

## Electron-ion Recombination Rate Coefficients of Be-like $^{40}\text{Ca}^{16+}$

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## ABSTRACT

Electron-ion recombination rate coefficients for beryllium-like calcium ions in the center of mass energy from 0 to 51.88 eV have been measured by employing the electron-ion merged-beam technique at the cooler storage ring CSRm at the Institute of Modern Physics, Lanzhou, China. The measurement energy range covers the dielectronic recombination (DR) resonances associated with the  $2s^2\ ^1S_0 \rightarrow 2s2p\ ^3P_{0,1,2},\ ^1P_1$  core

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excitations and the trielectronic recombination (TR) resonances associated with the  $2s^2\ ^1S_0 \rightarrow 2p^2\ ^3P_{0,1,2},\ ^1D_2,\ ^1S_0$  core excitations. In addition, theoretical calculations of the recombination rate coefficients have been performed for comparison with the experimental results using the state-of-the-art multi-configuration Breit-Pauli atomic structure code. Resonant recombination originating from parent ions in the long-lived metastable state  $2s2p\ ^3P_0$  ions has been identified in the recombination spectrum below 1.25 eV. A good agreement is achieved between the experimental recombination spectrum and the result of the AUTOSTRUCTURE calculations when fractions of 95% ground-state ions and 5% metastable ions are assumed in the calculation. It is found that the calculated TR resonance positions agree with the experimental peaks while the resonance strengths are much underestimated by the theoretical calculation. Temperature dependent plasma rate coefficients for DR and TR in the temperature range  $10^3 - 10^8$  K were derived from the measured electron-ion recombination rate coefficients and compared with the available theoretical results from the literature. In the temperature range of photoionized plasmas, the presently calculated rate coefficients and the recent results of [Gu \(2003\)](#) and [Colgan et al. \(2003\)](#) are up to 30% lower than the experimentally derived plasma rate coefficients, and the older atomic data are even up to 50% lower than the present experimental result. This is because strong resonances situated below electron-ion collision energies of 50 meV were underestimated by the theoretical calculation, which also has a severe influence on the rate coefficients in low temperature plasmas. In the temperature range of collisionally ionized plasmas, agreement within 25% was found between the experimental result and the present calculation as well as the calculation by [Colgan et al. \(2003\)](#). The present result constitutes a set of benchmark data for use in astrophysical modeling.

*Keywords:* atomic process – atomic data – plasma

## 1. INTRODUCTION

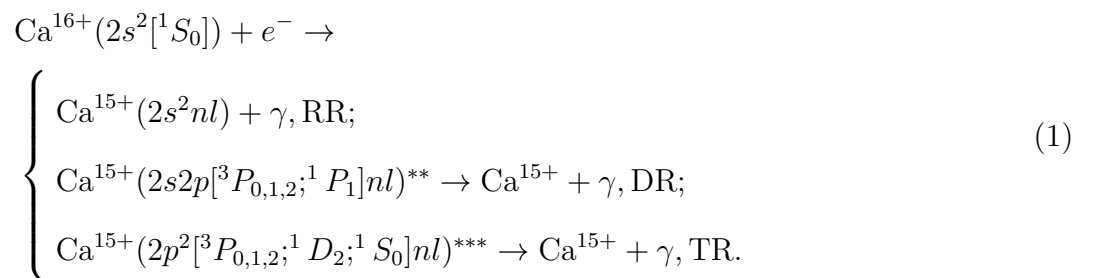
48 It has been estimated that more than 90% of the visible matter in our universe is in the plasma state  
49 (Beyer & Shevelko 2003). Cosmic atomic plasmas are divided into two broad classes (see Savin 2007,  
50 for a more in-depth discussion), i): photoionized plasmas, often found in planetary nebulae, X-ray  
51 binaries and active galactic nuclei; ii): collisionally ionized plasmas, often found in stars and galaxies.  
52 Various types of reactions taking place in astrophysical plasmas, including electron impact ionization,  
53 excitation, de-excitation and electron-ion recombination, can result in the emission of radiation. In  
54 order to explore the properties of astrophysical plasmas, such as, e.g., charge state distribution,  
55 temperature and elemental abundances (Beiersdorfer 2003; Kallman & Palmeri 2007), the X-ray  
56 observatories ASCA, Chandra (NASA) and XMM-Newton (ESA), have been launched to observe  
57 high resolution X-ray spectra from various cosmic sources (Paerels et al. 2003). To interpret the  
58 observed spectra by plasma modeling, accurate atomic data for electron-ion recombination processes,  
59 in particular, for radiative recombination (RR) and dielectronic recombination (DR), are crucial for  
60 astrophysicists.

61 The importance of DR in plasma was not appreciated until Burgess first recognized its significance  
62 in 1964 (Burgess 1964). Since then, DR has been considered to be a significant electron-ion recom-  
63 bination mechanism, governing the charge state distribution and the temperature in atomic plasmas  
64 and contributing to their line emission (Badnell 2007; Savin 2007). Reliable recombination rate coef-  
65 ficients are required for understanding and modeling laboratorial or astrophysical plasmas. Most of  
66 the available rate coefficients are from theory. However, the theoretical prediction of DR resonance  
67 positions and strengths particularly at low electron-ion collision energies is still a challenging task  
68 since an infinite number of states is involved in the DR process and relativistic many body effects  
69 should be taken into account in high orders. Presently available atomic structure codes are not able  
70 to provide resonance positions in the low energy region with sufficient precision. Unfortunately, small  
71 shifts of low energy DR resonance positions can translate into huge uncertainties of the temperature  
72 dependent rate coefficient in a plasma. In addition, recent experimental studies of low energy range  
73 DR have also shown that results from earlier computations of low-temperature DR rate coefficients  
74 are not reliable (Huang et al. 2018). Thus, accurate experimental DR rate coefficients are needed

