Dielectronic recombination experiment of P-like Tin on HIRFL–CSRm at Lanzhou

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Abstract. Total recombination rate coefficients of $^{112}$Sn$^{35+}$ ions have been firstly measured by employing the electron-ion merged-beams technique on the main cooler storage ring at Lanzhou. Using an electron beam energy detuning system, we precisely tuned the relative energies from 0 to 6.0 eV between the electron beam and the ion beam (momentum spread $\Delta p / p \sim 5 \times 10^{-4}$). A multi-configuration Breit-Pauli calculation utilizing kappa-averaged relativistic orbitals has been carried-out for the recombination rate coefficients. We find that there are obvious differences between the experimental total rate coefficients and the theoretical calculations.

1. Introduction

Dielectronic recombination (DR) is a fundamental recombination process for modeling of astrophysical and fusion plasmas, which plays an important role in determining both the level populations and the ionization balance therein [1, 2]. In addition, DR is a powerful tool to investigate the atomic structure and decay channels of atomic doubly excited states [3, 4, 5].

Generally, DR can be viewed as a two-step resonant process [1, 2, 3, 4, 5]. In the first step a doubly excited state is formed in the recombined ion through a resonant process involving the capture of a free electron and the simultaneous excitation of a bound electron. In the second step the doubly excited state decays by emitting photons to a state below the ionization threshold. During the past several decades recombination spectra for a number of ions have been measured by electron-beam-ion-traps [6, 7, 8] at high energies and by storage-ring facilities such as TSR [9] at Heidelberg, ESR [10] at GSI, and CRYRING [11] at Stockholm. In this work we have measured the DR spectrum of P-like $^{112}$Sn$^{35+}$, as a comparison, Novotný et al. [12] have measured the DR spectrum of Fe$^{11+}$ from the same isoelectronic sequence. The present
DR process involves the following electronic transitions:

\[
e^- + \text{Sn}^{35+} \left( 3s^2 3p^3 \left[ \frac{4}{2} S_{3/2} \right] \right) \rightarrow \begin{cases} 
\text{Sn}^{34+} (3s^2 3p^3 \left[ \frac{2}{2} D_{3/2,5/2} \right] \left[ 2P_{1/2,3/2} \right] \left[ n l \right]) \\
\text{Sn}^{34+} (3s 3p^4 \left[ n l \right]) \\
\text{Sn}^{34+} (3s^2 3p^2 3d \left[ n l \right]) \\
\text{Sn}^{34+} (3s 3p^3 3d \left[ n l \right]).
\end{cases}
\] (1)

\[
e^- + \text{Sn}^{35+} \left( 3s^2 3p^3 \left[ \frac{4}{2} S_{3/2} \right] \right) \rightarrow \begin{cases} 
\text{Sn}^{34+} \left( 3s^2 3p^2 4s \left[ n'l' \right] \right) \\
\text{Sn}^{34+} \left( 3s 3p^3 4s \left[ n'l' \right] \right)
\end{cases}
\] (2)

The incident electron is captured into a Rydberg level with a principal quantum number denoted by \( n \) (\( n' \)), where \( n \geq 6 \) and \( n' = 4 \). The transitions, where the innermost of the two excited electrons remain within the same shell, are denoted as \( \Delta n = 0 \) DR channel as shown in Eq. 1, in contrast denoted as \( \Delta n \neq 0 \) DR channel, such as \( \Delta n = 1 \) in Eq. 2. For the present work, the resonant strengths are mostly from the contribution of \( \Delta n = 0 \) DR channel.

2. Experiment

The recombination measurements of \( ^{112}\text{Sn}^{35+} \) were carried out on the main cooler storage ring (CSRm) [13] at the Institute of Modern Physics in Lanzhou (IMP). The \( ^{112}\text{Sn}^{35+} \) ions were produced in a superconducting electron cyclotron resonance ion source, then accelerated to 3.7 MeV/u in a cyclotron, and finally injected into the ring CSRm with a typical ion current of 20 \( \mu \)A and beam half-lifetime of 10 sec. The ion beam is merged with magnetically guided electron beam (beam radius about 2.92 cm) with fixed beam current of 113.7 mA in the cooling section. The cooling voltage and density of electron beam are -2.0990 kV and 9.95 \( \times 10^6 \) cm\(^{-3}\), respectively. After about 5 sec cooling, the momentum spread of ion beam is reduced to about \( 5 \times 10^{-4} \).

