ENERGY GAIN MEASUREMENTS OF Xe$^{9+}$ IONS IN COLLISIONS WITH He AND Ar

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Abstract. To clarify a collision dynamics of multiply charged Xe ions with rare gas target, we have measured energy gain spectra of Xe$^{9+}$ in collisions with He and Ar at 200 $\text{eV}/q$ and have compared with the theoretical energy gain peak calculated by the classical over barrier model. Using energy levels of excited Xe$^{8+}(nl)$ ions referred to the NIST atomic spectra database, we have determined capture states of Xe$^{9+}$ ions after single electron transfer.

1. Introduction

The study of collision dynamics of multiply charged ions with atoms and molecules at low energies is important not only in atomic physics but also in various applied fields. Recently, high temperature plasmas of heavy elements such as Xe and Sn have attracted great attention in developing extreme ultra-violet (EUV) light sources ($\lambda = 13.5$ nm) for the technology of the lithography in next generation[1]. In order to clarify emitting processes of EUV lights from the Xe or Sn plasmas, we should understand basic charge transfer processes in these plasmas since the EUV light is emitted as one of the de-exciting processes of excited states after the charge transfer.

An energy gain spectroscopy technique firstly developed by Ohtani et al is very useful to determine the final states of multiply charged ions in collisions with atoms or molecules[2]. For the collision systems involving Xe, Hvelplund et al have measured energy gain spectra of multiply charged Xe ions with rare gas targets. They identified the states into which an electron was captured for Xe$^{9+}$ ions based on classical over barrier model[3, 4]. Recently, Tanuma et al have measured EUV emission spectra from charge selected Xe and Sn ions extracted from ECR ion source with several targets[5]. They found that most of 13.5 nm EUV is mostly emitted from excited Xe ions for $q=10$ and Sn ions for $q \geq 10$.

To determine the states into which an electron is captured by multiply charged Xe ions with the energy gain spectra, precise energy levels for ground and excited states of multiply charged ions are necessary. Saloman has compiled available energy levels and observed spectral lines at all stages of ionization of Xe ions [6]. As a database of energy levels of excited multiply charged ions, it is well known that the NIST atomic spectra database is quite useful [7]. In the case for Xe$^{9+}$ ion, the 61 levels for the ground and excited Xe$^{8+}$ ions are presented in the NIST database which include 59 levels summarized by Saloman.

In this work we have measured energy gain spectra of Xe$^{9+}$ in collisions with He and Ar at 200 $\text{eV}/q$. Present results are compared with the predicted energy gain by the classical over barrier
calculation. We have also calculated potential curve crossings based on Coulomb repulsion using energy levels from NIST atomic spectra database and have determined capture levels after single electron transfer collisions.

2. Experimental

![Figure 1. Schematic diagram of experimental setup.](image)

The experiment was performed using the mini-EBIS atomic collision facility at Nara Women’s University. Fig. 1 shows a schematic diagram of our experimental setup[8]. Projectile ions extracted from the mini-EBIS ion source were mass-separated by an electromagnet analyzer and decelerated before entering collision region. The target gas flow is effused from a nozzle placed above 1 mm from the collision center. After charge transfer at the collision center, projectile ions are energy-analyzed by an electrostatic analyzer of a parallel plate type and are detected by a position sensitive detector system.

In the energy gain spectroscopy, the reaction energy, $Q$-value, can be determined by the energy gain $\Delta E$ of the projectile ion after the charge transfer. The energy gain can be given by following,

$$\Delta E = \left(\frac{m_1}{m_1 + m_2}\right)^2 E_0 \times \left\{ \cos \theta + \left[ \left(\frac{m_2}{m_1}\right)^2 \left(1 + \frac{m_1 + m_2}{m_1} \frac{Q}{E_0}\right) - \sin^2 \theta \right]^{1/2} \right\}^2 - E_0,$$

where $m_1$ and $m_2$ are the masses of the projectile and the target, respectively and $E_0$ and $\theta$ are the collision energy and the scattering angle of the projectile ions in the laboratory frame, respectively. Assuming the conditions $\theta \cong 0$ and $E_0 \gg Q$, $\Delta E \sim Q$.