75 to benchmark different theoretical approaches and to produce more reliable recombination data. It  
 76 should be noted that heavy-ion storage rings equipped with electron coolers are presently the only  
 77 tools to produce reliable low temperature DR rate coefficients with high precision. Previous DR  
 78 experiments were carried out at the storage rings, i.e., TSR at MPIK in Heidelberg (Schippers 2015),  
 79 ESR at GSI in Darmstadt, Germany (Brandau et al. 2015), and CRYRING at MSL in Stockholm,  
 80 Sweden (Schuch & Böhm 2007). More details about DR experiments at the storage rings can be  
 81 found in a recent review by Schippers (2012) and in the references cited therein.

82 Calcium is one of the most abundant elements in the solar system (Asplund et al. 2009; Feldman  
 83 & Laming 2000) and the solar element abundances reflect the element abundances in the universe  
 84 (Doscsek & Feldman 2010). Line emissions caused by  $2s2p\ ^1P_1 - 2s^2\ ^1S_0$  transition of Ca XVII  
 85 at 192.8 Å were widely observed in X-ray solar flare spectra by the Extreme-Ultraviolet Imaging  
 86 Spectrometer (EIS) on Hinode (Ko et al. 2009). Observation of the Tycho supernova remnant by  
 87 XMM-Newton and Cassiopeia A by Chandra have also revealed strong emissions from the calcium  
 88 ions (Decourchelle et al. 2001; Hwang & Laming 2003). A summary of the spectral lines for Ca XVII  
 89 can be found in a topical review by Doscsek & Feldman (2010) and the atomic data table compiled by  
 90 Landi & Bhatia (2009). In addition, laboratory study of the spectra of highly ionized calcium in the  
 91 100-250 Å range applied to solar flare diagnostics were performed at the TEXT tokamak (Lippmann  
 92 et al. 1987). Here, we present absolute rate coefficients for electron-ion recombination of Be-like  
 93 calcium ions from an experiment at the main cooler storage ring CSRm and from the theoretical  
 94 calculation using the AUTOSTRUCTURE code (Badnell 2011).

For Be-like  $\text{Ca}^{16+}$ , the most significant recombination channels in the experimental measurement energy range can be expressed as



Here  $\gamma$  denotes the decay photons. RR is the time reversal of direct photoionization, where a free electron is captured by an ion with emission of a photon simultaneously. DR is a two-step resonant process, in which a free electron is captured by an ion with simultaneous excitation of a core electron, forming a doubly excited ion at first. Subsequently, the unstable intermediate state decays either by autoionization or radiatively. The auto-ionization channel returns the system to the original charge state, whereas the radiative decay, when leading to a state below the ionization threshold, completes the DR process. In Be-like systems, due to the strong correlation between the two bound  $2s$  electrons, they can be excited simultaneously forming triply excited  $2p^2 nl$  levels with the initially free electron being captured to an atomic subshell  $nl$ . As there are three electrons associated with this process and a triply excited state is formed, it is termed trielectronic recombination (TR). The transition energies and lifetimes associated with the here discussed channels are listed in Table 1.

A number of DR experiments with Be-like ions have been performed at heavy-ion storage rings. Electron-ion recombination rate coefficients of  $C^{2+}$ ,  $N^{3+}$ ,  $O^{4+}$  (Fogle et al. 2005),  $F^{5+}$  (Ali et al. 2013),  $Ne^{6+}$  (Orban et al. 2008),  $Mg^{8+}$  (Schippers et al. 2004),  $Si^{10+}$  (Orban et al. 2010; Bernhardt et al. 2016),  $Ar^{14+}$  (Huang et al. 2017, 2018) and  $Fe^{22+}$  (Savin et al. 2006) have been measured as benchmark data for astrophysical plasma modeling. TR was first observed with Be-like  $Cl^{13+}$  at the TSR (Schnell et al. 2003), and hyperfine-induced transition rates of Be-like  $Ti^{18+}$  and  $S^{12+}$  were investigated by means of DR spectroscopy at the TSR (Schippers et al. 2007a,b, 2012). Furthermore, DR spectroscopy was used to investigate quantum electrodynamics (QED) and electron-electron correlation effects in  $Ge^{28+}$  and  $Xe^{50+}$  (Orlov et al. 2009; Bernhardt et al. 2015).

Here we report the first measurement of the electron-ion recombination spectrum of Be-like  $Ca^{16+}$ . This paper is structured as follows: The experimental setup and data analysis are presented in section 2. In section 3, we will give a brief introduction to the theoretical calculations with the AUTOSTRUCTURE code. Results of merged-beam recombination rate coefficients as well as plasma rate coefficients are presented and discussed in section 4. Conclusions are given and the most important results are summarized in section 5.