![Figure 1. Sketch of the experimental setup showing electron cooler section and the detector for recombined ions.](image-url)

The detuning voltages \( U_d \) were applied to the cathode of the electron cooler to change the electron energy with a minimum step of 1 V. During a measurement cycle, the electron energy was stepped with 10 ms for detuning, and 90 ms or 200 ms for electron cooling. As shown in Fig. 1, those ions which capture electrons are separated from the main beam by the first bending magnet downstream of the cooler and detected by the scintillator particle detector (YAP:Ce + PMT, \( \sim 100\% \) efficiency) [14]. The cut-off quantum number \( n_{\text{max}} \) limited by field ionization with magnetic strength \( B=0.117 \) T is \( n_{\text{max}}=171 \) [15].

For the electron gun of electron cooler on CSRm, variation of voltage ratio of the control electrode \( (U_{\text{contr}}) \) to the anode electrode \( (U_{\text{anode}}) \) leads to change of electron density distribution along the beam radius[16, 17]. In present work, we set \( U_{\text{contr}}=0.1781 \) kV and \( U_{\text{anode}}=1.2166 \)
\[ E_e = -e(U_{\text{cath}} + U_{sp}), \]

where \( e \) is the elementary charge and \( U_{sp} \) is the space-charge potential defined as

\[ U_{sp} = \frac{I_e r_e m_e c^2}{e \nu_e} \left[ 1 + 2 \ln \left( \frac{b}{a} \right) \right], \]

where \( r_e \) is the classical electron radius, \( m_e \) the electron rest mass, \( b = 20 \text{ cm} \) the diameter of the beam tube, \( a = 5.84 \text{ cm} \) the diameter of the electron beam, and \( \nu_e \) the electron velocity.

For the present electron beam current \( I_e = 113.7 \text{ mA} \) and the cathode voltage \( U_{\text{cath}} = -2.0990 \text{ kV} \), one gets the space-charge potential \( U_{sp} \sim 70 \text{ V} \). Thus the corrected electron energy is used to calculate the relative kinetic energy at the center-of-mass system (c.m.)

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

where \( m_x, \beta_x, \) and \( \gamma_x (x = e, i) \) are the mass and Lorentz factors, respectively. \( e, i \) denote the electron and the ion, respectively. \( c \) is the speed of light, and \( \theta \) is the angle between the electron and the ion beams. Generally, \( \theta \) is optimized to approaching zero mrad by minimizing the width of the ion beam.

From the recombination counting rate measured at relative energy \( E_{rel} \) of the electron and the ion, the experimental rate coefficient \( \alpha \) can be deduced by \[19, 20\]

\[ \alpha = \frac{R}{\eta N_i n_e (1 - \beta_e \beta_i)}. \]

where \( R \) is the background-subtracted count rate, \( \eta \) is the ratio of the effective cooling section length (3.40 m) to the ring circumference (161.00 m). \( N_i \) and \( n_e \) are the number of stored ions and density of electron beam, respectively.

The measured rate coefficient \( \alpha \) is related to the total cross section \( \sigma \) by \[18, 19, 20\]

\[ \alpha(v_{rel}) = \langle \sigma v \rangle = \int \sigma(v) v f(\vec{v}, v_{rel}) d^3 v, \]

where \( f(\vec{v}, v_{rel}) \) is the distribution of the electron velocity \( \vec{v} \), relative to the ions around the average longitudinal relative velocity \( v_{rel} \). Since the electron mass is much smaller than the ion mass, the velocity distribution is set by the distribution of the electrons, which is described by a “flattened” Maxwellian distribution with different temperatures in the longitudinal \( T_\parallel \) and transversal \( T_\perp \) directions,

\[ f(\vec{v}, v_{rel}) = \frac{m_e}{2 \pi k T_\perp} \exp \left[ -\frac{m_e v_\perp^2}{2 k T_\perp} \right] \times \left( \frac{m_e}{2 \pi k T_\parallel} \right)^{1/2} \times \exp \left[ -\frac{m_e (v_\parallel - v_{rel})^2}{2 k T_\parallel} \right], \]

where \( k \) is the Boltzmann constant, and \( v_\perp \) and \( v_\parallel \) are the transversal and longitudinal components of \( \vec{v} \).
3. Results and discussion

