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${}^6P^e—{}^6P^o$ transitions in boron-like ions with $Z=8-13$

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Abstract

The energies, fine structure splittings, transition rates and lifetimes of inner-shell excited sextet states $1s2s2p^2nl$, ($n=2-7$; $l=s, p, d$) and $1s2p^33p$ of the boron isoelectronic sequence ($Z=8-13$) are investigated by multi-configuration Rayleigh-Ritz variation method. The mass polarization effect and relativistic corrections are included by first-order perturbation theory. Configuration structures of the high- n inner-shell excited sextet series ${}^6S^{e,o}(m)$ and ${}^6P^{e,o}(m)$ ($m=1-5$) of boron-like Na^{6+} ion are assigned. The wavelengths and transition rates of electric-dipole transitions between ${}^6P^e(m)$ and ${}^6P^o(m)$ ($m=1-5$) states are calculated. The quantum electro-dynamics (QED) effects and higher-order relativistic corrections are also considered to obtain more accurate transition wavelengths. The predicted transition wavelengths agree well with the available theoretical and experimental data. The lifetimes for the inner-shell excited sextet states ${}^6P^e(m)(m=1-5)$ are also reported and

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discussed with the increase of nuclear charge number Z . These theoretical data are useful for the identification of spectral lines in experiments and the design of XUV and soft X-ray lasers.

1. Introduction

In recent years, the inner-shell excited states are of great interest because they are helpful to study the multi-electronic processes found in ion-atom interaction and also in multiple photoionization[1,2], identify the spectral lines in astrophysical plasma diagnostics[3, 4], and design the schemes for X-ray and XUV lasers[5-7]. In the non-relativistic LS coupling approximation, the alignment of the spins of the outer electrons with the unpaired inner-shell electron spin results in states of high multiplicity. For the inner-shell high spin excited states of boron-like ions, the lowest energy configuration is $1s2s2p^3\ ^6S^o$ which embedded in continua, however cannot autoionize, due to spin conservation rule. Its Rydberg states, as well as many other inner-shell sextet series, are against Coulomb autoionization. They decay mainly by optical radiative transitions and the spin-induced autoionization via relativistic interactions. Often the autoionization rate via relativistic interaction is several orders of magnitude smaller than the optical radiative rate. Therefore, the decay of these inner-shell excited sextet states could be investigated with a high accuracy considering only optical radiative transitions. Experimentally, the beam-foil collision excitation is the major experimental method to observe the transitions spectra of the inner-shell excited sextet states. In 1992, Blanke et al.[8] made the first observation on the optical transitions between the inner-shell excited sextet states of five-electron

nitrogen, oxygen and fluorine ions. Spectral lines between such sextet states were identified from $1s2s2p^23s\ ^6P$ and $1s2s2p^23d\ ^6P$. Another interesting experimental study of the transition properties for the inner-shell excited sextet states of boron-like ions is the observations of VUV spectra between doubly excited sextet states in O^{3+} , F^{4+} , and Ne^{5+} ions by Lin et al.[7, 9]. Some new lines are identified from the transitions $1s2s2p^23p\ ^6L—1s2p^33p\ ^6P$.

Theoretically, there are a few calculations of certain energy levels and transition data of the considered boron-like ions available in the literature. Most of the theoretical work used the configuration interaction (CI) method: multiconfiguration Hartree-Fock method (MCHF) [7, 9, 10], multiconfiguration Dirac-Fock method (MCDF) [7-9, 11, 12], and the linear Z-expansions method [13,14]. For the sextet states of boron-like ions, the CI method is quite effective. Generally, more configurations are better for good precision. Therefore, the accurate energies and transition data could be obtained by fully considering configuration interaction in the calculation. A few accurate theoretical results of the sextet states of boron-like ions have been reported. For example, Lin et al. [7, 9] and Lapierre et al. [13] reported the energies, lifetimes, transition rates and wavelengths of electric-dipole transitions from the inner-shell excited terms $1s2s2p^2nl\ ^6P^e—1s2s2p^3\ ^6S^o$ ($n=3-4$, $l=s, d$), $1s2s2p^23p\ ^6L—1s2p^33p\ ^6L'$ in O^{3+} , F^{4+} , and Ne^{5+} ions. Blanke et al.[8] and Miecznik et al.[10] presented the theoretical calculations on the electric dipole transitions for the sextet states $1s2s2p^3\ ^6S^o$; $1s2s2p^23s$, $1s2s2p^23d$, $1s2p^33p\ ^6P^e$ of N^{2+} , O^{3+} , and F^{4+} ions by MCHF and MCDF method. Due to the strong electron correlation effects and the

computational instability, most of the previous theoretical literatures concentrated on the low-lying sextet states. For the high-lying Rydberg sextet states, little work had been reported. Besides, in some beam–foil spectral studies of sextet states in the boron isoelectronic sequence, some lines are rather weak and blend with each other. Hence, more accurate theoretical investigations on these sextet states in the boron isoelectronic sequence are strongly needed to help identifications. Therefore, energy level and transition data diagrams of boron isoelectronic sequence, especially for the inner-shell sextet Rydberg series are still far from complete.