## 2. EXPERIMENT AND DATA ANALYSIS

**Table 1.** Excitation energies and lifetimes of  $\text{Ca}^{16+}$  levels.

| Level                | Excitation energy         |                            | Lifetime<br>(s)     |
|----------------------|---------------------------|----------------------------|---------------------|
|                      | NIST <sup>a</sup><br>(eV) | (Wang et al. 2015)<br>(eV) |                     |
| $1s^2 2s^2 \ ^1S_0$  | 0                         | 0                          | $\infty$            |
| $1s^2 2s 2p \ ^3P_0$ | 32.024                    | 32.0355                    | 2.3[6] <sup>b</sup> |
| $1s^2 2s 2p \ ^3P_1$ | 33.409                    | 33.4235                    | 1.475[-7]           |
| $1s^2 2s 2p \ ^3P_2$ | 36.817                    | 36.8259                    | 3.600[-3]           |
| $1s^2 2s 2p \ ^1P_1$ | 64.301                    | 64.2983                    | 8.948[-11]          |
| $1s^2 2p^2 \ ^3P_0$  | 85.435                    | 85.4478                    | 1.231[-10]          |
| $1s^2 2p^2 \ ^3P_1$  | 87.617                    | 87.6299                    | 1.148[-10]          |
| $1s^2 2p^2 \ ^3P_2$  | 90.068                    | 90.0797                    | 1.146[-10]          |
| $1s^2 2p^2 \ ^1D_2$  | 98.956                    | 98.9378                    | 3.325[-10]          |
| $1s^2 2p^2 \ ^1S_0$  | 119.914                   | 119.903                    | 5.736[-11]          |

<sup>a</sup> Energy levels taken from NIST atomic spectra database (Kramida et al. 2018).

<sup>b</sup> Lifetime associated with the E1M1 two-photo transition is estimated according to the calculated results by Fritzsche et al. (2015).

122 The experiment was performed at the main cooler storage ring (CSRm) at the Institute of Modern  
 123 Physics in Lanzhou, China. A detailed description of the experimental setup and the experimental  
 124 procedures for DR experiments at the CSRm have already been given by Huang et al. (2015, 2018).  
 125 Here we will only briefly describe the electron-ion recombination experiment with Be-like  $^{40}\text{Ca}^{16+}$  at  
 126 the CSRm.

127 The  $^{40}\text{Ca}^{16+}$  ions were produced in a superconducting electron cyclotron resonance (ECR) ion  
 128 source, accelerated by a sector focused cyclotron, and then injected into the CSRm at an energy of  
 129 8.42 MeV/u. Every injection pulse of ions was sufficient to provide a maximum ion beam current of

130 about  $90 \mu\text{A}$ , corresponding to  $1.4 \times 10^8$  ions stored in the ring. The storage lifetime of the ion beam  
 131 was about 50 s. During the experiment, the 35 kV electron cooler was employed to maintain the  
 132 high quality ion beam by means of electron cooling. The electron beam was also used as an electron  
 133 target in the recombination experiment. In the cooler section, the ion beam was merged with the  
 134 electron beam over an effective interaction length  $L = 4.0$  m. In order to generate a colder electron  
 135 beam to reach a higher experimental resolution, it was magnetically expanded (Danared 1993). The  
 136 magnetic fields applied at the cathode and the cooler section were 125 mT and 39 mT, respectively.  
 137 The expanded diameter of the electron beam was  $d \sim 62$  mm and the electron density in the cooler  
 138 section was  $9.2 \times 10^5 \text{ cm}^{-3}$  in the cooler section. The recombined ions formed in the cooling section  
 139 were separated from the main ion beam in the first dipole magnet downstream from the electron  
 140 cooler and detected by a movable scintillation particle detector (YAP:Ce+PMT) with nearly 100%  
 141 efficiency (Wen et al. 2013).

142 To ensure a high ion-beam quality, the stored ions were electron-cooled for about 2 s after their  
 143 injection pulses into the storage ring. During the electron cooling, the electron energy was set at  
 144 the cooling energy of 4.62 keV, which corresponds to zero electron-ion collision energy in the center  
 145 of mass frame. Offset voltages were applied to the cathode voltage by a suitably designed detuning  
 146 system to obtain non-zero collision energies. In addition, a DC current transformer (DCCT) was used  
 147 to monitor the ion beam current and the lifetime of the ion beam in the ring in real time. Two ion  
 148 beam position monitors (BPM) and one electron BPM were utilized to monitor the spatial overlap  
 149 of the electron beam and the ion beam in the cooling section. Schottky-noise signals were recorded  
 150 and analyzed by a Tektronix RSA3408 spectrum analyzer to monitor the revolution frequency and  
 151 the momentum spread of the ions. The latter was  $\Delta p/p \sim 2.2 \times 10^{-4}$ .

The absolute recombination rate coefficient as a function of the collision energy can be deduced  
 from the energy dependent detector count rate  $R(E)$  as

$$\alpha(E) = \frac{R(E)}{N_i n_e (1 - \beta_e \beta_i)} \frac{C}{L}. \quad (2)$$

152 Here,  $N_i$  is the number of the stored ions in the ring,  $n_e$  is the electron density,  $C = 161.0$  m and  
 153  $L = 4.0$  m denote the circumference of the ring and the length of the effective interaction section,  
 154 respectively. RR and DR evolve from the same initial charge state to the same final charge state and  
 155 they are indistinguishable quantum mechanically. Therefore, the deduced rate coefficient comprises  
 156 of these two parts as well as an background resulting from collisions of stored ions with residual-gas  
 157 particles. In this work, the RR rate coefficient and the background were subtracted by an empirical  
 158 formula described by [Schippers et al. \(2000\)](#).

