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Dielectronic Recombination of Xe$^{10+}$ Ions and Satellite Line of Xe$^{9+}$ Ions

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EUV light sources from compact plasmas are now intensively studied for the next generation of lithography. The multicharged Xe ions emit EUV emission and are now investigated extensively. However we do not know the detailed atomic processes for the Xe ions. We study in this paper on dielectronic and radiative recombination processes of Xe ions. We have calculated the energy levels, radiative transition probabilities (Ar), autoionization rates (Aa), and radiative recombination cross section for Xe$^{10+}$ ions using the FAC code. The dielectronic recombination rate coefficient ($\alpha_{DR}$) from the Xe$^{10+}$ ions and the related dielectronic satellite lines are obtained. We studied the n- and l-dependence for Ar, Aa, dielectronic recombination rate coefficient ($\alpha_{DR}$), and radiative recombination rate coefficient ($K_{rr}$). The dielectronic recombination processes from the $4d^8 + e \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl + h\nu$ and the $4d^8 + e \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl + h\nu$ become important at low plasma temperature $T_e \approx 10$eV for line intensities. Also, the radiative recombination rate coefficient is smaller than the values of the dielectronic recombination processes in our interested temperature region at $T_e = 1$eV - 1000eV.

Keyword: Dielectronic recombination, Satellite line, Xe$^{10+}$, Radiative recombination
1. Introduction

Dielectronic recombination (DR) [1-5] is the dominant electron-ion recombination process for low charged ions in high-temperature and low density plasmas. Therefore, it is very important in determining the ionization balance. Another very important role of dielectronic recombination is connected with the presence of so-called satellite lines produced through the radiative decay of autoionizing states. Such spectral lines give information not only about ion structure but also about plasma parameters i.e., plasma density and plasma temperature, and therefore, played an essential role in X-ray spectroscopy and plasma diagnostics. The dielectronic recombination is a resonant, two step processes in which a multicharged ion $X_Z$ captures a free electron with simultaneous excitation of the target electron and creates a doubly excited ion $X_{Z-1}^{*1}$, which then decays by a radiative transition.

$$X_Z(i_0) + e \rightarrow X_Z^{*1}(i) \rightarrow X_{Z-1}^{*1}(f) + h\nu$$

(1)

where $X_{Z-1}^{*1}$ expresses the autoionization state of the $X_{Z-1}$ ion and $i_0$, $i$, and $f$ denote the sets of quantum states of an ion in the initial state($i_0$), doubly excited target electron state($i$), and final state($f$). Another competitive process for the decay of an ion $X_Z^{*1}$ is the autoionization process. As the interest about Xenon ions grows recently for EUV sources, many people are working on the research about Xenon ions. We need data about atomic collisional processes of Xenon ion to analyze Xenon spectra. However, as long as we know, there are few papers which give us enough data of the dielectronic recombination rate coefficient to each final bound state. These data are necessary to estimate the population of the excited states by a collisional radiative model. In this report, we calculated the data for the dielectronic recombination from $Xe^{10+}$ ions to the excited states of $Xe^{9+}$ ions. We investigate the $4d^75p^1nl$ and $4d^74f^1nl$ states as autoionizing states, which are important for the dielectronic recombination process. We
use the Flexible Atomic Code (FAC)[6-8] for calculating the atomic data for dielectronic recombination rate coefficient. In section 2, we describe the atomic data about the energy levels, the radiative transition probabilities, and the autoionization rates. In section 3, we calculate the DR rate coefficient to the excited states and the total DR rate coefficients. In section 4, we obtain the dielectronic satellite lines through the radiative transitions of $4d^75p^1nl - 4d^8nl$ and $4d^74f^1nl - 4d^8nl$. In section 5, we calculate the total radiative recombination rate coefficient of Xe$^{10+}$ ions. Finally, in section 6, we summarize our results.

2. Atomic data using Flexible Atomic Code (FAC)

The atomic structure calculation in the FAC[6-8] made by M. F. Gu is based on the relativistic configuration interaction with independent particle basis wavefunctions. These basis wavefunctions are derived from a local central potential, which is self-consistently determined to represent electronic screening of the nuclear potential. The bound states of the atomic system are calculated in the configuration mixing approximation with convenient specification of mixing schemes. The radial orbitals for the construction of basis states are derived from a modified self-consistent Dirac-Fock Slater interaction on a fictitious mean configuration with fractional occupation numbers, representing the average electron cloud of the configurations included in the calculation. The radiative transition rates are calculated in a single multipole approximation with arbitrary ranks. This means that the interference between different multipoles is not taken into account, although rates corresponding to arbitrary multipoles can be calculated. For a given multipole operator $O^L_M$, and initial and final states of the transition $\psi_i = \sum_\nu b_\nu \Phi_\nu$ and $\psi_f = \sum_\mu b_f \Phi_\mu$, the line strength of the transition is

$$S_{fi} = |\langle \psi_f | O^L_M | \psi_i \rangle|^2.$$  \hspace{1cm} (2)
The weighted oscillator strength and transition rates are given by

\[ g_{fi} = [L]^{-1} \omega (\alpha \omega)^{2L-2} S_{fi}, \]  

\[ g_f A_{fi} = 2\alpha^3 \omega^2 g_{fi} f_i, \]  

where \([L] = 2L + 1\), \(L\) is the total orbital angular momentum, \(\omega = E_i - E_f\) is the transition energy and \(\alpha\) is the fine structure constant. The calculation of the autoionization rates is based on the distorted-wave (DW) approximation. The method implements an efficient interpolation procedure for the calculation of the autoionization radial integral. The calculation of autoionization rates is the major task in any distorted-wave treatments of resonant processes. The present method to calculate the autoionizing rate is similar to that of Oreg et al. [9], which uses an efficient factorization-interpolation procedure for the calculation of the autoionization radial integrals. The autoionization transition rate can be written as