In the present work, we study the energy levels, fine structure splittings, transition rates, wavelengths, and lifetimes of the inner-shell excited sextet states $1s2s2p^2nl$, ($n=2-7$; $l=s, p, d$) and $1s2p^33p\ ^6L^{\circ,0}(L=S, P)$ of the boron isoelectronic sequence ($Z=8-13$) by Rayleigh-Ritz variation method with multi-configuration interaction wave functions. Configuration structures of the high-lying sextet series of boron-like Na^{6+} ion are assigned by energies, contribution to normalization of angular-spin components, and relativistic perturbation corrections. The configuration assignments are further confirmed by fine structure splittings. Transition rates and wavelengths with quantum electro-dynamics effects and higher-order relativistic corrections between $^6P^{\circ}(m)$ and $^6P^0(m)$ ($m=1-5$) electric-dipole transitions are calculated and compared with available reference results. The lifetimes for the inner-shell excited sextet states $^6P^{\circ}(m)$ ($m=1-5$) are also calculated and discussed with the increase of nuclear charge number Z .

2. Theoretical method

The zeroth-order nonrelativistic Hamiltonian for a five-electron system is given

by (in a.u.)

$$H_0 = \sum_{i=1}^5 \left[-\frac{1}{2} \nabla_i^2 - \frac{Z}{r_i} \right] + \sum_{\substack{i,j=1 \\ i < j}}^5 \frac{1}{r_{ij}}. \quad (1)$$

The perturbation operators are

$$H' = H_1 + H_2 + H_3 + H_4 + H_5, \quad (2)$$

where

$$H_1 = -\frac{1}{8c^2} \sum_{i=1}^5 \mathbf{P}_i^4 \quad \text{is correction to kinetic energy;} \quad (3)$$

$$H_2 = -\frac{Z\pi}{2c^2} \sum_{i=1}^5 \delta(\mathbf{r}_i) \quad \text{is Darwin term;} \quad (4)$$

$$H_3 = -\frac{\pi}{c^2} \sum_{\substack{i,j=1 \\ i < j}} (1 + \frac{8}{3} \mathbf{s}_i \cdot \mathbf{s}_j) \delta(\mathbf{r}_{ij}) \quad (5)$$

is the electron-electron contact term;

$$H_4 = -\frac{1}{2c^2} \sum_{\substack{i,j=1 \\ i < j}} \frac{1}{r_{ij}} \left[\mathbf{P}_i \cdot \mathbf{P}_j + \frac{\mathbf{r}_{ij}(\mathbf{r}_{ij} \cdot \mathbf{P}_i) \cdot \mathbf{P}_j}{r_{ij}^2} \right], \quad (6)$$

is the orbit-orbit interaction term;

$$H_5 = -\frac{1}{M} \sum_{\substack{i,j=1 \\ i < j}} \nabla_i \cdot \nabla_j, \quad (7)$$

is the mass polarization correction, where M is the nuclear mass.

For the five-electron system, the basis function is written as

$$\Psi_b(1, 2, 3, 4, 5) = A \sum_i C_i \phi_{n(i), l(i)}(R) Y_{l(i)}^{LM}(\Omega) \chi_{SS_z}, \quad (8)$$

where A is the antisymmetrization operator and the radial basis function is Slater orbitals,

$$\phi_{n(i), l(i)}(R) = \prod_{j=1}^5 r_j^{n_j} \exp(-\alpha_j r_j). \quad (9)$$

A different set of nonlinear parameters α_j is used for each angular-spin component.

The angular part is

$$Y_{l(i)}^{LM}(\Omega) = \sum_{m_j} \langle l_1 l_2 m_1 m_2 | l_{12} m_{12} \rangle \times \langle l_{12} l_3 m_{12} m_3 | l_{123} m_{123} \rangle \\ \times \langle l_{123} l_4 m_{123} m_4 | l_{1234} m_{1234} \rangle \times \langle l_{1234} l_5 m_{1234} m_5 | LM \rangle \prod_{j=1}^5 Y_{l_j m_j}(\Omega_j). \quad (10)$$

For the inner-shell excited sextet states of a five-electron ion, the angular and spin wave function are simply represented by

$$l(i) = \{[(l_1, l_2) l_{12}, l_3] l_{123}, l_4\} l_{1234}, l_5, \\ \chi_{ss_z} = \{[(\frac{1}{2}, \frac{1}{2}) 1, \frac{1}{2}] \frac{3}{2}, \frac{1}{2}\} 2, \frac{1}{2}. \quad (11)$$

The linear parameters C_i and the nonlinear parameters α_j are optimized in the energy calculation processes. Then the non-relativistic energy is obtained by Rayleigh-Ritz variational method.

$$\delta E_b = \delta \langle H_0 \rangle = \delta \frac{\langle \Psi_b | H_0 | \Psi_b \rangle}{\langle \Psi_b | \Psi_b \rangle}. \quad (12)$$

To saturate the functional space and improve the non-relativistic energy, the restricted variational method is used to calculate the restricted variational energy ΔE_{RV} . The explicit expressions of the restricted variational calculation were given in [15, 16] and they will not be repeated here.

In addition to ΔE_{RV} , the total energy is further improved by including the mass polarization effect ΔE_{mp} and relativistic corrections ΔE_{rel} with first-order perturbation theory. The relativistic perturbation operators considered in this work are the correction to the kinetic energy, the Darwin term, the electron-electron contact term, and the orbit-orbit interaction term.

$$\Delta E_{mp} = \langle \Psi_b | H_5 | \Psi_b \rangle, \Delta E_{rel} = \langle \Psi_b | H_1 + H_2 + H_3 + H_4 | \Psi_b \rangle. \quad (13)$$