The electron-ion collision energy in the center of mass frame was calculated using

$$E_{rel} = \sqrt{m_e^2 c^4 + m_i^2 c^4 + 2m_e m_i \gamma_e \gamma_i c^4 (1 - \beta_e \beta_i \cos \theta)} - m_e c^2 - m_i c^2 \quad (3)$$

159 where  $m_e$  and  $m_i$  are the electron and ion rest mass, respectively,  $c$  is the speed of light,  $\beta_e = v_e/c$   
 160 and  $\beta_i = v_i/c$  are the electron and ion velocities in the laboratory frame, and  $\gamma_e$  and  $\gamma_i$  denote the  
 161 respective Lorentz factors. The angle  $\theta$  between the electron and ion beam is considered to be zero in  
 162 the present experiment. Space charge effects were taken into account. Drag force effects were found  
 163 to be negligible. The measurement covers the electron-ion collision energies in the center of mass  
 164 frame ranging from 0 to 51.88 eV which corresponds to detuning voltages in the range 0-900 V. In  
 165 the present experiment, the same power supplies were used as in the recombination experiment with  
 166 Be-like  $\text{Ar}^{14+}$  at CSRm. Thus, the experimental energy scale has been recalibrated by a factor of  
 167 1.05 in the same manner as described by [Huang et al. \(2018\)](#).

### 168 3. THEORY

169 To fully understand the measured electron-ion recombination rate coefficients, the resonant recom-  
 170 bination cross sections were calculated by the distorted-wave collision package AUTOSTRUCTURE  
 171 ([Badnell 2011](#)). AUTOSTRUCTURE is a versatile code that is able to calculate energy levels, os-  
 172 cillator strengths, radiative/autoionization rates, and many other quantities using semi-relativistic  
 173 kappa-averaged wave functions. The calculations for  $\text{Ca}^{16+}$  were performed in the same way as for  
 174  $\text{Ar}^{14+}$  (see [Huang et al. 2018](#), for further details). In particular, the core excited energies were ad-



175 justed to match the spectroscopic values from NIST atomic spectra database ([Kramida et al. 2018](#)).  
 176 Fractions of 95% ground-state ions and 5% metastable ions were assumed in the calculation.

In order to compare the experimentally derived electron-ion recombination rate coefficients with the theoretical calculation directly, the calculated cross sections were multiplied by the electron velocity and convoluted with the velocity distribution of the electrons for the experiment:

$$\alpha(E) = \int_{-\infty}^{+\infty} \sigma(v) v f(v, T_{\parallel}, T_{\perp}) d^3v, \quad (4)$$

177 where  $f(v, T_{\parallel}, T_{\perp})$  is the anisotropic electron velocity distribution, which is characterized by the  
 178 parallel and perpendicular electron temperatures  $k_B T_{\parallel} = 0.8 \text{ meV}$  and  $k_B T_{\perp} = 40 \text{ meV}$  ([Huang et al.](#)  
 179 [2015](#)).