\[ Aa = 2 \sum_k \left| \langle \psi_f, \kappa; J_T M_T | \sum_{i<j} \frac{1}{r_{ij}} | \psi_i > \right|^2 \]  

where \(\psi_i\) is the autoionizing state, \(\psi_f\) is the final state which has one less electron than \(\psi_i\), \(\kappa\) is the relativistic angular quantum number of the free electron. The total angular momentum of the coupled final state must be equal to that of \(\psi_i\), i.e., \(J_T = J_i\) and \(M_T = M_i\). Also, the partial photoionization (PI) cross section can be expressed in terms of the differential oscillator strength (in atomic unit), and the partial radiative recombination (RR) cross section is related to the PI through the Milne relation

\[ \sigma_{PI} = 2\pi\alpha \frac{1 + \alpha^2 \epsilon}{1 + 0.5\alpha^2 \epsilon} \frac{df}{dE} \]  

\[ \sigma_{RR} = \frac{\alpha^2 g_i}{2 \ g_f} \frac{\omega^2}{\epsilon(1 + 0.5\alpha^2 \epsilon)} \sigma_{PI} \]  

where \(\alpha\) is the fine structure constant, \(g_i\) and \(g_f\) are the statistical weights of the bound states before and after the photoionization takes place respectively, \(\omega\) is the photon energy,
and $\epsilon$ is the energy of the ejected photo-electron. The differential oscillator strength, $df/dE$, may be calculated similarly to the bound-bound oscillator strength through the generalized line strength

$$\frac{df}{dE} = \frac{\omega}{g_i}[L]^{-1}(\alpha\omega)^{2L-2}S,$$

where $L$ is the rank of the multipole operator inducing the transition, $[L]$ denotes $2L + 1$, and the generalized line strength is

$$S = \sum_{\kappa J_T} |< \psi_f, \kappa; J_T \parallel O^L \parallel \psi_i >|^2,$$

where $\kappa$ is the relativistic quantum number of the free electron, $J_T$ is the total angular momentum of the free state when the final bound state is coupled to the continuum electron, and $O^L$ is the multipole operator inducing the transition.

Table 1 shows all the final energy levels of the $4p^64d^8$ configuration of Xe$^{10+}$ ions from the levels of the $4p^64d^9$ configuration of Xe$^{9+}$ ion which we calculated using the FAC code. Numbers marked in the first column of the table will be used to identify different energy levels. Figures 1 and 2 show the energy levels of the ground and excited states of Xe$^{10+}$ and of the autoionizing and excited states of Xe$^{9+}$. Figure 1 shows the levels for the transitions $4d - 4f$ whereas figure 2 shows the levels for transitions for $4d - 5p$. Through these figures, we know that the levels of $4d^74f^2, 4d^74f^15l$, and $4d^75p^15d^1(5f^1, 5g^1)$ are crossing the ionization limit of Xe$^{9+}$. Some of the levels are autoionizing states which are above the ionization limit of Xe$^{9+}$ and other levels are below the ionization limit. Tables 2 and 3 show the comparison of the averaged radiative transition ($4d^8nl - 4d^75p^1n'l'$) rates ($\bar{Ar} \equiv \frac{\Sigma_{i,j}g_{ij}Ar_{ij}}{\Sigma_j g_i}$) and autoionization rates ($\bar{Aa} \equiv \frac{\Sigma_{i,j}g_{ij}Aa_{ij}}{\Sigma_j g_i}$) calculated with the HULLAC[10] and the FAC program. Through above result, we can know that two calculations show similar result.
3. Dielectronic recombination rate coefficients for Xe$^{10+}$

The Dielectronic recombination (DR) rate coefficients, $\alpha_{DR}(i_0, f; T_e)$, for electrons in the Maxwellian distribution can be expressed as

$$\alpha_{DR}(i_0, i, f; T_e) = \left(\frac{\hbar^3}{2\pi m_e k_B T_e}\right)^{3/2} \frac{1}{2g_{i_0}} Qd(i_0, i, f) e^{-\frac{E_{i,i_0}}{k_B T_e}},$$

(10)

where $T_e$ is the electron temperature, $m_e$ is the electron mass, $\hbar$ is the Plank constant, $k_B$ is the Boltzmann constant, $g_i$ and $g_{i_0}$ are the statistical weights of the autoionizing state ($i$) formed by dielectronic capture and the target state ($i_0$) before dielectronic capture, and $E_{i,i_0}$ is the resonance energy calculated from the ionization limit. This schematic diagram for DR is shown in Fig I.

The intensity factor ($Qd$) for the dielectronic satellite lines from $i$ to $f$ are given by

$$Qd(i_0, i, f) = \frac{g_i Aa(i, i_0) Ar(i \rightarrow f)}{\sum_{all i'} Aa(i, i'_0) + \sum_{all f'} Ar(i \rightarrow f')}.$$

(11)

where $g_i$ and $g_0$ are the statistical weights of the intermediate(autoionization) state $i$ and initial state $i_0$ of Xe$^{10+}$, $Ar(i \rightarrow f)$ is the radiative decay rate from the level $i$ to the level $f$, $Aa(i, i_0)$ is the autoionization rate from the level $i$ to the level $i_0$. The sum over $i'_0$ runs over all the levels in the next higher ion reachable from the level $i$ by autoionization, and the sum over $f'$ runs over all bound levels reachable from the level $i$ by radiative decay.