Then the total energy is obtained by

$$E_{total} = E_b + \Delta E_{RV} + \Delta E_{mp} + \Delta E_{rel}. \quad (14)$$

The fine structure splittings are calculated including the spin-orbit, spin-other-orbit and spin-spin operators. They are given by [17]

$$H_{so} = \frac{Z}{2c^2} \sum_{i=1}^5 \frac{\mathbf{l}_i \cdot \mathbf{s}_i}{r_i^3}, \quad (15)$$

$$H_{soo} = -\frac{1}{2c^2} \sum_{\substack{i,j=1 \\ i \neq j}}^5 \left[\frac{1}{r_{ij}^3} (\mathbf{r}_i - \mathbf{r}_j) \times \mathbf{p}_i \right] \cdot (\mathbf{s}_i + 2\mathbf{s}_j), \quad (16)$$

$$H_{ss} = -\frac{1}{c^2} \sum_{\substack{i,j=1 \\ i < j}}^5 \frac{1}{r_{ij}^3} \left[\mathbf{s}_i \cdot \mathbf{s}_j - \frac{3(\mathbf{r}_{ij} \cdot \mathbf{s}_i)(\mathbf{r}_{ij} \cdot \mathbf{s}_j)}{r_{ij}^2} \right], \quad (17)$$

where the $\mathbf{s}_i$ and $\mathbf{l}_i$ are the spin and orbital angular momentum of the i th electron.

The LSJ coupling scheme is used to calculate the fine-structure splitting, namely

$$\Psi_{LSJ_z} = \sum_{M,S_z} \langle LSMM_S | JM_J \rangle \Psi_b(1, 2, 3, 4, 5). \quad (18)$$

The fine-structure energy levels are calculated by first-order perturbation theory,

$$(\Delta E_{FS})_J = \langle \Psi_{LSJ_z} | H_{SO} + H_{SOO} + H_{SS} | \Psi_{LSJ_z} \rangle. \quad (19)$$

To estimate QED effects and higher-order relativistic contributions for the transition wavelengths, the screened hydrogenic formula is used. Here, we only consider the corrections for the different electrons between the initial and final states. The detailed calculation formula have been illustrated in Ref.[18], and we will not repeat here.

3. Results and discussion

The wave function used for the sextet states of boron-like ions in this work is a

multi-configuration wave function. In the energy calculation of these sextet states, we found the radial and angular correlations are very important. To reach a high accuracy, large basis sets are included. For many of the sextet states considered in this work, the number of angular-spin components up to 75. For even-parity states, the important angular series $[l_1 l_2 l_3 l_4 l_5]$ are $[000l, l]$, $[001l, (l+1)]$, $[011l, l]$, $[002l, l]$, $[011l, l+2]$, $[111l, (l+1)]$ etc. For odd-parity states, the available angular series should be $[001l, l]$, $[011l, (l+1)]$, $[000l, (l+1)]$, $[001l, (l+2)]$, $[111l, l]$, etc. In both case, the initial value of l is 1. For each angular spin component, five nonlinear parameters are included for Slater orbitals. These non-linear parameters are individually optimized in the variation process. For some sextet states, more than 1900 linear parameters are used in this work. To obtain the best basis function, the angular component $[l_1 l_2 l_3 l_4 l_5]$ with energy contribution more than 1×10^{-5} a.u. is included in Ψ_b . The angular component $[l_1 l_2 l_3 l_4 l_5]$ that contributes less than 1×10^{-5} a.u. but more than 1×10^{-6} a.u. is included in the restricted variational calculations. Using the restricted variational method, all the important angular-spin components are included in Ψ_b without omission. In this work, the restricted variational energy improvements ΔE_{RV} are about hundreds of μ a.u.. Then we can obtain the non-relativistic energy of the inner-shell excited sextet states, namely, $E_b + \Delta E_{RV}$. The relativistic perturbation corrections to the energies of these inner-shell excited sextet states are significant contributions. The relativistic ΔE_{rel} and the mass polarization ΔE_{mp} corrections to the energy are calculated by first-order perturbation theory. Then the total energy (E_{total}) is obtained by adding $E_b + \Delta E_{RV}$, ΔE_{rel} , ΔE_{mp} . In the calculation, we found the ${}^6S^{e,0}$ states converges faster,

there are fewer angular coupling terms that make a significant contribution, and correlation effects between the angular components are more apparent. However, for the ${}^6P^{e,o}$ sextet states, the electron correlation and configuration interaction effects between the various angular components are very strong, therefore more than 70 angular components are included for these states. In Table 1, we list $E_b + \Delta E_{RV}$, ΔE_{mp} , ΔE_{rel} , E_{total} for the ${}^6S^{o,e}(m)$ and ${}^6P^{e,o}(m)$ ($m=1-5$) states of boron-like Na^{6+} ion. Results from Safronova et al [14] using 1/Z perturbation theory are also listed in Table 1. Our calculated results are in fairly agreement with the theoretical results from Ref.[14]. The energy of $1s2s2p^3 {}^6S^o$ state -103.3159 a.u. is lower than the present data -103.2497 a.u.. It may result from the 1/Z perturbation program takes into account the correlation energy in the frame of the second order perturbation theory in Ref.[14]. For the sextet states of Na^{6+} ion, there are no other theoretical results available for comparison. It needs further theoretical results to verify in the future.