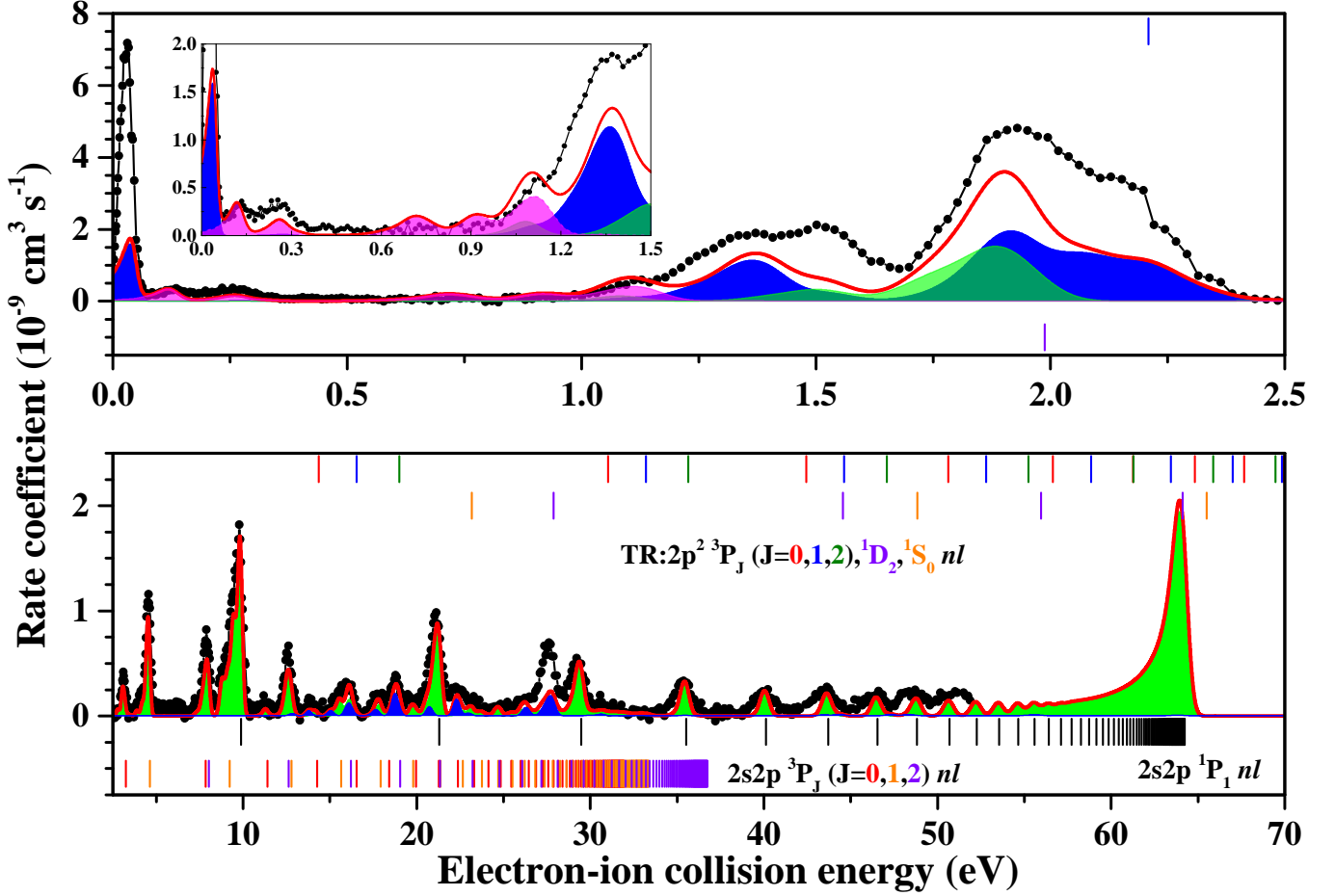
## 180 4. RESULTS AND DISCUSSION

### 181 4.1. Merged-beam recombination rate coefficients

The absolute merged-beam recombination rate coefficients for Be-like calcium ions are displayed in Figure 1. The measured spectrum covers the energy range 0-51.88 eV. It contains DR resonances associated with excitation of the  $2s^2$  core to the  $2s2p \ ^3P_{0,1,2}$  and  $2s2p \ ^1P_1$  levels and significant TR contributions. The resonance positions of each Rydberg state can be estimated from the Rydberg formula

$$E_{res}(n) = E_{exc} - R \frac{q^2}{n^2} \quad (5)$$

182 where  $R \approx 13.60569 \text{ eV}$  is the Rydberg constant,  $q = 16$  is the primary ion charge state,  $n$  denotes the  
 183 principal quantum number of the captured electron, and  $E_{exc}$  is the core-excitation energy. Values for  
 184  $E_{exc}$  are listed in Table 1 for a number of transitions of interest. The formula works well for high- $n$   
 185 resonances where the interaction between the Rydberg electron and the core electrons is very weak.  
 186 However, the low- $n$  resonance positions are dominated by the complex fine structure of the associated  
 187 multiply excited configurations. In the storage ring electron-ion recombination experiments at CSRm,  
 188 the recombined ions traverse one toroidal magnet, three quadrupole magnets and one dipole magnet  
 189 on their way to the detector. The motional electric fields that the ions experience in these magnets



**Figure 1.** Absolute electron-ion recombination rate coefficients of Be-like Ca as a function of collision energy. The experimental result (the connected filled circles) covers the energy range 0-51.88 eV. The presently calculated field-ionization-free rate coefficient (the red solid line) accounts for fractions of 95% ground-state ions and 5%  $2s2p \ ^3P_0$  metastable ions. The pink shaded area shows the rate coefficient originating from the metastable state ions. DR and TR rate coefficients are denoted by shaded green and blue curves, respectively. The vertical bars below the spectra denote the estimated resonance positions (Eq. 5) for the  $\Delta N = 0$  series of DR resonances associated with  $2s^2 \ ^1S_0 \rightarrow 2s2p \ ^3P_{0,1,2}, ^1P_1$  core excitations. TR resonance positions associated with the  $2s^2 \ ^1S_0 \rightarrow 2p^2 \ ^3P_{0,1,2}, ^1D_2, ^1S_0$  core excitations are indicated by the differently colored vertical bars above the spectra.

190 lead to field ionization of Rydberg electrons with their principal quantum numbers  $n > n_{cutoff}$  will  
 191 be field-ionized at the magnets before being detected. The field-ionized ions cannot be separated  
 192 from the primary ion beam and, consequently, will not be detected. The cut-off quantum number  
 193  $n_{cutoff}$  can be estimated by a simple formula (Fogle et al. 2005). However, the present experimental

194 recombination spectrum does not cover high- $n$  Rydberg levels converging to the  $2s2p(^1P_1)$  series limit  
 195 at 64.301 eV and the  $2s2p(^3P_J)$  series limits at about 32-37 eV (Table 1) are not prominently visible,  
 196 either, such that there are no marked field-ionization effects on the presently measured DR spectrum.

197 The green shaded area in Figure 1 denotes the calculated  $2s^2 \rightarrow 2s2p \Delta N = 0$  DR rate coefficient.  
 198 It is clear that, the features below 50 meV, around 1.5 eV and 27.5 eV, can not be attributed to DR  
 199 resonances. It can be seen from Figure 1 that the experimental features agree better with the solid red  
 200 line which takes TR contributions into account. The first resonances situated below 50 meV, which  
 201 can be attributed to TR, are significantly stronger than any other resonance feature in the spectrum.  
 202 The resonance strengths of this feature and of those at around 1.5 eV and 27.5 eV, which are also  
 203 dominated by TR, are all underestimated by the theoretical calculation. However, the calculated  
 204 resonance positions fit with the experimental result well. Therefore, the discrepancies between the  
 205 experimental rate coefficients and calculated result are mainly due to the underestimation of the TR  
 206 resonance strengths. As described by Schnell et al. (2003), the formation of the intermediate levels  
 207 depends sensitively on the details of configuration mixing, making the calculation of trielectronic  
 208 recombination a challenge for atomic-structure theory.