---

**Figure I.** Dielectronic recombination process
The autoionizing states formed by dielectronic capture may either autoionize, or radiatively decay. The radiative decay to the states below the ionization limit completes the recombination process. The radiative branching ratio for dielectronic recombination can be expressed as $\frac{A_r^{(i \rightarrow f)}}{\sum A_a + \sum A_r}$. Usually, the states of each complex, designated as $n'l'n_l$, where the excited core electron ($n'l'$) and the capture electron ($n_l$) have the principle quantum numbers, $\Delta n' = 0$ and $\Delta n' = 1$ are considered separately. The $\Delta n' = 0$ resonances, where the transition of the core electron does not change its principle quantum number, and $\Delta n' = 1$ resonances, where the principle quantum number of the core electron changes by one unit, make dominant contributions to the total DR rate coefficients at temperatures of interest. Figure 3-(a) shows the average $\bar{A}r[\equiv \Sigma g_i A_{ij}/\Sigma g_i]$ values of the $4d^74f^1nd \rightarrow 4d^8nd$ and $4d^75p^1nd \rightarrow 4d^8nd$ as a function of the principle quantum number $n$ at $l = 2$. Figure 3-(b) shows the average $\bar{A}a[\equiv \Sigma g_i A_{a,ij}/\Sigma g_i]$ values of the $4d^74f^1nd \rightarrow 4d^8 + e$ and $4d^75p^1nd \rightarrow 4d^8 + e$ as a function of the principle quantum number $n$ at $l = 2$. Figure 4-(a) shows the average $\bar{A}r$ of transition of $4d^74f^17l \rightarrow 4d^87l$ and $4d^75p^17l \rightarrow 4d^87l$ as a function of the angular quantum number $l$ and figure 4-(b) shows the average $\bar{A}a$ of transition of $4d^74f^17l \rightarrow 4d^8 + e$ and $4d^75p^17l \rightarrow 4d^8 + e$ as a function of the angular quantum number $l$. The average $\bar{A}r$ keeps almost constant with increasing $l$ but the average $\bar{A}a$ is decreased with increasing $l$, except $l = 3$. The summation over $nl$, however, can potentially involve large number of terms. For high $n$, the contributions for large $l$ are small. For estimating contributions from autoionizing states with higher $n$ levels for $n > 15$, we use empirical scaling laws.

\[
\begin{align*}
Ar(4d^74f^1nl \rightarrow 4d^8nl) & \simeq Ar(4d^74f^115l \rightarrow 4d^815l), \\
Ar(4d^75p^1nl \rightarrow 4d^8nl) & \simeq Ar(4d^75p^115l \rightarrow 4d^815l), \\
Aa(4d^74f^1nl, 4d^8) & \simeq Aa(4d^74f^115l, 4d^8)\left(\frac{15}{n}\right)^3, \\
Aa(4d^75p^1nl, 4d^8) & \simeq Aa(4d^75p^115l, 4d^8)\left(\frac{15}{n}\right)^3.
\end{align*}
\]
We extrapolate $A_r$ and $A_a$ values from $n = 15$ for the scaling. When we calculate the
dielectronic recombination rate coefficients, we calculate the data of $n \leq 15$ and $l \leq n - 1$
by the FAC code. In order to obtain the DR rate coefficient, we assumed the population
density of the ground state $4d^8(i_0)$ is proportional to the statistical weight.

$$
\alpha_{DR}(i, f) \equiv \frac{1}{2} \left( \frac{\hbar^3}{2\pi m_e k_B T_e^2} \right)^{3/2} \frac{\sum_{i_0} g_0 Qd(i_0, i, f) / g_0}{\sum_{i_0} g_0} \times e^{-\left( \frac{\Delta E}{k_B T_e} \right)}
$$

Figures 5 and 6 show the dielectronic recombination rate coefficients for the $4d^8 + e \rightarrow 4d^7 4f^4 nd \rightarrow 4d^8 nd + h\nu$ and $4d^8 + e \rightarrow 4d^7 5p^1 nd \rightarrow 4d^8 nd + h\nu$, respectively, for diferent values $n$ with a fixed $l$ value as a function of electron temperature. The maximum position of the dielectronic recombination rate coefficients moves towards high temperature region with increasing $n$ for $n < 10$, whereas, the maximum position of the dielectronic recombination rate coefficients does not change with increasing $n$ for $n > 10$. Figures 7 and 8 show the temperature dependence of the dielectronic recombination rate coefficient calculated for different $l$ with a fixed $n = 7$. The value of the
dielectronic recombination rate coefficients for the $4d^8 + e \rightarrow 4d^7 4f^1 7l \rightarrow 4d^8 7l + h\nu$ and $4d^8 + e \rightarrow 4d^7 5p^1 7l \rightarrow 4d^8 7l + h\nu$ increase with increasing $l$ and reach the maximum at $l = 5$. This is because $A_a$ values decrease rapidly and are comparable to $A_r$ values for $l > 5$ as shown in figure 4. Also, the maximum position of these values moves towards high temperature region with increasing $l$. Figures 9 and 10 show the dielectronic recombination rate coefficients summed over all $l$ but for each different $n$ as a function of the electron temperature. The maximum values of the dielectronic recombination rate coefficients for the $4d^8 \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl$ and $4d^8 \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl$ moves from 10eV to 50eV for high $n$. The difference of the values between $n$ and $n + 1$ of the dielectronic recombination rate coefficient for the $4d^8 \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl$ and $4d^8 \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl$ decreases as $n$ value increases as shown in figures 9 and 10. We can see that the results of the
dielectronic recombination rate coefficients for the $4d^8 + e \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl + \hbar \nu$ and $4d^8 + e \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl + \hbar \nu$ at $n = 4$ and 5 are different from other levels, because the values of $E_{i,i_0}$ of $4d^7 4f^1 nl$ and $4d^7 5p^1 nl$ at $n = 4$ and 5 are much smaller than other. The DR rate coefficient for $n = 4$ and 5 are large at low temperatures as shown in figures 9 and 10. The total dielectronic recombination rate coefficient is given by

$$\alpha_{\text{DR}}^\text{tot}(T_e) = \frac{1}{2} \left( \frac{\hbar^3}{2\pi m_e k_BT_e} \right)^{3/2} \sum_{i,f} < Qd(i_0, i, f)/g_0 > e^{-\left(\frac{\Delta E_s}{k_BT_e}\right)}$$ (17)