The assigned configuration structure of each sextet state is also given in the first column of Table 1. In our calculation, the configuration structure is not apparent. Therefore, efforts should be made to identify them. Here, we identify the configuration structure of each inner-shell sextet state by the following factors: energy, percentage contributions of basis states with various angular components to the eigenvector, relativistic effect correction, and the fine structure splitting. These sextet series are numbered according to their energy position in the series. The lowest energy level is numbered as (1). In the second column of Table 1, we list the most important angular component and its percentage contribution to the eigenvector for each sextet

state. The main angular component of ${}^6S^e(1)$, ${}^6S^o(1)$, ${}^6P^e(1)$, ${}^6P^o(1)$ states are $sspp$, $ssppp$, $ssppp$, $ssppp$, respectively. According to the Pauli's exclusion principle, the configuration structures of ${}^6S^e(1)$, ${}^6S^o(1)$, ${}^6P^e(1)$, ${}^6P^o(1)$ are identified as $1s2s2p3s3p$, $1s2s2p^3$, $1s2s2p^23s$, $1s2s2p^23p$, respectively. The $ssppd$, $spppp$, $sppdd$, $ssppp$ are the main configuration of ${}^6S^e(2)$ (94.81%), ${}^6S^e(3)$ (91.98%), ${}^6S^e(4)$ (88.51%), ${}^6S^e(5)$ (93.17%) of Na^{6+} ion. Therefore, we identify them as $1s2s2p3p3d$, $1s2p^3p^2$, $1s2p^23d^2$, and $1s2s2p3s4p$, respectively. For the ${}^6S^o(m)$ ($m=1-5$) series, all the main angular components are $ssppp$, and the configuration structures of these states could be assigned as Rydberg series. However, we found that relativistic perturbations ΔE_{rel} of ${}^6S^o(3)$ and ${}^6S^o(5)$ are -0.1220 a.u. and -0.1189 a.u., which are obviously smaller than the relativistic perturbation values of ${}^6S^o(1)$, ${}^6S^o(2)$, and ${}^6S^o(4)$ states. As we know, for a nl electron, when the main quantum number n is fixed, the larger main quantum number l the smaller the relativistic correction. The relativistic correction of $2p$ is apparently smaller than that of $2s$ electron. Therefore, it is reasonable to identify ${}^6S^o(3)$ as $1s2p^33s$ rather than $1s2s2p^24p$, and ${}^6S^o(5)$ as $1s2p^34s$ rather than $1s2s2p^25p$. For the ${}^6P^{e,o}(m)$ ($m=1-5$) series, the configuration structures are identified by similar method. Furthermore, formulae (15-17) indicate the fine structure splittings rely on the orbital and spin angular moments, so the assigned configuration structures of these ${}^6P^{e,o}$ series could be further determined by the fine structure splittings. The fine structure splittings of ${}^6P^{e,o}(m)$ ($m=1-5$) sextet states of Na^{6+} ion are given in the last two columns of Table 1. For ${}^6P^e(1)$ and ${}^6P^e(4)$ states, the fine structure splittings are $\nu_{2.5-1.5} = 1015\text{cm}^{-1}$, $\nu_{3.5-2.5} = 968\text{cm}^{-1}$ and $\nu_{2.5-1.5} = 1028\text{cm}^{-1}$, $\nu_{3.5-2.5} = 983\text{cm}^{-1}$,

respectively. Whereas for the ${}^6P^e(2)$ and ${}^6P^e(5)$ states, the fine structure splittings are $\nu_{2.5-1.5} = -372\text{cm}^{-1}$, $\nu_{3.5-2.5} = -525\text{cm}^{-1}$ and $\nu_{2.5-1.5} = -408\text{cm}^{-1}$, $\nu_{3.5-2.5} = -554\text{cm}^{-1}$, respectively. The large differences of fine structure splittings between ${}^6P^e(1)$, ${}^6P^e(4)$ and ${}^6P^e(2)$, ${}^6P^e(5)$ indicate the configuration structures of ${}^6P^e(1)$, ${}^6P^e(4)$ are quite different from those of ${}^6P^e(2)$, ${}^6P^e(5)$. For the ${}^6P^o(m)$ ($m=1-5$) states, all the fine structure splittings are similar, which indicate they have the similar configuration structures. These results are consistent with our configuration structure assignment listed in Table 1. To our knowledge, for these fine structure splittings of Boron-like Na^{6+} ion, no experimental and theoretical data are available to compare with at present. The investigations on fine structure splittings are helpful to determine configuration structures for the high- n series.

The energy levels for the inner-shell excited sextet states ${}^6S^{e,o}(m)$ and ${}^6P^{e,o}(m)$ ($m=1-5$) series of boron-like O^{3+} , F^{4+} , Ne^{5+} , Mg^{7+} and Al^{8+} ions have been reported in our earlier work [18,19]. It should be mentioned that we recalculated the wave functions and energies of $1s2s2p^27p$ ${}^6P^o$ and $1s2p^33p$ ${}^6P^e$ states for the boron-like O^{3+} , F^{4+} , Ne^{5+} ions in this work. Here, our calculated energy of the $1s2s2p^27p$ ${}^6P^o$ state of O^{3+} ion is -48.310361 a.u., which differs from the -48.365821 a.u. in Ref.[18]. The energies for the $1s2p^33p$ ${}^6P^e$ states of O^{3+} , F^{4+} , Ne^{5+} ions are -48.621921 a.u., -62.906296 a.u., and -79.074802 a.u., respectively, which are slightly higher than the corresponding results -48.622576 a.u., -62.916567 a.u., and -79.080466 a.u. in Ref.[18]. Here, more angular-spin partial waves are included in the calculation, therefore, the energy levels and wave functions should be more accurate than the results in Ref.[18]. In Table