Using merged electron and ion beams in CSRm, total rate coefficients of $^{112}\text{Sn}^{35+}$ ions have been measured at c.m. energy from 0 to 6.0 eV and are shown in Fig. 2 along with the experimental errors. The uncertainty of the experimental energy scale stems mainly from uncertainties of the voltages $U_d$ and $U_{cath}$ and from the uncertainty of the ion velocity. The error of the absolute energy scale is estimated to be $\pm 0.08$ eV and $\pm 0.21$ eV for c.m. energies of 0.7 eV and 6.0 eV, respectively. The error of the absolute rate coefficient comprises $\pm 5\%$ uncertainty from ion current determination, $\pm 10\%$ for the electron density, and $\pm 1\%$ for statistics uncertainty.

For comparison with experimental results, a multi-configuration Breit-Pauli calculation utilizing kappa-averaged relativistic orbitals AUTOSTRUCTURE code[21] has been used to calculate total rate coefficients, which were convolved with the electron temperatures $kT_{\perp} = 0.20$ eV and $kT_{\parallel} = 5.18$ meV and considered electron correlation for $\Delta n = 0$ channels. The resonance strengths are mostly from the contributions of $\Delta n = 0$ channels, while only few transitions from $3l$ to $4s$ of $\Delta n = 1$ channels locate in the present energy region. It can be seen in Fig. 2 that there are obvious differences between the experimental total rate coefficients and the theoretical ones. This phenomenon is similar to that shown in Fig. 2 in Ref. [12]. The resonant positions of experimental rate coefficients are in roughly agreement with the calculated ones only at electron energy of about 2.1 eV and 5.7 eV, while the theoretical values of total rate coefficients are in disagreement with experimental ones. In the view of theory, there is a lot of sensitivity to small changes in the calculated energies, not just to the corresponding shifts in resonance position but also to the opening and closing of channels. This may be the source of the poor agreement between theory and experiment.

![Figure 2.](image)

**Figure 2.** Experimental total rate coefficients (solid circles) and the theoretical result calculated by AUTOSTRUCTURE code [21] (solid line) as a function of relative energy.