where $g_i$ and $g_0$ are the statistical weights of the intermediate(autoionization) state $i$ of Xe$^{9+}$ and initial states $i_0$ of Xe$^{10+}$, $\Delta E_s$ and $< Qd(i_0)/g_0 >$ represent the average value over all initial state the Xe$^{10+}$($4d^8$). Figure 11 shows the total dielectronic recombination rate coefficient calculated for the following $4d^8 \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl$ and $4d^8 \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl$ processes. The number I and II represent the transition of $4d^8 \rightarrow 4d^7 4f^1 nl \rightarrow 4d^8 nl$ and $4d^8 \rightarrow 4d^7 5p^1 nl \rightarrow 4d^8 nl$, respectively, including $n = 4 \rightarrow 100$, $l = n - 1$ for $n \leq 15$, and $l = 0 \rightarrow 6$ for $n > 15$. The I’ and II’ represent the transitions including $n = 1 \rightarrow 15$ and $l = n - 1$. The total dielectronic recombination rate coefficients have the maximum values at around 50eV and the temperatures at maximum values increase towards higher electron temperature with larger $n$ and $l$.

4. Satellite lines of Xe$^{10+}$

The satellite lines [5,11,12] for Xe$^{10+}$ parent emission of the types $4d^8 \rightarrow 4d^7 4f^1$ and $4d^8 \rightarrow 4d^7 5p^1$ transitions are emitted by the radiative stabilization from the doubly excited states in the Xe$^{9+}$ ions: $4d^7 4f^1 nl \rightarrow 4d^8 nl$ and $4d^7 5p^1 nl \rightarrow 4d^8 nl$. During the stabilization, the additional $nl$ electron (a nonparticipating, so-called spectator electron) perturbs the other orbitals by shielding the nuclear charge resulting in a transition wavelength somewhat longer than that of the parent transition. These satellite lines are of great interest in fields of study involving laboratory, astrophysics and particularly in diagnostics.
of plasmas, where they are used to determine the electron temperature or electron density through intensity ratios. The doubly excited states are populated by the processes of dielectronic capture:

\[ e^- + Xe^{10+} (4d^8) \rightarrow Xe^{9+} (4d^7 4f^1 nl) \rightarrow Xe^{9+} (4d^8 nl) + h\nu, \quad (18) \]
\[ e^- + Xe^{10+} (4d^8) \rightarrow Xe^{9+} (4d^7 5p^1 nl) \rightarrow Xe^{9+} (4d^8 nl) + h\nu \quad (19) \]

The dielectronic recombination process is resonated by the incident electron energy, required being equal to the energy of the doubly excited state relative to the ionization energy of the Xe\(^{9+}\) ion. The autoionization takes place only when the energy of the doubly excited states is above the threshold energy. The ionization energy from the ground state 4\(p^6 4d^9\) of Xe\(^{9+}\) ion is about 1,627,000 cm\(^{-1}\) (201.7 eV)[13]. The emissivity of a dielectronic satellite transition from the autoionizing state \(i\) to a final state \(f\) is proportional to a \(Qd(i_0, i, f)\) factor which expresses the rate of dielectronic capture into the autoionizing state followed by radiative decay to the final state. Thus, the intensity of a satellite lines produced by dielectronic recombination can be expressed by Eq. (10). Tables 4 - 6 show the wavelength(\(\lambda\)), radiative transition probability(\(Ar\)), autoionization rate(\(Aa\)), energy difference(\(\delta E_i\)) between the autoionization state(\(i\)) and the initial state(\(i_0\)), and the intensity factor(\(Qd\)) for the transitions from the 4\(d^8(i_0) \rightarrow 4d^7 4f^2(i) \rightarrow 4d^8 4f^1(f)\) at \(i_0 = 0, 4,\) and 6 of the Xe\(^{10+}\) ions which capture the free electron. Tables 7 - 9 show the wavelength(\(\lambda\)), radiative transition probability(\(Ar\)), autoionization rate(\(Aa\)), energy difference(\(\delta E_i\)) between the autoionization state(\(i\)) and the initial state(\(i_0\)), and the intensity factor(\(Qd\)) for the transitions from the 4\(d^8(i_0) \rightarrow 4d^7 5p^1 5d^1(i) \rightarrow 4d^8 4f^1(f)\) at \(i_0 = 0, 4,\) and 6 of the Xe\(^{10+}\) ions which capture the free electron. Here the \(g_f\) is statistical weight of the each final excited state of the Xe\(^{9+}\) and the \(g_i\) is statistical weight of the autoionization state of the Xe\(^{9+}\). We select the strong satellite lines which have the values \(Qd\) larger than 10\(^{10}\). When the satellite line of Xe\(^{9+}\) are observed, the
satellite line appear near the parent emission of Xe$^{10+}$. The parent emission lines are generally produced by an excitation process. It is necessary to know the contribution of satellite lines on the excitation lines. We calculated the excitation rate coefficient from level $i$ to level $i'$ ($C_{i,i'}$) using the FAC code. Figures 12 and 13 show the collisional excitation rate coefficients for the $4d^8(2J=8) \rightarrow 4d^74f^1(2J=8)$ (111.572Å) and $4d^8(2J=8) \rightarrow 4f^75p^1(2J=10)$ (135.859Å) of Xe$^{10+}$ ions and the dielectronic recombination rate coefficients for the $4d^8(2J=8) \rightarrow 4d^74f^2(2J=15) \rightarrow 4d^84f^1(2J=13)$ (112.3256Å) and $4d^8 \rightarrow 4d^75p^15d^1(2J=11) \rightarrow 4d^85d^1(2J=13)$ (136.0335Å) as a function of electron temperature for the lines which intensities are the largest. Through these results, we can expect that the satellite line intensity is larger than the excitation intensity at low temperature ($Te < 10eV$). Here we assumed the line intensity by excitation is proportional to the excitation from the ground state.