209 As a Be-like  $^{40}\text{Ca}^{16+}$  ion with zero nuclear spin, its  $2s2p\ ^3P_0$  excited level can only decay to the  
 210 ground-state by E1M1 two-photon transition (Marques et al. 1993; Cheng et al. 2008; Fritzsche et al.  
 211 2015). Correspondingly, the associated lifetime of this state is about  $2.3 \times 10^6$  s, which is much  
 212 longer than the experimental timescale. A fraction of the circulating ions in the storage ring were  
 213 expected to be at the  $2s2p\ ^3P_0$  level during the experiment. Ions in other excited levels can decay  
 214 to the ground-level during the electron cooling delay before the measurement since their lifetimes  
 215 are rather short compared to the 2 s delay time (see Table 1). The fractions of the long-lived  $^3P_0$   
 216 metastable level when extracted from an ECR ion source were discussed by Urban et al. (2001).  
 217 Accordingly, the percentage of the metastable ions decreases with increasing charging state within  
 218 the Be-like isoelectronic sequence. For example, metastable fractions of 60%, 40%, 35% and 14% were  
 219 found for  $\text{C}^{2+}$ ,  $\text{N}^{3+}$ ,  $\text{O}^{4+}$ , and  $\text{Ne}^{6+}$  ion beams, respectively. Since we also used an ECR ion source  
 220 to produce a Be-like calcium ion beam, a fraction of 5% metastable calcium ions was estimated.

221 This corresponds roughly to what was previously assumed for neighboring members of the Be-like  
 222 isoelectronic sequence of ions such as Ar<sup>14+</sup> (Huang et al. 2018) and Ti<sup>18+</sup> (Schippers et al. 2007a).  
 223 A separate calculation of electron-ion recombination for 5%  $2s2p\ ^3P_0$  metastable ions was conducted  
 224 using AUTOSTRUCTURE code resulting in the pink shaded curve in the inset of Figure 1. It is found  
 225 that most of the resonance features below 1.25 eV. For an overall comparison with the experimental  
 226 recombination spectrum shown in Figure 1, the rate coefficients for ground-level and metastable ions  
 227 were scaled to 95% and 5%, respectively. With this adjustment, the overall agreement between the  
 228 experiment and theory is satisfactory except for the strong TR resonances as discussed above.

229 The uncertainty of the measured rate coefficients is estimated to be less than 30% (at a  $1\sigma$  confidence  
 230 level), including a 15% uncertainty due to statistics, electron and ion beam current, electron-ion  
 231 interaction length, the background subtraction, an uncertainty of 5% from the estimated metastable  
 232 content and an uncertainty of 20% due to the electron density distribution profile and the position  
 233 of the ion beam in this profile.

#### 234 4.2. Plasma recombination rate coefficients

For the applications in plasma modeling and astrophysics, plasma recombination rate coefficients for  
 the resonant recombination channels are needed. The temperature dependent plasma rate coefficient  
 $\alpha(T_e)$  can be obtained by convoluting the RR-subtracted experimental recombination rate coefficient  
 with a Maxwell-Boltzmann electron energy distribution of temperature  $T_e$  (Schippers et al. 2001):

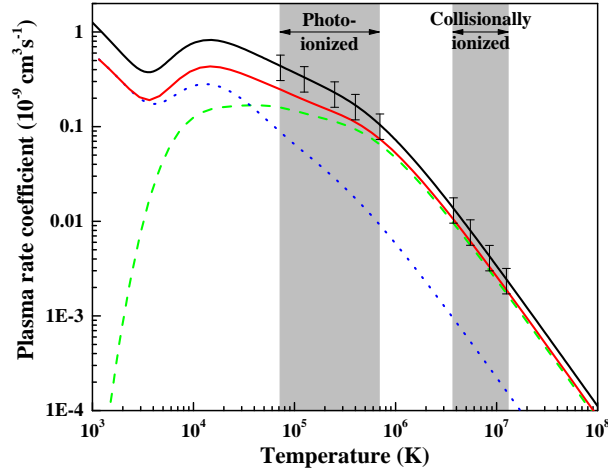
$$\alpha(T_e) = \int \alpha(E) f(E, T_e) dE, \quad (6)$$

$f(E, T_e)$  is the electron energy distribution:

$$f(E, T_e) = \frac{2E^{1/2}}{\pi^{1/2}(kT_e)^{3/2}} \exp\left(-\frac{E}{kT_e}\right). \quad (7)$$

235 Temperature dependent plasma rate coefficient derived from the experimental result and the AU-  
 236 TOSTRUCTURE calculated rate coefficient are displayed in Figure 2. Since the presently measured  
 237 rate coefficient misses the  $^1P_1$  series limit, the measured electron-ion recombination rate coefficient  
 238 from 42 to 70 eV was replaced by the AUTOSTRUCTURE calculation including the recombination

239 into states up to  $n_{max} = 1000$ . It should be noted that the contribution from recombination into res-  
 240 onance levels with  $n > 1000$  can be considered to be very small and, thus, be safely neglected. Such  
 241 a derived plasma rate coefficient is called field-ionization-free plasma recombination rate coefficient.  
 242 It is shown as a black solid line in Figure 2 and 3. To compare with the theoretical rate coefficients  
 243 from the literature, the calculated metastable contribution was subtracted from the experimentally  
 244 derived rate coefficient. The remaining rate coefficient was then renormalized to a 100% ground-level  
 245 ion beam by dividing it by a factor of 0.95. The dashed and dotted lines in Figure 2 show the DR and  
 246 TR contributions, respectively. The vertical error bars denote the 30% uncertainty of the measured  
 247 recombination rate coefficient.



