam could be scanned to more than 1500 eV. The DR spectroscopy of HCIs and radioactive nuclides will be accessed.

In addition, a new facility HIAF is in design phase, and will be constructed by IMP in China [29]. An electron cooler and a separated ultra-cold electron target will be installed at SRing@HIAF, which will provide a unique opportunity for DR spectroscopy of highly charged ions. The investigation of the strong field QED, and interface of atomic and nuclear physics are foreseen by the DR experiments at SRing@HIAF [25].

5. Acknowledgements

This work is partly supported by the National Key R&D Program of China under Grant No. 2017YFA0402300, the NSFC through No. 11320101003, No. 91336102, No. 11604003, No. U1732133, Key Research Program of Frontier Sciences, CAS, Grant No. QYZDY-SSW-SLH006 and the Strategic Priority Research Program of the Chinese Academy of Sciences, Grant No. XDB21030900. The authors would like to thank the crew of Accelerator Department for skillful operation of the CSR accelerator complex.

References

[1] Müller A 2008 Adv. At. Mol. Opt. Phys. (Berlin: Academic Press) p 293-417
[2] Schippers S 2015 Nucl. Instrum. Meth. B 350 61-65
[3] Brandau C, Kozhuharov C 2012 Atomic Processes in Basic and Applied Physics (Berlin: Springer) p 283-306
[4] Schuch R, Böhm S 2007 J. Phys.: Conf. Ser. 88 012002
[5] DeWitt D R, et al. 1991 Phys. Rev. A 44 7185-7188
[6] McLaughlin D J, et al. 1996 Phys. Rev. A 54 2040-2049
[7] Rourke B E O, et al. 2004 J. Phys. B: At. Mol. Opt. Phys. 37 2343
[8] Mahmood S, et al. 2012 Astrophy. J. 754 86
[9] Tu B, et al. 2016 Phys. Rev. A 93 032707
[10] Beilman M, et al. 2009 Phys. Rev. A 80 050702
[11] Schnell M, et al. 2003 Phys. Rev. Lett. 91 043001
[12] Fogle M, Badnell N R 2005 Astron. Astrophys. 442 757-766
[13] Ali S, et al. 2013 Astron. Astrophys. 557 906-908
[14] Orban I, et al. 2008 Astron. Astrophys. 489 829-835
[15] Schippers S, et al. 2004 Astron. Astrophys. 421 1185-1191
[16] Orban I, et al. 2010 Astrophy. J. 721 1603-1607
[17] Savin D W, et al. 2006 Astrophy. J. 642 1275-1285
[18] Schippers S, et al. 2012 Phys. Rev. A 85 012513
[19] Schippers S, et al. 2007 Phys. Rev. Lett. 98 033001
[20] Orlov D A, et al. 2009 J. Phys.: Conf. Ser. 163 012058
[21] Bernhardt D, et al. 2015 J. Phys. B: At. Mol. Opt. Phys. 48 144008
[22] Bhatia A K, Landi E 2008 Atom Data Nucl Data 94 223-256
[23] Landi E, et al. 2001 Astrophy. J. 556 912
[24] Huang Z K, et al. 2015 Phys. Scr. T166 014023
[25] Huang Z K, et al. 2017 Nucl. Instrum. Meth. B 408 135-139
[26] Meng L-J, et al. 2013 Chin. Phys. C 37 017004
[27] Wen W Q, et al. 2013 Nucl. Instrum. Meth. B 317 731-733
[28] Kilgus G, et al. 1992 Phys. Rev. A 46 5730-5740
[29] Ma X, et al. 2017 Nucl. Instrum. Meth. B 408 169-173