2-Table 4, we give the systematic transition rates and wavelengths for the transitions between ${}^6P^o(m)$ and ${}^6P^e(m)$ ($m=1-5$) states of the boron isoelectronic sequence with $Z=8-13$. The transition rates are given in both dipole length gauge A_l and dipole velocity gauge A_v . In present work, the A_l and A_v results are generally in good agreement with each other, which reflects our calculated wave functions are reasonably accurate. Most of deviations between A_l and A_v results are less than 5%. For example, in Table 2, the A_l and A_v for the transition $1s2s2p^23p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$ of O^{3+} ion are 1.23×10^8 and 1.22×10^8 , respectively. In Table 3, both of A_l and A_v for the transition $1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$ of Ne^{5+} ion are the same value 1.32×10^9 . In Table 2-Table 4, the calculated transition wavelengths for the transitions between ${}^6P^o(m)$ and ${}^6P^e(m)$ ($m=1-5$) together with other literature results are also tabulated. In order to obtain accurate transition wavelengths, the quantum electro-dynamics effects and higher-order relativistic corrections are taken into account. The corrected transition wavelengths are also listed in Tables 2-4. As can be seen from Tables 2-4, the quantum electro-dynamics effects and higher-order relativistic corrections are important for the transitions of $1s2s2p^2np\ {}^6P^o \rightarrow 1s2s2p^2ns\ {}^6P^e$ and $1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^2np\ {}^6P^o$. For the transitions of $1s2s2p^2np\ {}^6P^o \rightarrow 1s2s2p^2nd\ {}^6P^e$, the corrections are very small and can be neglected. The corrected wavelengths are in good agreement with other experimental and theoretical data. For example, for the transition $1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$, our calculated result is 686.14 Å, which agrees with the MCHF result 686.34 Å [7] and the experimental data 687.44 Å [7]. For the transition $1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$ in Ne^{5+} ion, our calculated wavelength

λ is 519.41 Å, which is in good agreement with the experimental data 520.35 Å [7] and also in accord with the MCHF value 517.56 Å [7] and the MCDF value 515.72 Å [7]. As can be seen from Table 2-Table 4, these transition wavelengths gradually become shorter as Z increases, some wavelengths have extend to the soft X-ray spectrum range.

As autoionization transitions via relativistic interaction are forbidden, the level lifetimes of these inner-shell excited sextet states could be computed with a high accuracy considering only electric-dipole transitions. In this work, the level lifetimes τ are obtained by $\tau = \frac{1}{\sum_{E_k < E_i} A_{ik}}$, A_{ik} is the electric-dipole transition rate from E_i level to E_k level. The final states considered in this work are: $1s2s2p^3\ ^6S^o$, $1s2s2p^23p\ ^6S^o$, $1s2s2p^24p\ ^6S^o$, $1s2p^33s\ ^6S^o$, $1s2s2p^23p\ ^6P^o$, $1s2s2p^24p\ ^6P^o$, $1s2s2p^23p\ ^6D^o$, $1s2s2p^24f\ ^6D^o$, $1s2p^33d\ ^6D^o$, $1s2s2p^24p\ ^6D^o$. In our calculation, we found the most important transition channels are $^6P \rightarrow ^6S$ for these $^6P^{e,o(m)}$ ($m=1-5$) sextet series. Table 5 gives the lifetimes for the $1s2s2p^23s$, $1s2s2p^23d$, $1s2s2p^24s$, $1s2s2p^24d$, and $1s2p^33p\ ^6P^e$ sextet states of the boron isoelectronic sequence ($Z=8-13$). As can be seen from Table 5, our calculated results are in good agreement with the experimental results. It should be mentioned that our calculated lifetimes differ from the data from Ref.[18] for the $1s2p^33p\ ^6P^e$ state. In this work, we recalculated the wave functions and the transition rates of $1s2p^33p\ ^6P^e$ states. In our calculation, we found that the [00011] angular series give significant contributions to the transition rates for the $1s2p^33p\ ^6P^e \rightarrow 1s2s2p^2np\ ^6S^o$ transitions. The transition rates for the important transition $1s2p^33p\ ^6P^e \rightarrow 1s2s2p^3\ ^6S^o$ are significantly smaller than the data in Ref.[18].

For example, in this work, the transition rates of $1s2p^33p\ ^6P^e \rightarrow 1s2s2p^3\ ^6S^o$ in O^{3+} ion is 6.79[8], which are two orders of magnitude smaller than 1.16[10] in Ref.[18]. Therefore, our calculated lifetimes for the $1s2p^33p\ ^6P^e$ states in O^{3+} , F^{4+} , Ne^{5+} ions are significant larger than the results from Ref.[18]. Most of our results are within the experimental uncertainty except the lifetime of $1s2s2p^23s\ ^6P$ in O^{3+} ion. For this state, our calculated value 139.28 ps are larger than the experimental data 99 ± 12 ps. However, our data agrees well with the MCHF result 140.7 ps[10] and MCDF result 125 ps[8]. We show in Fig. 1 the variation trend of level lifetimes for $1s2s2p^23s$, $1s2s2p^23d$, $1s2s2p^24s$, $1s2s2p^24d$, and $1s2p^33p\ ^6P^e$ sextet states with the Z increase from 8 to 13. As can be seen from Fig.1, all the lifetimes become short with the Z increase. The lifetime of $1s2s2p^2ns\ ^6P^e$ state is larger than that of $1s2s2p^2nd\ ^6P^e$ state. For the $^6P^e$ Rydberg series, the lifetimes become larger with the n increase. In view of the interest in these inner-shell excited sextet states for the boron-like ions, and the lack of complete data on the energy levels and optical transition decay, we believe our calculated results will be useful for the related experimental study in the future.