$$I_{parent}(i', i_0) = C_{i_0,i}n_zn_e,$$

Figures 14(a)-16(a) show the intensity factor ($Qd$) of the satellite transitions from $4d^74f^2$ to $4d^84f^1$ for the initial configuration ($4d^8$) with different $J$-values ($i_0 = 0, 4, 6$) of the Xe$^{10+}$ ions. Figures 14(b)-16(b) show the intensity factor ($gAr$) for lines emitted from the excited state $4d^74f^1$ to the ground state $4d^8$ of the Xe$^{10+}$ ions ($i_0 = 0, 4, 6$). For these lines, the population densities of the excited states are assumed proportional to the statistical weights $g$ of the excited states. Here the intensity factors are convoluted by the Gaussian profiles with spectral Doppler width $\Delta \sigma = 0.0138\text{Å}$. It is shown that the spectra are quite different when the initial state $J$ is different. Figures (a) and (b) of the figures 17 to 19 compare the intensity factor ($Qd$) of the satellite transitions from the states of $4d^75p^15d^1$ to $4d^85d^1$ for the different initial states $4d^8$ ($i_0 = 0, 4, 6$) of the Xe$^{10+}$ ions and the intensity factor ($gAr$) for the lines emitted from the excited state $4d^75p^1$ to the ground state $4d^8$ of the Xe$^{10+}$ ions ($i_0 = 0, 4, 6$).
We compare the spectral shape of excitation lines and satellite lines for the intensity averaged over the initial ground states \((4d^8)\) given in Table 1. The population densities of the ground states are assumed to be proportional to the statistical weights. In the case of satellite lines, the DR rate coefficient is the same as the intensity of the satellite lines from the dielectronic recombination process. Thus the intensity of the satellite lines from the dielectronic recombination process is given by

\[
I_{\text{satellite}}(i, f) = \frac{1}{2} \left( \frac{\hbar^3}{2\pi m_e k_B T_e} \right)^{3/2} e^{-\frac{(\Delta E_s)}{k_B T_e}} < Qd(i_0, i, f)/g_0 > n_z n_e, \tag{21}
\]

where \(g_i\) and \(g_{i_0}\) are the statistical weights of the intermediate (autoionization) state \(i\) of \(\text{Xe}^{9+}\) and initial states \(i_0\) of \(\text{Xe}^{10+}\), \(\Delta E_s\) and \(< Qd(i_0)/g_0 >\) represent the average values over all initial state of the \(\text{Xe}^{10+}(4d^8)\). In the case of lines produced by direct excitation, the excitation rate coefficient contributes to the intensity of lines. For the line intensities by excitation, we assumed that the population densities of the excited states are proportional to the statistical weights:

\[
I_{\text{parent}}(i', i_0) \propto g_{i'} A_{i', i_0}. \tag{21}
\]

Figures 20(a) and 20(b) compare the average intensity factor \(< Qd(4d^74f^2, 4d^84f^1)/g_0 >\) for the satellite transitions from the states of \(4d^74f^2\) to \(4d^84f^1\) after the initial states \((4d^8)\) of the \(\text{Xe}^{10+}\) ions captures the free electron and the intensity factor \((g_{i' Ar}(4d^8, 4d^74f^1)))\) for the lines from \(4d^74f^1\) to \(4d^8\) of the \(\text{Xe}^{10+}\) ions. Also, figures 21(a) and 21(b) compare the average intensity factor \(< Qd(4d^75p^14d^1, 4d^85d^1)/g_0 >\) for the satellite transitions from the states of \(4d^75p^15d^1\) to \(4d^85d^1\) and the intensity factor \((g_{i' Ar}(4d^8, 4d^75p^1)))\) for the lines from \(4d^75p^1\) to \(4d^8\) of the \(\text{Xe}^{10+}\) ions. When we observe the satellite lines, the lines for the transitions \(4d^74f^1nl - 4d^8nl\) and \(4d^75p^1nl - 4d^8nl\) including \(n > 4\) are observed. We calculated the spectra summing up to \(n = 7\) for \(\sum_{n=4}^{7} < Qd(4d^8, 4d^74f^1nl, 4d^8nl)/g_0 >\) and \(\sum_{n=5}^{7} < Qd(4d^8, 4d^75p^1nl, 4d^8nl)/g_0 >\). They are shown in figures 22 and 23. Comparing to the values shown in Figs. 20 and 22 or Figs. 21 and 23, we can know the contribution of high \(n\) are important for the satellite line. We know that the dielectronic satellite lines of \(\text{Xe}^{9+}\)
ions appear near the excitation lines of Xe$^{10+}$ ions and the dielectronic satellite lines have values of intensities that can not be ignored at low temperature. For identification of the spectrum from the highly charged ions, we need the information of the direct excitation of the parent ions.

5. Radiative recombination processes

In radiative recombination, a free electron is directly captured by a target, releasing its kinetic energy and binding energy of the final bound state to the emitted photon. Radiative recombination is an important contributor to the total recombination rate coefficient at least in some temperature ranges. When we consider the recombination processes, it is necessary to know the contribution of radiative recombination.

$$e^- + Xe^{10+}(4d^8) \rightarrow Xe^{9+}(4d^8\text{nl}) + h\nu$$  \hspace{1cm} (22)

Generally, the radiative recombination (RR) cross section is obtained from the photoionization (PI) cross sections through the Milne relation. The PI cross section for the $n \leq 10$ shells are calculated in the distorted-wave approximation, taking into account the electronic dipole operator. The wave functions of bound and continuum orbitals are obtained by solving the single-electron Dirac equations with a spherical model potential, which is based on the self-consistent Dirac-Fork-Slater calculation. The atomic code for our calculation is the FAC code. The PI cross sections is computed at electron energies of $E_e < 10E_{th}$, where the $E_{th}$ values are the ionization thresholds for corresponding shells. For $E_e > 10E_{th}$, the FAC code used a simplified version of the formula suggested by Verner et al.[14] until 10000eV, 

$$\sigma_{PI}(E_e) = \sigma_0 x^{-3.5 - 1 + p/2}(\frac{1 + b}{\sqrt{x} + b})^p$$ \hspace{1cm} (23)
where $x = (E_0 + E_e)/E_0$, $l$ is the orbital angular momentum of the photoionized shell, and $\sigma_0$, $E_0$, $p$, and $b$ are fit parameters. For the photoionization of a particular $nl$ shell, we calculate the exact nonrelativistic cross sections of the hydrogenic ion with the residual nuclear charge and fit them with the above equation, fixing $E_0$ to be the binding energy of the orbital. Therefore, the FAC code includes these two kind of calculations, which are the exact calculation at $E_e < 10E_{th}$ and fit formula at $E_e > 10E_{th}$. We obtained the radiative recombination to the excited state $nl$ from the the photoionization of a particular $nl$ shell.

