High resolution low-energy dielectronic recombination rate coefficients of beryllium-like germanium: QED test bench for two-valence-electron systems

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Abstract. Low-energy dielectronic recombination resonances of beryllium-like Ge\textsuperscript{28+} have been studied by electron collision spectroscopy in the heavy-ion storage ring TSR using a twin-electron beam technique combined with an ultracold photoelectron source. Rich resonance structure below 1.7 eV is observed which mainly arises from resonant capture of the free electron to 9\textit{l} Rydberg states accompanied by excitation of inner valence electrons from the 2s\textit{2}(1\textit{S}\textsubscript{0}) ground state to 2s2\textit{p}(1\textit{P}\textsubscript{1}). The positions of resonances below 0.3 eV are measured with an accuracy better than 0.5 meV. Accurate calculations of Rydberg binding energies for these resonances are still required in order to derive a precise value for the 1\textit{S}\textsubscript{0} – 1\textit{P}\textsubscript{1} transition energy, which may give the opportunity for high-accuracy testing of QED corrections to atomic energy levels for a two valence electron system.

1. Introduction
In a dielectronic recombination (DR) process the capture of a free electron into a Rydberg state is accompanied by excitation of inner electrons. Radiative decay of this intermediate autoionizing state completes the recombination. DR is a resonant process which takes place when the core excitation energy equals the sum of electron-ion collision energy and Rydberg binding energy. In many cases of lithium-like and beryllium-like systems, binding energies of high Rydberg states can be calculated with high accuracy [1]. In these cases, measurements of the DR rate coefficient at high energy resolution are tools to precisely derive the transition energies of the core valence electrons. The highest precision is reached when studying resonances of low energies (ideally below ~ 0.1 eV).
this case the experimental resolution reaches an optimal value about equal to the transverse electron temperature $kT_\perp$, which is better than 1 meV for the TSR’s ultra cold electron target.

Measurements of low-energy DR resonances of lithium-like $\text{Sc}^{18+}$, performed at the Heidelberg Test Storage Ring (TSR) with a cold photoelectron target, allowed us to determine the $2s_1/2-2p_3/2$ transition energy with an accuracy of 4.6 ppm, less than 1% of the few-body effects on radiative corrections [2]. Following these studies we have investigated beryllium-like heavy ions with low-energy DR resonances where quantum-electrodynamical (QED) corrections to atomic energy levels are large, making the systems promising candidates for accurate QED tests with two valence electrons.

In this paper we present high resolution measurements of the electron-ion recombination rate coefficient of beryllium-like germanium. The study revealed a series of sharp low-energy resonances. In the range from about 0.1 eV up to 1.8 eV dielectronic recombination is governed by $(2s^2 2p^1 P_1)^{19} l$, resonances. Additional dielectronic $(2s^2 2p^3 P_0)^{14} l$ and trielectronic $(2p^2 1D_2)^7 l$ resonances can also contribute to the low-energy part of the recombination rate spectrum. Accurate calculations of Rydberg binding energies for these resonances are still required to derive a precise value for the $^1 S_0 - ^1 P_1$ transition energy.

2. Experimental overview

The experiment at the Heidelberg TSR was carried out with beryllium-like $^{74}\text{Ge}^{28+}$. The MPIK tandem accelerator was used to inject ions of kinetic energies of about 340 MeV into the TSR. The TSR’s twin-beam electron facility was used for these measurements [3]. Phase space cooling of ions was provided by a collinear electron beam of high density ($1.6 \times 10^7 \text{ cm}^{-3}$) from the electron cooler at a cathode voltage of about 2.56 kV, yielding a stored ion beam with a relative momentum spread below $10^{-4}$ and of cross-section diameter ~1 mm. The cooling time was below 1 s, the lifetime of the stored ion beam, limited by radiative recombination in the cooler, was about 45 s. For the measurements a continuous injection scheme with a repetition rate of about 1-3 s was used, leading to a stored ion current of 5-10 $\mu$A after a few minutes of accumulation.