4. Conclusions

In this work, we have calculated the energy levels, fine structure splittings, transition rates and wavelengths, lifetimes of the inner-shell excited sextet states $1s2s2p^2nl$, ($n=2-7$; $l=s, p, d$) and $1s2p^33p\ ^6L^{e,o}$ ($L=S, P$) for Z from 8 to 13, using the Rayleigh-Ritz variation method. Some energy levels for the high- n sextet Rydberg series are reported for the first time. The configuration structures for the $^6S^{o,e}(m)$ and $^6P^{e,o}(m)$ ($m=1-5$) sextet series are assigned. Our results show that the study on the fine

structure splittings is helpful to determine the configuration structures. We have also studied the systematic electric-dipole transition rates, wavelengths, lifetimes for these states. The quantum electro-dynamics effects and higher-order relativistic corrections are considered to obtain accurate transition wavelengths. It is found that these corrections are important for the transitions of $1s2s2p^2np\ ^6P^o \rightarrow 1s2s2p^2ns\ ^6P^e$ and $1s2p^33p\ ^6P^e \rightarrow 1s2s2p^2np\ ^6P^o$. These calculated results are compared with the existing experimental and theoretical data in the literature. Variation trend of the lifetimes for $1s2s2p^23s$, $1s2s2p^23d$, $1s2s2p^24s$, $1s2s2p^24d$, and $1s2p^33p\ ^6P^e$ sextet states are discussed with the increase of nuclear charge number Z and main quantum number n . It is found that the lifetimes of these sextet series shorten gradually with the increase of nuclear charge number Z . For the $^6P^e$ Rydberg series, the lifetimes become longer with the n increase. We hope these calculated results will be useful in future experiments.

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Table 1. Energies (a.u.) for the core-excited states ${}^6S^{o,e}(m)$ and ${}^6P^{o,e}(m)$ ($m=1-5$) of B-like Na^{6+} ion.

$E_b + \Delta E_{RV}$ is the non-relativistic energy, ΔE_{mp} is the mass polarization correction. ΔE_{rel} is the relativistic correction. E_{total} is the total energy. $\nu_{2.5-1.5}(\text{cm}^{-1})$ is the fine structure splitting of $J=2.5-1.5$ and $\nu_{3.5-2.5}(\text{cm}^{-1})$ is the fine structure splitting of $J=3.5-2.5$.

Configuration state	Major angular (Percentage %)	$E_b + \Delta E_{RV}$	ΔE_{mp}	ΔE_{rel}	E_{total}	$\nu_{2.5-1.5}$	$\nu_{3.5-2.5}$
$1s2s2p3s3p\ {}^6S^e(1)$	<i>ssssp</i> (97.12)	-92.6157	-0.0002	-0.1360	-92.7519		
$1s2s2p3p3d\ {}^6S^e(2)$	<i>ssppd</i> (94.81)	-92.0189	-0.0002	-0.1301	-92.1493		
$1s2p^23p^2\ {}^6S^e(3)$	<i>spppp</i> (91.98)	-91.5408	-0.0004	-0.1178	-91.6591		
$1s2s2p3s4p\ {}^6S^e(4)$	<i>ssssp</i> (88.51)	-90.9382	-0.0002	-0.1348	-91.0732		
$1s2p^23d^2\ {}^6S^e(5)$	<i>sppdd</i> (93.17)	-90.9413	-0.0005	-0.1134	-91.0552		
$1s2s2p^3\ {}^6S^o(1)$	<i>ssppp</i> (99.89)	-103.1134	-0.0005	-0.1359	-103.2497		
					-103.3159 ^a		
$1s2s2p^23p\ {}^6S^o(2)$	<i>ssppp</i> (99.86)	-97.8718	-0.0004	-0.1343	-98.0064		
$1s2p^33s\ {}^6S^o(3)$	<i>ssppp</i> (99.80)	-97.2017	-0.0005	-0.1220	-97.3242		
$1s2s2p^24p\ {}^6S^o(4)$	<i>ssppp</i> (99.90)	-96.4634	-0.0003	-0.1337	-96.5975		
$1s2p^34s\ {}^6S^o(5)$	<i>ssppp</i> (99.95)	-95.5968	-0.0005	-0.1189	-95.7162		
$1s2s2p^23s\ {}^6P^e(1)$	<i>ssssp</i> (98.82)	-98.2132	-0.0003	-0.1378	-98.3513	1015	968
$1s2s2p^23d\ {}^6P^e(2)$	<i>ssppd</i> (97.42)	-97.6376	-0.0003	-0.1329	-97.7707	-372	-525
$1s2p^33p\ {}^6P^e(3)$	<i>spppp</i> (97.27)	-96.9931	-0.0005	-0.1191	-97.1127	129	264
$1s2s2p^24s\ {}^6P^e(4)$	<i>ssssp</i> (99.38)	-96.5873	-0.0003	-0.1351	-96.7227	1028	983
$1s2s2p^24d\ {}^6P^e(5)$	<i>ssppd</i> (99.62)	-96.3697	-0.0003	-0.1326	-96.5026	-408	-554

$1s2s2p^23p\ ^6P^o(1)$	$ssppp(99.86)$	-97.9620	-0.0004	-0.1345	-98.0968	401	748
$1s2s2p^24p\ ^6P^o(2)$	$ssppp(99.90)$	-96.4915	-0.0003	-0.1338	-96.6257	340	689
$1s2s2p^25p\ ^6P^o(3)$	$ssppp(99.91)$	-95.8514	-0.0003	-0.1335	-95.9852	320	669
$1s2s2p^26p\ ^6P^o(4)$	$ssppp(99.92)$	-95.5138	-0.0003	-0.1335	-95.6476	292	671
$1s2s2p^27p\ ^6P^o(5)$	$ssppp(99.94)$	-95.3103	-0.0003	-0.1337	-95.4443	303	653

^a Ref.[14]

Table 2. Transition rates (A_l, A_v) (s^{-1}) and wavelength λ ($\text{\AA}$) for the core-excited sextet states transition ${}^6P^o \rightarrow {}^6P$ of B-like O^{3+} and F^{4+} ions. λ' is the transition wavelength with the QED and high-order relativistic corrections. The number in brackets indicates the power of 10.