The radiative recombination cross section obtained from the FAC code is fitted by series of terms containing various powers of $u = E_e/E_{th}$ for $u \leq 10$. This fitting formula is given by,

$$\sigma_{nl}^{low} = \frac{1}{u(u+1)} \sum_{i=0}^{3} a_i u^i. \quad (u \leq 10) \quad [cm^2]$$

For higher energies we need different fitting formula as

$$\sigma_{nl}^{high} = \frac{1}{u(u+1)} \times 10^{\sum_{i=0}^{6} a_i u^i}. \quad (10 \leq u \leq 1000) \quad [cm^2]$$

Here $a_i$ is a fitting parameter. The cross section fitting formula is used until $n \leq 10$ shell.

Figures 24 and 25 show the photoionization cross sections and radiative recombination cross sections calculated for different $l$ with fixed $n = 5$. The energy dependence of the PI cross section for $4d^85d^1$ near the threshold are flat and this feature produce the slow decay of the RR cross section at $E_e > 100eV$. The radiative recombination cross section for $n > 10$ shells is estimated using the semiclassical Kramers formula[7].

$$\sigma_n(x) = 2.1 \times 10^{-22} \frac{n}{x(x+1)}, \quad (x = E_e/E_0) \quad [cm^2]$$

where $n$ is the principle quantum number, $E_0 = z^2Ry/n^2$, Ry is the Rydberg energy, and $z$ is the residual charge of the ion. The Maxwellian averaged rate coefficients of the partial $n$ shells are calculated numerically using the cross sections for the temperature
range $10^{-3} - 10^3$ eV.

$$K_{rr}^{nl}(T_e) = 6.6941 \times 10^{-14} \sqrt{E_{nl}/\beta^{3/2}} \int_0^\infty u\sigma_{nl}(u)e^{-\beta u} du,$$

(27)

where $\beta = E_n/kT_e$ and $\sigma_{nl}(u) = \sigma_{nl}^{low}(u) + \sigma_{nl}^{high}(u)$. Figure 26 shows the temperature dependence of the radiative recombination rate coefficients calculated for different $l$ with fixed $n = 5$. Figure 27 shows the radiative recombination rate coefficients summed over all $l$ but each different $n$ as a function of the electron temperature. The value of the radiative recombination rate coefficient decreases with increasing $n$. Also the difference of the values between $n$ and $n + 1$ of the radiative recombination rate coefficients decreases as $n$ value increases. Thus, the total radiative recombination rate coefficient into all states of the $Xe^{9+}$ ions can be written in the form

$$K_{rr}^{tot}(T_e) = \sum_{n=4}^{10} K_{rr}^n(T_e) + \sum_{n=11}^{1000} 5.18 \times 10^{-14} \times z\beta'^{3/2}e^{-\beta'}E_1(\beta'), \quad [cm^3 s^{-1}]$$

(28)

where $\beta' = \frac{z^2Ry}{n^2kT_e}$. Figure 28 shows the total radiative recombination rate coefficient represented by the solid line and the total dielectronic recombination rate coefficient represented by the dotted line. Through the figure, we know that the value of the radiative recombination rate coefficient is smaller than the value of the dielectronic recombination rate coefficient in our interest temperature region at $T_e = 1$ eV - 1000 eV.

6. Summary

We calculated the energy levels, the radiative transition probabilities ($Ar$), autoionization rates ($Aa$), the intensity factors ($Qd$) of the dielectronic satellite spectra of $Xe^{9+}$, and the dielectric and radiative recombination rate coefficients of $Xe^{10+}$ ion by the use of FAC code. We took into account the $4d^74f^1nl$ states and the $4d^75p^1nl$ states of $Xe^{9+}$ ions. We investigated the $l$- and $n$-dependence for $Ar$ and $Aa$. The values of $Aa$ decrease as $l$ increases for large $l$, but the values of $Ar$ keep almost constant for large $l$. The $Ar$
values for the $4d^7 4f^1 nl \rightarrow 4d^8 nl$ and the $4d^7 5p^1 nl \rightarrow 4d^8 nl$ processes keep constant as $n$ increases, respectively and the $Aa$ values decrease as the $n$ values increase. The values of $Ar$ for the transitions of $4d^7 4f^1 nl \rightarrow 4d^8 nl$ are much larger than those for the transition $4d^7 5p^1 nl \rightarrow 4d^8 nl$ for the Xe$^{9+}$. We obtained the $Aa$ values by the extrapolation according to scaled factor $n^{-3}$ for $n > 15$. We obtained the dielectronic recombination, the direct excitation, the radiative recombination rate coefficients of Xe$^{10+}$ using the FAC Code and compared these results. Also we obtained the satellite lines from Xe$^{9+}$ ions. Through these results, we could know that the total dielectronic recombination rate coefficients have the maximum values at around 50eV. The temperatures at maximum values of dielectronic recombination rate coefficients move towards higher electron temperature with larger $n$ and $l$. The dielectronic satellite lines of Xe$^{9+}$ ions appear near the excitation lines of Xe$^{10+}$ ions and the intensities of the dielectronic satellite lines can not be ignored at low temperate $Te < 10eV$. For identification of the spectrum from the highly charged ions, we need the information of the direct excitation of the parent ions. By our calculation, the radiative recombination rate coefficient is found smaller than the values of the dielectronic recombination processes in our interest temperature region at $Te = 1eV - 1000eV$.