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| Reference | Authors and Details |
|-----------|---------------------|
| [1] | Müller A, 2008 *Adv. At. Mol. Opt. Phys.* 55 293 |
| [2] | Badnell N R, O’Mullane M G, Summers H P, Altun Z, Bautista M A, Colgan J, Gorczyca T W, Mitnik D M, Pindzola M S, and Zatsarinny O, 2003 *Astron. Astrophys.* 406 1151 |
| [3] | Larsson M, 1995 *Rep. Prog. Phys.* 58 1267 |
| [4] | Phaneuf R A, Havener C C, Dunn G H, and Müller A, 1999 *Rep. Prog. Phys.* 62 1143 |
| [5] | Dolder K T and Peart B, 1976 *Rep. Prog. Phys.* 39 693 |
| [6] | Knapp D A, Marrs R E, Levine M A, Bennett C L, Chen M H, Henderson J R, Schneider M B, and Scofield J H, 1989 *Phys. Rev. Lett.* 62 2104 |
| [7] | McLaughlin D J, Hahn Y, Takács E, Meyer E S, and Gillaspj D J, 1996 *Phys. Rev. A* 54 2040 |
| [8] | Zhang X, Crespo López-Urrutia J R, Guo P, Mironov P, Shi X, González Martínez A J, Tawara H, and Ullrich J, 2004 *J. Phys. B: At. Mol. Opt. Phys.* 37 2277 |
| [9] | Lestinsky M, Lindroth E, Orlov D A, Schmidt E W, Schippers S, Böhm S, Brandau C, Sprenger F, Terekhov A S, Müller A, and Wolf A, 2005 *Phys. Rev. Lett.* 100 033001 |
| [10] | Brandau C, Kozhuharov C, Harman Z, Müller A, Schippers S, Kožuhedub Y S, Bernhardt D, Böhm S, Jacobi J, Schmidt E W, Mokler P H, Bosch F, Kluge H-J, Stöhler Th, Beckert K, Beller P, Nolden F, Steck M, Gumberidze A, Reuschi R, Spillmann U, Currell F J, Tupitsyn I I, Shabaev V M, Jentschura U D, Keitel C H, Wolf A, and Stachura Z, 2008 *Phys. Rev. Lett.* 100 073201 |
| [11] | Schuch R, Lindroth E, Madzunkov S, Fogle M, Mohamed T, and Indelicato P, 2005 *Phys. Rev. Lett.* 95 183003 |
| [12] | Novotný O, Badnell N R, Bernhardt D, Grieser M, Hahn M, Krantz C, Lestinsky M, Müller A, Repnow R, Schippers S, Wolf A, and Savin D W, 2012 *Astrophys. J.* 753 57 |
| [13] | Xia J W, Zhan W L, Wei B W, Yuan Y J, Song M T, Zhang W Z, Yang X D, Yuan P, Gao D Q, Zhao H W, Yang X T, Xiao G Q, Man K T, Dang J R, Cai X H, Wang Y F, Cai Y, Qiao W M, Ruo Y N, He Y, Mao L Z, and Zhou Z Z, 2002 *Nucl. Instr. and Meth. A* 488 11 |
| [14] | Wen W Q, Ma X, Xu W Q, Meng L J, Zhu X L, Gao Y, Wang S L, Zhang P J, Zhao D M, Liu H P, Zhu L F, Yang X D, Li J, Ma X M, Yan T L, Yang J C, Yuan Y J, Xia J W, Xu H S, and Xiao G Q, 2013 *Nucl. Instrum. Meth. Phys. Res. B* in press |
| [15] | Zong W, Schuch R, Gao H, DeWitt D R, and Badnell N R, 1998 J. *Phys. B: At. Mol. Opt. Phys.* 31 3729 |
| [16] | Bocharov V, Bubley A, Boimelstein Yu, Veremeenko V, Voskoboinikov V, Goncharov A, Grishanov V, Dranchnikov A, Evtushenko Yu, Zapiatkin N, Zakhvatkin N, Ivanov A, Kokoulin V, Kolmogorov V, Kondaurov M, Konstantinov E, Konstantinov S, Krainov G, Kriuchkov A, Kuper E, Medvedko A, Mironenko L, Panasiuk V, Parkhomchuk V, Petrov S, Reva V, Svischev P, Skarbo B, Smirnov B, Sukhina B, Tiumov M, Shirokov V, Shrainer K, Yang X D, Zhao H W, Wang Z X, Li J, Zhang J H, Zhang W, Yan H B, Yan H H, and Xia G X, 2004 *Nucl. Instrum. and Meth. A* 532 144 |
| [17] | Xia G X, Xia J W, Yang J C, Liu W, Wu J X, Yin X J, Zhao H W, and Wei B W, 2003 *Nucl. Instr. and Meth. A* 508 239 |
| [18] | Gilgus, Habs D, Schwalm D, Wolf A, Badnell N R, and Müller A, 1992 *Phys. Rev. A* 46 5730 |
| [19] | Bernhardt D, Brandau C, Harman Z, Kozhuharov C, Müller A, Scheid W, Schippers S, Schmidt E W, Yu D, Artemyev A N, Tupitsyn I I, Böhm S, Bosch F, Currell F J, Franze B, Gumberidze A, Jacobi J, Mokler P H, Nolden F, Spillmann U, Stachura Z, Steck M, and Stöhlker Th, 2011 *Phys. Rev. A* 83 020701(R) |
| [20] | Schmidt E W, Bernhardt D, Müller A, Schippers S, Fritzscbe S, Hoffmann J, Jaroshevich A S, Krantz C, Lestinsky M, Orlov D A, Wolf A, Lukić D, and Savin D W, 2007 *Phys. Rev. A* 76 032717 |
| [21] | Badnell N R, 2011 *Comput. Phys. Commun.* 182 1528 |