The ultra cold electron target was used for collision spectroscopy, employing a low electron beam density of $5.2 \times 10^5 \text{ cm}^{-3}$ from the cryogenic photoelectron source. The photocathode gun delivered a magnetically guided dc electron beam of about 350 $\mu$A, emitted in space charge limited mode by a p-GaAs photocathode of diameter 3 mm cooled by liquid nitrogen. Details of the cryogenic photocathode gun can be found elsewhere [4-5]. The transverse energy of the electron beam was reduced by adiabatic magnetic expansion (guiding field ratio: 20) and the electron temperatures of the target beam after acceleration to the final energy were about 1.5 meV and 0.04 meV in the transverse and longitudinal direction respectively. The electron beam overlapped the stored $^{74}\text{Ge}^{28+}$ beam in an interaction region of length 1.5 m. For recombination spectrum measurements the electron-ion collision energies in the c.m. frame are varied by detuning the acceleration voltage of the electron target from the cooling voltage [2]. The zero collision energy corresponds to matched electron and ion velocities at the cooling voltage.

The recombination rate of electrons and $^{74}\text{Ge}^{28+}$ ions was measured by counting the $^{74}\text{Ge}^{27+}$ product ions using a detector behind the first ion-bending dipole magnet downstream of the interaction region of the electron target. The measured rate spectrum allowed to derive the recombination rate coefficient as a function of electron-ion collision energy using the measured ion and electron beam currents, the electron target voltage, and the well-understood electron space charge corrections to the latter.

3. Results and discussion

The overview spectrum of the $^{74}\text{Ge}^{28+}$ recombination rate coefficient in the energy range of 0-8.5 eV is shown in figure 1a. Calculated energy positions of $l$-series limits for dielectronic $2s2p^1 P_1 9l$ (1.70 eV), $^3 P_1 4l$ (0.22 eV), $^3 P_1 4l$ (7.76 eV), $^3 P_1 11l$ (4.34 eV) and trielectronic $2p^2 1D_2 7l$ (7.70 eV) capture resonances are also shown. Resonances from other dielectronic and trielectronic terms lie at higher energies and not considered here. To estimate the positions of $l$-series limits, the excitation energies
from the $2s^2$ ground state to $1P_1$ (133.46±0.04 eV), $3P_1$ (62.25±0.01 eV) and $3P_2$ (92.53±0.015 eV) were taking from spectroscopic measurements in tokamak plasmas [6]. The transition energies for $3P_0$ (54.64 eV) and $1D_2$ (225.58 eV) are Z-interpolated data of theoretical values obtained by a

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\begin{align*}
    (2s2p^3P_0)_{14l} & \\
    (2s2p^3P_1)_{9l} & \\
    (2s2p^3P_2)_{11l} & \\
    (2p^21D_2)_{7l} & \\
    (2s2p^3P_1)_{14l} & \\
\end{align*}
\]

\[
\begin{align*}
    P_{1/2} & \\
    P_{3/2} & \\
    d_{3/2} & d_{5/2} & f_{5/2} & f_{7/2} & \text{?} \\
\end{align*}
\]

\[
\begin{align*}
    (2s2p^3P_1)_{9P_{1/2}} & \\
    (2s2p^3P_1)_{9P_{3/2}} & \\
\end{align*}
\]

\[
\begin{align*}
    (2s2p^3P_1)_{14l} & \\
    \text{?} & \\
    (2s2p^3P_1)_{14l} & \\
\end{align*}
\]

\[
\begin{align*}
    J & 1/2 & 3/2 & 5/2 \\
\end{align*}
\]

\[
\begin{align*}
    (2p^21D_2)_{7l} & \\
    (2s2p^3P_1)_{14l} & \\
\end{align*}
\]