**Acknowledgment**

One of the authors(M.-Y. Song) acknowledges Professor Y. -D. Jung and Professor R. M. More for useful discussions on atomic collisions and for M. F. Gu for guidance about the FAC code.
Reference


Table 1: Energy levels of $4p^64d^8(Xe^{10+})$ ions. The energy of these levels is measured from the ground level ($4p^64d^9$) of the Xe$^{9+}$ ion

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<th>energy (eV)</th>
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Table 2: Comparison of the averaged radiative transition ($4d^8nd - 4d^74f^1nd$) rate ($\bar{Ar}$) and autoionization rate ($\bar{Aa}$) calculated with different theoretical models. [a : FAC, b : HULLAC]

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Table 3: Comparison of the averaged radiative transition ($4d^8nd - 4d^75p^1nd$) rate ($\bar{Ar}$) and autoionization rate ($\bar{Aa}$) calculated with different theoretical models. [a : FAC, b : HULLAC]

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Table 4: Atomic data of $\lambda$, Ar, $Aa$, $\delta E_{if}$, and $Qd$ for the transition from the states of 4$d^74f^2$ to 4$d^84f$ with the initial states 4$d^8(i_0 = 0)$ of the $Xe^{10+}$ ions

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Table 6: Atomic data of $\lambda$, Ar, Aa, $\delta E_{if}$, and Qd for the transition from the states of $4d^74f^2$ to $4d^84f$ with the initial states $4d^8(i_0 = 6)$ of the $Xe^{10+}$ ions

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Table 7: Atomic data of $\lambda$, $Ar$, $Aa$, $\delta E_{if}$, and $Qd$ for the transition from the states of $4d^5p^15d$ to $4d^55d$ with the initial states $4d^5 (i_0 = 0)$ of the $Xe^{10+}$ ions

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Table 8: Atomic data of $\lambda$, Ar, Aa, $\delta E_{if}$, and $Qd$ for the transition from the states of $4d^7 5p^1 5d$ to $4d^8 5d$ with the initial states $4d^8(i_0 = 6)$ of the $Xe^{10+}$ ions

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Table 9: Atomic data of $\lambda$, Ar, Aa, $\delta E_{i_f}$, and Qd for the transition from the states of 4d$^7$5p$^1$5d to 4d$^8$5d with the initial states 4d$^8(i_0 = 4)$ of the Xe$^{10+}$ ions

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Figure 1: Energy level diagram of $4p^64d^74f^1$, $4p^64d^8$ of the Xe$^{10+}$ ions and $4p^64d^74f^2$, $4p^64d^74f^15l$, $4p^64d^84f^1$, $4p^64d^85l$, and $4p^64d^9$ of the Xe$^{9+}$ ions.
Figure 2: Energy level diagram of $4p^6 4d^7 5p^1$, $4p^6 4d^8$ of the $Xe^{10+}$ ions and $4p^6 4d^7 5p^1 5l$, $4p^6 4d^8 5l$, and $4p^6 4d^9$ of the $Xe^{8+}$ ions.
Figure 3: (a) The average $\bar{A}_r \equiv \Sigma g_i A_{ij} / \Sigma g_i$ values of the $4d^74f^1nd \rightarrow 4d^8nd$ and $4d^75p^1nd \rightarrow 4d^8nd$ calculated with different $n$ values at $l = 2$. (b) The average $\bar{A}_a \equiv \Sigma g_i A_{ai,3l} / \Sigma g_i$ values of the $4d^74f^1nd \rightarrow 4d^8 + e$ and $4d^75p^1nd \rightarrow 4d^8 + e$ calculated with different $n$ values at $l = 2$. 


Figure 4: (a) The average $\bar{A}r$ of transition of $4d^7 4f^1 7l \rightarrow 4d^8 7l$ and $4d^7 5p^1 7l \rightarrow 4d^8 7l$ calculated with different $l$ values at $n = 7$. (b) The average $\bar{A}a$ of transition of $4d^7 4f^1 7l \rightarrow 4d^8 + e$ and $4d^7 5p^1 7l \rightarrow 4d^8 + e$ calculated with different $l$ values at $n = 7$. 
Figure 5: Dielectronic recombination rate coefficient for $4d^8 - 4d^7 4f^1 nd - 4^8 nd$ calculated with different $n$ values as function of the plasma temperature.
Figure 6: Dielectronic recombination rate coefficient for $4d^8 - 4d^75p^4nd - 4d^8nd$ calculated with different $n$ values as function of the plasma temperature.
Figure 7: Dielectronic recombination rate coefficient for $4d^8 - 4d^7 4f^1 7l - 4d^8 7l$ calculated with different $l$ values as function of the plasma temperature.
Figure 8: Dielectronic recombination rate coefficient for $4d^8 - 4d^7 5p^1 7l - 4d^8 7l$ calculated with different $l$ values as function of the plasma temperature.
Figure 9: Dielectronic recombination rate coefficient for $4d^8 - 4d^7 4f^1 nl - 4d^8 nl$ calculated with different $n$ values as function of the plasma temperature.
Figure 10: Dielectronic recombination rate coefficient for $4d^8 - 4d^7 5p^1 nl - 4d^8 nl$ calculated with different $n$ values as function of the plasma temperature.
Figure 11: Total dielectronic recombination rate coefficient obtained by the summation of the each dielectronic recombination rate coefficient for these autoionizing states of I, II, I', and II'