**Figure 2.** Plasma rate coefficients for DR and TR of Be-like  $\text{Ca}^{16+}$  as a function of the electron temperature. The solid black line is the experimentally derived  $\Delta N = 0$  DR and TR rate coefficients. The theoretical results deduced from the AUTOSTRUCTURE code for  $\Delta N = 0$  DR and TR are shown as green dashed line and blue dotted line, respectively. The red solid line is the sum of the calculated DR and TR rate coefficients. The approximate temperature ranges where  $\text{Ca}^{16+}$  is expected to form in photoionized plasmas and collisionally ionized plasmas are indicated by grey shaded areas and associated arrows (Kallman & Bautista 2001; Bryans et al. 2009). The error bars denote a 30% experimental uncertainty.

248 The temperature range in Figure 2 is from  $10^3$  K to  $10^8$  K. It includes the ranges where Be-like  
 249 Ca forms in photoionized and collisionally ionized plasmas. The grey shaded areas with associated  
 250 arrows indicate these temperature ranges. The boundaries of these ranges correspond to the tem-

251 perature where the fractional abundance of Be-like Ca is 10% of its maximum value [Kallman &](#)  
 252 [Bautista \(2001\)](#); [Bryans et al. \(2009\)](#). TR resonances dominate the rate coefficient for temperatures  
 253 below  $3.5 \times 10^4$  K. They play an important role in photoionized plasmas while the TR contribution  
 254 to the rate coefficient is less than 10% in the temperature range of collisionally ionized plasmas. For  
 255 temperatures below  $5.5 \times 10^4$  K where the TR contribution is higher than 40%, the deviation between  
 256 the experimentally derived plasma rate coefficient and the AUTOSTRUCTURE calculation is more  
 257 than 45%. Over the temperature range of photoionized plasmas this deviation decreases from 45%  
 258 to 30% with the decrease of the TR contribution. An agreement of better than 25%, i.e., within the  
 259 experimental uncertainty is found between the present experimental result and the AUTOSTRUC-  
 260 TURE calculation in the collisionally ionized temperature range. A reasonable explanation is that  
 261 the theoretical calculation underestimates the TR resonance strengths below 50 meV, around 1.5 eV  
 262 and 27.5 eV.

For a convenient use of our data in plasma modeling codes, the presently derived plasma rate  
 coefficients were fitted with the function:

$$\alpha(T_e) = T_e^{-3/2} \sum_i c_i \exp\left(-\frac{E_i}{kT_e}\right). \quad (8)$$

263 The fitted values of  $c_i$  and  $E_i$  are listed in Table 2. The fitted results reproduce the data to within  
 264 1% across the entire temperature range of Figure 2. The fitted parameters resulting from the AU-  
 265 TOSTRUCTURE calculation are also presented.

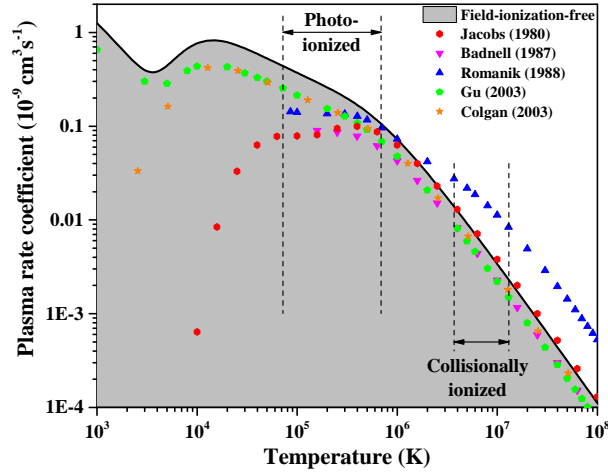
266 In Figure 3, the experimentally derived field-ionization-free plasma rate coefficient is compared with  
 267 the theoretically calculated ones from the literature. Results of [Jacobs et al. \(1980\)](#) and [Romanik](#)  
 268 [\(1988\)](#) include DR associated with the  $\Delta N = 0$  and  $\Delta N = 1$  core transitions. Romanik declared  
 269 that their results may be incomplete below  $8.5 \times 10^4$  K for Be-like Ca due to the omission or energy  
 270 uncertainty of resonances ([Romanik 1988](#)). Calculation of  $\Delta N = 0$  and  $\Delta N = 1$  DR had also been  
 271 performed by [Badnell \(1987\)](#) and collected by [Mazzotta et al. \(1998\)](#), here we just present the  
 272 calculated rate coefficient of  $\Delta N = 0$  DR. Theoretical calculations by [Gu \(2003\)](#) with the FAC code  
 273 and by [Colgan et al. \(2003\)](#) with the AUTOSTRUCTURE code provided rate coefficients of  $\Delta N = 0$

**Table 2.** Fitted parameters for the resonant recombination channels derived from the experimental and calculated rate coefficients. The units of  $c_i$  and  $E_i$  are  $10^{-5}\text{cm}^3\text{s}^{-1}\text{K}^{3/2}$  and eV, respectively.

| No. | Experiment       |         | AUTOSTRUCTURE |         |
|-----|------------------|---------|---------------|---------|
|     | $(n_{max}=1000)$ |         |               |         |
| i   | $c_i$            | $E_i$   | $c_i$         | $E_i$   |
| 1   | 5.0219           | 0.55388 | 3.6230        | 0.05795 |
| 2   | 6.1690           | 0.03800 | 47.571        | 1.3072  |
| 3   | 260.09           | 3.2522  | 151.74        | 4.8012  |
| 4   | 453.85           | 1.7154  | 257.92        | 2.0015  |
| 5   | 1193.7           | 9.2268  | 825.99        | 10.562  |
| 6   | 2916.7           | 23.188  | 1610.5        | 25.048  |
| 7   | 6298.3           | 57.720  | 5795.4        | 60.088  |

DR and TR for temperatures from  $10^3$  K to  $10^8$  K. It should be noted that the plot of [Colgan et al. \(2003\)](#) as shown in Figure 3 is the revised  $\Delta N = 0$  rate coefficients from the [OPEN-ADAS](#) website.