**Figure 1.** High resolution recombination rate coefficients of beryllium-like $^{74}\text{Ge}^{28+}$. Energy positions of $l$-series limits for dielectronic $2s2p^1P_19l$, $3P_0_{14l}$, $3P_1_{14l}$, $3P_2_{11l}$ and trielectronic $2p^21D_27l$ resonances are also shown. The low-energy part of the spectrum below 0.5 eV (“c”) is fitted with seven resonances convoluted with an electron energy distribution ($kT_\perp=1.7$ meV, $kT_\parallel=0.47$ meV).
multiconfiguration Dirac-Fock technique for excitation energies of beryllium-like ions with different nuclear charge $Z$ [7]. The same interpolation procedure was also applied for $^1P_1$, $^3P_1$ and $^3P_2$ to estimate the accuracy of the interpolation (about 0.5 eV) by comparison to spectroscopic data [6]. Rydberg binding energies were calculated using the H-like formula with $Z_{\text{eff}}=Z-4$, which should be good enough to estimate $l$-series limits when the effect of the smeared potential from the core electrons is small for high orbital angular momentum quantum numbers.

The rich structure below 2 eV (see figure 1b) is governed by resonant capture of a free electron to the 9$l$ Rydberg state accompanied by transition of a valence electron from the 2$s^2$ ground state to the 2$s2p$ orbital forming a $^1P_1$ singlet state. The estimated positions of $^1P_1$ 9$l$ resonances, calculated in a Dirac-Fock potential from 1$s^22s^2$ [8], are also shown. While the 9$s$ and 9$p_{1/2}$ binding energies are below the 2$s2p$ $^1P_1$ excitation energy, 9$p_{3/2}$ is very closely above.

The most “attractive” resonances lie at low energies (see Figure 1c), where the highest resolution can be obtained. Below 0.4 eV six resonances (without counting the radiative recombination peak at zero energy) are clearly observed. The fitting of these resonances (see Figure 1c) was done by convolution with an electron energy distribution with electron temperatures of $kT_e=1.7$ meV and $kT_e$=0.47 meV, the latter being a fitting parameter. The strongest resonance lies at 0.1132 eV. The fitting suggests that there is one more broad resonance close to the strongest one. The widths of this resonance as well as of a resonance at 0.328 eV were fitting parameters. The remaining resonances were assumed to be δ-peaks, and only their positions and strengths were fitted. However, to get precise (better than 0.5 meV) positions of these low-energy resonances it is important to assign all peaks and to calculate their natural width. In the $^1P_1$ 9$l$ series the splitting of 9$p_{3/2}$ resonance due to $j,j$ coupling, with total angular momentum $J=1/2, 3/2$ or 5/2, is expected to give three resonances split by typically [1] about 10-100 meV. The assignment of the fine structure levels and of the other resonances is still an open question (calculation in progress [8]). Candidates are (2s2p $^3P_0$)14$l$ or (2p$^2$ $^1D_2$)7$l$ dielectronic resonances. Despite the fact that the (2p$^2$ $^1D_2$)7$l$ series limit lies far above threshold at 7.7 eV the $l$-resonances from this term can be shifted strongly to low energies (comparable to $^2P_{1/2}$ and $^3P_{21/2}$) due to their small principal quantum number $n$ and because of their orbital configuration being 2$p^7$ rather than 2$s2p$.

In conclusion, high resolution measurements of low-energy electron capture recombination rate coefficient have been performed for beryllium-like germanium. Rich resonance structure at low energies is found. Dielectronic 2$s2p$ ($^1P_1$,9$p_{3/2}$)$_{J=1/2}$, 3/2, 5/2 resonances are supposed to give the main contribution to the low-energy part of the spectrum. Contributions from other terms (2s2p $^3P_0$)14$l$ and (2p$^2$ $^1D_2$)7$l$ are also expected. To derive the $S_0^0-P_1$ transition energy, accurate calculation of the Rydberg binding energies of the excited ions is still required. The obtained data may give the opportunity to test QED corrections with high accuracy for atomic energy levels for two valence electron systems.

Acknowledgments
The authors wish to thank Dr. E. Lindroth for fruitful discussions. The great support of this experiment by the TSR team, in particular from behalf of Dr. M. Grieser and Dr. R. Repnow, is gratefully acknowledged.

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