Transition	O^{3+}			F^{4+}		
	A_l/A_v	λ	λ'	A_l/A_v	λ	λ'
$1s2s2p^23p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	1.23[8]/1.22[8]	3071.12	3071.42	1.66[8]/1.64[8]	2472.97	2473.39
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	6.60[8]/6.40[8]	665.21	665.22	1.71[9]/1.68[9]	463.35	463.37
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	3.89[8]/4.00[8]	497.94	497.95	1.01[9]/1.03[9]	343.34	343.35
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	2.46[8]/2.53[8]	439.39	439.40	6.08[8]/6.07[8]	300.88	300.88
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	1.07[8]/1.10[8]	405.24	405.25	5.28[8]/5.24[8]	292.08	292.09
$1s2s2p^23d\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	1.40[8]/1.38[8] ^a	2474.23	2474.23 ^a	1.80[8]/1.78[8] ^a	1970.06	1970.06 ^a
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	1.91[8]/1.94[8]	1292.81	1292.81	4.13[8]/4.15[8]	802.43	802.43
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	7.71[7]/7.72[7]	782.18	782.18	1.66[8]/1.68[8]	499.84	499.84
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	4.02[7]/4.00[7]	646.79	646.79	8.51[7]/8.36[7]	414.65	414.65
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	1.54[7]/1.56[7]	575.42	575.42	6.87[7]/6.76[7]	398.13	398.13
$1s2s2p^24s\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	4.05[8]/4.08[8]	947.65	947.64	2.12[8]/2.00[8]	629.91	629.90
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^24s\ {}^6P^e$	2.50[7]/2.39[7]	8167.66	8168.44	3.62[7]/3.59[7]	6013.71	6014.59
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^24s\ {}^6P^e$	1.22[8]/1.05[8]	1593.85	1593.88	2.63[8]/2.28[8]	1086.14	1086.17
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^24s\ {}^6P^e$	8.15[7]/7.89[7]	1117.30	1117.31	1.37[8]/1.65[8]	750.91	750.92
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^24s\ {}^6P^e$	3.59[7]/3.70[7]	920.14	920.15	1.21[8]/1.47[8]	698.40	698.42
$1s2s2p^24d\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	7.96[8]/7.99[8]	755.23	755.23	1.10[9]/1.07[9]	514.47	514.47
$1s2s2p^24d\ {}^6P^e \rightarrow 1s2s2p^24p\ {}^6P^o$	3.20[7]/2.69[7]	6829.79	6829.79	4.13[7]/4.06[7]	5265.16	5265.16
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^24d\ {}^6P^e$	9.67[7]/7.48[7]	2788.94	2788.94	1.46[8]/1.42[8]	1771.56	1771.56
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^24d\ {}^6P^e$	3.88[7]/3.28[7]	1597.02	1597.02	7.49[7]/7.29[7]	1025.11	1025.11
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^24d\ {}^6P^e$	1.10[7]/1.29[7]	1222.59	1222.59	4.54[7]/5.20[7]	929.70	929.70
$1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	1.08[9]/1.05[9]	685.75	686.14	2.81[9]/2.69[9]	586.24	586.66

	1.01[9]/1.48[9] ^a		686.65 ^a , 687.44 ^b , 686.34 ^c , 679.44 ^d	2.87[9]/2.84[9] ^a		594.36 ^a , 592.96 ^b , 589.01 ^c , 587.32 ^d
$1s2p^3 3p \ ^6P^e \rightarrow 1s2s2p^2 4p \ ^6P^o$	3.37[6]/2.17[6]	3564.02	3574.59	4.77[5]/3.92[5]	20820.62	20307.46
$1s2s2p^2 5p \ ^6P^o \rightarrow 1s2p^3 3p \ ^6P^e$	7.87[4]/7.57[4]	4456.44	4440.02	8.96[7]/8.81[7]	1246.22	1244.33
$1s2s2p^2 6p \ ^6P^o \rightarrow 1s2p^3 3p \ ^6P^e$	1.54[5]/1.75[5]	2032.51	2029.09	5.24[7]/5.41[7]	824.09	823.26
$1s2s2p^2 7p \ ^6P^o \rightarrow 1s2p^3 3p \ ^6P^e$	7.61[4]/8.55[4]	1462.48	1460.70	3.25[7]/4.53[7]	761.28	760.58

^a Ref.[18]^b Ref.[7]---Experiment^c Ref.[7]---MCHF^d Ref.[7]---MCDF

Table 3. Transition rates (A_l, A_v) (s^{-1}) and wavelength λ ($\text{\AA}$) for the core-excited sextet states transition ${}^6P^o \rightarrow {}^6P$ of B-like Ne^{5+} and Na^{6+} ions. λ' is the transition wavelength with the QED and high-order relativistic corrections. The number in brackets indicates the power of 10.