We have routinely checked long-lying excited ions in the primary ion beam by means of a beam attenuation method [8, 9]. The mini-EBIS was operated with a DC mode at a pressure around $10^{-8}$ Pa under liquid nitrogen temperature, so that practically no long-lying excited ions were produced via electron capture collisions with residual gases inside the ion source [10]. It is noted that most long-lying excited ions, if any, may be quenched easily inside the ion source because the confinement time of about 1 ms is sufficiently long to quench such ions.
3. Results and discussion

Measured energy gain spectra of Xe\(^{9+}\) in collisions with He and Ar at 200 eV/q are shown in Figure 2. The energy resolution of the energy analyzer is around 0.01. The energy width of primary ion beam was measured to be around 10 eV at full width at half maximum (FWHM). In the measured energy gain spectra, both spectra have similar structures and there are single peaks at about 27 eV and 20 eV for He and Ar, respectively. Each energy width of energy gain spectra for both targets are about 20 eV. This indicates that many final states of Xe\(^{8+}(nl)\) after the single electron transfer contribute in the present collision systems. Note that small structures around 40 eV and 55 eV for both targets are regarded as contributions from transfer ionization processes via autoionizing double electron capture states.

In the classical over the barrier frame, the peak energy of energy gain spectra for single electron transfer can be predicted as follows,

\[
Q = \frac{(q - 1)}{2\sqrt{q}} I_1,
\]

where \(q\) is charge state of projectile and \(I_1\) is the ionization potential of the target. In the case for single electron capture of Xe\(^{9+}\) ions, the predicted values are 28.1 eV and 18.0 eV for He and Ar, respectively. These results are fairly consistent with measured ones. That is, the classical over barrier model reasonably works out in these collision systems since it is considered that many excited states of multiply charged Xe ions exist almost continuously.

To determine final states of projectile after the charge transfer, we have used energy levels for ground and excited states of Xe\(^{8+}\) ions referred to NIST Atomic Spectra Database[6]. Figure 3 shows calculated potential curves using these energy levels. Noting that the results of energy gain spectra correspond to the energy differences between initial and final states in the potential curves, we can find capturing energy levels after single electron transfer. The major channels for these collision systems can be estimated as follows,

\[
\begin{align*}
\text{Xe}^{9+} + \text{He} & \rightarrow \text{Xe}^{8+}(4d^65f^1,4d^66p^1) + \text{He}^+, \\
\text{Xe}^{9+} + \text{Ar} & \rightarrow \text{Xe}^{8+}(4d^66f^1,4d^67p^1) + \text{Ar}^+.
\end{align*}
\]

It should be noted that many energy levels between Xe\(^{8+}(5f)\) and Xe\(^{8+}(7p)\) in the figure 3 must exist almost continuously although such energy levels are not found in the NIST atomic spectra database. The contributions of major channels can be determined when the database are fulfilled. It is required for precise analysis to fulfill energy levels of the highly charged Xe ions.

![Figure 2](image1)

**Figure 2.** Measured energy gain spectra of Xe\(^{9+}\) ions in collisions with He and Ar at 200 eV/q.
4. Conclusion
We have measured energy gain spectra of $\text{Xe}^{9+}$ in collisions with He and Ar at 200 eV/q. Predictions by the classical over barrier model are fairly consistent with experimental results. Using energy levels from the NIST Atomic Spectra Database, we have determined capturing state of $\text{Xe}^{9+}$ ions after single electron transfer. Fulfilling database for highly charged ions are required.

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References
[1] Bakashi V 2006 EUV source for Lithography (Washington: SPIE press)
[2] Ohtani S, Kaneko Y, Kimura M, Kobayashi N, Iwai T, Matsumoto A, Okuno K, Takagi S, Tawara H and Tsurubuchi S 1982 J. Phys. B 15 L533
[3] Hvelplund P 1987 J. Phys. B: At. Mol. Opt. Phys. 20 2515
[4] Niehaus A. 1986 J. Phys. B: At. Mol. Opt. Phys. 19 2925
[5] Tanuma H, Ohashi H, Shibuya E, Kobayashi K, Okuno T, Fujioka S, Nishimura H and Nishihara K 2005 Nucl. Instr. Meth. B 235 331
[6] Saloman E B 2004 J. Phys. Chem. Ref. Data 33 765
[7] Rakchenko, Yu., Kramida, A.E., Reader, J., and NIST ASD Team (2008). NIST Atomic Spectra Database (version 3.1.5): http://physics.nist.gov/asd3
[8] Ishii K, Inoue Y, Ogawa H, Itoh A and Sakamoto N 2007 J. Phys. Conf. Ser. 58 275
[9] Okuno K 1986 J. Phys. Soc. Japan 55 1504
[10] Ishii K, Itoh A and Okuno K 2004 Phys. Rev. A 70 042716