$I : 4d^8 - 4d^7 4f^1 nl - 4d^8 nl (n = 4 − 100, l = 0 − 6), II : 4d^8 - 4d^7 5p^1 nl - 4d^8 nl (n = 5 − 100, l = 0 − 6), I' : 4d^8 - 4d^7 4f^1 nl - 4d^8 nl (n = 5 − 15, l = n − 1), II' : 4d^8 - 4d^7 5p^1 nl - 4d^8 nl (n = 5 − 15, l = n − 1)$.
Figure 12: Comparison of rate coefficient of satellite line for $[4d^8(2J = 8) \rightarrow 4d^74f^2(2J = 15) \rightarrow 4d^84f^1(2J = 13) : 112.3256\text{Å}]$ (dashed line) and rate coefficient of collisional excitation line for the $[4d^8(2J = 8) \rightarrow 4d^74f^1(2J = 8) : 111.572\text{Å}]$ of $Xe^{10+}$ (solid line) ions as function of the plasma temperature.
Figure 13: Comparison of rate coefficient of satellite line for $[4d^8(2J = 8) \rightarrow 4d^75p^15d^1(2J = 11) \rightarrow 4d^85d^3(2J = 13): 136.0335\AA]$ (dashed line) and rate coefficient of collisional excitation line for the $[4d^8(2J = 8) \rightarrow 4d^75p^1(2J = 10): 135.859\AA]$ of Xe$^{10+}$ (solid line) ions as function of the plasma temperature.
Figure 14: Satellite lines produced by dielectronic recombination \((4d^8 \, ^3F_4 \rightarrow 4d^7 \, ^4f^2 \rightarrow 4d^8 \, ^4f^1)\) of \(Xe^{9+}\) ion and radiative line that is obtained by radiative decay \((4d^7 \, ^4f^1 \rightarrow 4d^8 \, ^3F_4)\) of \(Xe^{10+}\) ion. [(a) : Satellite line, (b) : radiative line]
Figure 15: Satellite lines produced by dielectronic recombination ($4d^8 \, ^3P_0 \rightarrow 4d^7 \, 4f^2 \rightarrow 4d^8 \, 4f^1$) of Xe$^{9+}$ ion and radiative line that is obtained by radiative decay ($4d^7 \, 4f^1 \rightarrow 4d^8 \, ^3P_0$) of Xe$^{10+}$ ion. [(a) : Satellite line, (b) : radiative line]
Figure 16: Satellite lines produced by dielectronic recombination \( (4d^8 1G_4 \rightarrow 4d^7 4f^2 \rightarrow 4d^8 4f^3) \) of \( \text{Xe}^{9+} \) ion and radiative line that is obtained by radiative decay \( (4d^7 4f^1 \rightarrow 4d^8 1G_4) \) of \( \text{Xe}^{10+} \) ion. [(a) : Satellite line, (b) : radiative line]
Figure 17: Satellite lines produced by dielectronic recombination ($4d^8 \, ^3F_4 \rightarrow 4d^75p^15d^1 \rightarrow 4d^85d^3$) of $Xe^{9+}$ ion and radiative line that is obtained by radiative decay ($4d^75p^1 \rightarrow 4d^8 \, ^3F_4$) of $Xe^{10+}$ ion. [(a) : Satellite line, (b) : radiative line]
Figure 18: Satellite lines produced by dielectronic recombination \((4d^8 \, 3P_0 \rightarrow 4d^75p^15d^1 \rightarrow 4d^85d^3)\) of \(Xe^{9+}\) ion and radiative line that is obtained by radiative decay \((4d^75p^1 \rightarrow 4d^8 \, 3P_0)\) of \(Xe^{10+}\) ion.\([a)\) : Satellite line, \((b)\) : radiative line]
Figure 19: Satellite lines produced by dielectronic recombination \( (4d^8 \, ^1G_4 \rightarrow 4d^75p^15d^1 \rightarrow 4d^85d^3) \) of \( \text{Xe}^{9+} \) ion and radiative line that is obtained by radiative decay \( (4d^75p^1 \rightarrow 4d^8 \, ^1G_4) \) of \( \text{Xe}^{10+} \) ion. [(a) : Satellite line, (b) : radiative line]
Figure 20: Satellite lines produced by dielectronic recombination ($4d^8 \rightarrow 4d^7 4f^2 \rightarrow 4d^6 4f^3$) of $Xe^{9+}$ ion and radiative line that is obtained by radiative decay ($4d^7 4f^1 \rightarrow 4d^8$) of $Xe^{10+}$ ion. 
[(a) : Satellite line, (b) : radiative line]
Figure 21: Satellite lines produced by dielectronic recombination \( (4d^8 \rightarrow 4d^75p^15d^1 \rightarrow 4d^85d^3) \) of \( Xe^{9+} \) ion and radiative line that is obtained by radiative decay \( (4d^75p^1 \rightarrow 4d^8) \) of \( Xe^{10+} \) ion. [(a) : Satellite line, (b) : radiative line]
Figure 22: The satellite spectra for $\sum_{n=4}^{T} <Q_d(4d^8, 4d^7f^1nl, 4d^8nl)/g_0>$. 
Figure 23: The satellite spectra for $\sum_{n=5}^{7} < Qd(4d^8, 4d^7 5p^1 nl, 4d^8 nl) / g_0 >$. 
Figure 24: Photoionization cross section of $Xe^{9+}$ ions calculated for different $l$ with fixed $n = 5$. 
Figure 25: Radiative recombination cross section of $Xe^{10+}$ ions calculated for different $l$ with fixed $n = 5$. 
Figure 26: Radiative recombination rate coefficient of $Xe^{10+}$ ions calculated for different $l$ with fixed $n = 5$. 
Figure 27: Radiative recombination rate coefficient of $Xe^{10+}$ ions summed over all $l$ but each different $n$ as function of the electron temperature.
Figure 28: Comparison of total Dielectronic recombination rate coefficient for $4d^8 - 4d^7 4f^1 nl, 4d^7 5p^1 nl - 4d^8 nl$ (solid line) [$n = 4-100$] and the radiative recombination rate coefficient for the $4d^8 \rightarrow 4d^8 nl$ (dashed line) [$n = 4-1000$] of $Xe^{10+}$ ions as function of the plasma temperature.