For temperatures below  $5 \times 10^4$  K the calculated plasma rate coefficient by [Gu \(2003\)](#) and [Colgan et al. \(2003\)](#) are more than 45% lower than the experimentally derived one. A probable reason is that the predictions of the low temperature DR and TR rate coefficients are not reliable. The data of [Jacobs et al. \(1980\)](#) are even lower for these temperatures since TR was not included in the calculations. At temperatures about  $4 \times 10^5$  K, where Be-like Ca is most abundant in photoionized plasmas, the calculated rate coefficients by [Gu \(2003\)](#) and [Colgan et al. \(2003\)](#) are 35% lower than the experimental result. Rate coefficient calculated by [Badnell \(1987\)](#) is about 50% lower than the experimental result since TR was not included in the calculation. The deviation of the theoretical calculated rate coefficients from the experimental results is probably due to the fact that the TR resonances and the low temperature DR resonances can not be calculated with sufficient precision. In the temperature range  $4 \times 10^6 - 1.3 \times 10^7$  K where Be-like Ca is formed in collisionally ionized plasmas such as solar strong active regions and flares in the upper solar atmosphere. In this temperature range, the calculated data by [Badnell \(1987\)](#) and [Gu \(2003\)](#) are about 35% lower than the experimental



**Figure 3.** Comparison of the present field-ionization-free resonant plasma recombination rate coefficient (black solid line) with theoretical results for Be-like Ca from the literature. The rate coefficients calculated by [Jacobs et al. \(1980\)](#) and [Badnell \(1987\)](#) are displayed as red hexagons and magenta down-triangles, respectively. The calculations by [Romanik \(1988\)](#) and [Gu \(2003\)](#) are represented as blue up-triangles and green pentagons, respectively. The orange stars show the  $\Delta N = 0$  DR and TR rate coefficients calculated by [Colgan et al. \(2003\)](#). The temperature ranges where the abundance of Be-like Ca exceeds 10% of its maximum abundance in photoionized and collisionally ionized plasmas are indicated by vertical dashed lines and associated arrows ([Kallman & Bautista 2001](#); [Bryans et al. 2009](#)).

289 result. An agreement of better than 25% was found between the experimentally derived plasma rate  
 290 coefficient and the calculation by [Colgan et al. \(2003\)](#). The calculated data of [Jacobs et al. \(1980\)](#)  
 291 and [Romanik \(1988\)](#) are higher than the experimental data. This is mainly because their calculation  
 292 included the  $\Delta N = 0$  and  $\Delta N = 1$  DR while the experimentally derived plasma rate coefficients only  
 293 include the resonant recombination associated with  $\Delta N = 0$  core excitations. The contribution from  
 294  $\Delta N = 1$  DR cannot be neglected for collisionally ionized plasmas, by  $5 \times 10^6$  K it is larger than the  
 295  $\Delta N = 0$ , and was accounted-for by [Colgan et al. \(2003\)](#), for example.

## 296 5. CONCLUSION

297 Absolute rate coefficients for electron-ion recombination of Be-like  $^{40}\text{Ca}^{16+}$  have been measured at  
 298 the CSRm in the energy range 0-51.88 eV. In addition, theoretical results from the AUTOSTRUC-  
 299 TURE code are presented and compared with the present experimental results. Good agreement  
 300 was found between calculation and experiment as far as DR resonances are concerned. However,



301 the calculated TR resonance strengths underestimate the experimental ones, and this translates into  
302 a deviation between the experimental and theoretical plasma rate coefficients exceeding the exper-  
303 imental uncertainty. Several resonances originating from the long-lived  $2s2p\ ^3P_0$  metastable ions  
304 have been identified in the measured spectrum. The calculation for 95% ions in the ground state  
305 and 5% ions in the metastable state agrees well with the experimental results for these resonances.  
306 The present investigation indicates that the calculation of TR resonances is still a challenging task  
307 for the state-of-the-art ATUOSTRUCTURE code while the DR resonances can be calculated with a  
308 reasonably high precision.

309 Experimentally derived field-ionization-free temperature dependent plasma rate coefficients were  
310 presented and compared with the available theoretical results. The experimentally derived plasma  
311 rate coefficients are higher than the theoretical data in the photoionized zone where TR resonances  
312 are important. In a collisionally ionized plasma where  $\text{Ca}^{16+}$  is most abundant in solar active region  
313 and flares, the rate coefficients are dominated by DR resonances, and an agreement of better than  
314 25% is found between the present experimental result and the more recent calculation by [Colgan](#)  
315 [et al. \(2003\)](#) and the present AUTOSTRUCTURE calculation. Our data provide a benchmark for  
316  $\text{Ca}^{16+}$  recombination data used in astrophysical modeling.

317  
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