Transitions	Ne^{5+}			Na^{6+}		
	A_l/A_v	λ	λ'	A_l/A_v	λ	λ'
$1s2s2p^23p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	2.08[8]/2.06[8]	2071.25	2071.76	2.47[8]/2.41[8]	1790.35	1790.96
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	3.66[9]/3.62[9]	342.58	342.59	6.92[9]/6.87[9]	264.05	264.06
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	2.17[9]/2.18[9]	251.63	251.64	4.06[9]/4.05[9]	192.57	192.58
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	1.32[9]/1.32[9]	220.52	220.53	2.45[9]/2.44[9]	168.53	168.53
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	1.43[9]/1.21[9]	209.86	209.86	1.61[9]/1.61[9]	156.74	156.75
$1s2s2p^23d\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	2.16[8]/2.15[8] ^a	1636.32	1636.32 ^a	2.59[8]/2.53[8]	1397.26	1397.26
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	7.63[8]/7.68[8]	547.90	547.90	1.27[9]/1.31[9]	397.94	397.94
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	3.18[8]/3.18[8]	347.20	347.20	5.42[8]/5.49[8]	255.19	255.19
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	1.67[8]/1.67[8]	290.63	290.63	2.89[8]/2.88[8]	214.61	214.61
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	2.04[8]/1.54[8]	272.39	272.39	1.78[8]/1.76[8]	195.86	195.86
$1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	1.56[9]/1.55[9]	518.95	519.41	1.92[9]/1.91[9]	463.01	463.50
	1.52[9]/1.54[9] ^a		522.62 ^a , 520.35 ^b , 517.56 ^c , 515.72 ^d			
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	7.14[6]/6.73[6]	1963.44	1956.93	9.12[6]/7.43[6]	935.61	933.63
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	5.87[5]/5.28[5]	639.24	638.55	1.40[6]/5.82[5]	404.12	403.75
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	1.29[6]/1.33[6]	470.59	470.22	5.22[5]/3.26[5]	311.00	310.78
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	9.23[5]/9.85[5]	424.56	424.25	2.14[5]/1.14[5]	273.10	272.93

$1s2s2p^24s\ ^6P^e \rightarrow 1s2s2p^23p\ ^6P^o$	2.94[9]/2.36[9]	443.20	443.19	3.78[9]/3.90[9]	331.59	331.59
$1s2s2p^24p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	4.00[7]/4.04[7]	5557.27	5558.62	5.28[7]/4.27[7]	4697.36	4698.96
$1s2s2p^25p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	7.14[8]/6.91[8]	809.73	809.76	1.57[9]/1.41[9]	617.82	617.85
$1s2s2p^26p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	4.93[8]/4.79[8]	556.91	556.93	8.15[8]/9.29[8]	423.82	423.83
$1s2s2p^27p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	5.43[8]/4.23[8]	493.57	493.58	5.78[8]/6.36[8]	356.42	356.43
$1s2s2p^24d\ ^6P^e \rightarrow 1s2s2p^23p\ ^6P^o$	3.56[9]/3.04[9]	375.27	375.27	6.38[9]/6.31[9]	285.81	285.81
$1s2s2p^24d\ ^6P^e \rightarrow 1s2s2p^24p\ ^6P^o$	5.21[7]/5.05[7]	4376.20	4376.20	4.95[7]/6.68[7]	3701.42	3701.42
$1s2s2p^25p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	2.76[8]/2.77[8]	1209.87	1209.87	4.97[8]/4.89[8]	880.64	880.64
$1s2s2p^26p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	1.32[8]/1.39[8]	720.90	720.90	2.22[8]/2.31[8]	532.92	532.92
$1s2s2p^27p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	2.26[8]/1.54[8]	618.21	618.21	1.29[8]/1.38[8]	430.54	430.54

^a Ref. [18]^b Ref. [7]---Experiment^c Ref. [7]---MCHF^d Ref. [7]---MCDF

Table 4. Transition rates (A_i, A_v) (s^{-1}) and wavelength λ ($\text{\AA}$) for the core-excited sextet states transition ${}^6P^o \rightarrow {}^6P$ of B-like Mg^{7+} and Al^{8+} ions. λ' is the transition wavelength with the QED and high-order relativistic corrections. The number in brackets indicates the power of 10.

Transition	Mg^{7+}			Al^{8+}		
	A_i/A_v	λ	λ'	A_i/A_v	λ	λ'
$1s2s2p^23p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	2.89[8]/2.81[8]	1571.11	1571.83	3.30[8]/3.25[8]	1399.65	1400.47
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	1.20[10]/1.19[10]	209.88	209.89	1.94[10]/1.93[10]	170.98	171.00
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	6.95[9]/6.94[9]	152.18	152.19	1.13[10]/1.12[10]	123.32	123.33
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	4.13[9]/4.13[9]	132.83	132.83	6.72[9]/6.64[9]	107.46	107.47
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23s\ {}^6P^e$	2.74[9]/2.70[9]	123.38	123.38	4.28[9]/4.26[9]	99.78	99.79
$1s2s2p^23d\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	2.98[8]/2.96[8]	1220.21	1220.21	3.38[8]/3.27[8]	1082.56	1082.56
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	2.03[9]/2.07[9]	302.24	302.24	3.08[9]/3.05[9]	237.51	237.51
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	9.49[8]/8.61[8]	195.50	195.50	1.10[9]/1.31[9]	154.55	154.55
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	4.18[8]/4.48[8]	164.67	164.67	6.31[8]/6.87[8]	130.42	130.42
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2s2p^23d\ {}^6P^e$	2.46[8]/2.69[8]	150.39	150.39	3.94[8]/4.16[8]	119.28	119.28
$1s2p^33p\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	2.19[9]/2.19[9]	416.04	416.55	2.46[9]/2.43[9]	377.00	377.53
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	1.35[7]/1.21[7]	579.85	578.86	2.57[7]/1.74[7]	402.98	402.37
$1s2s2p^25p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	1.68[6]/2.06[6]	283.20	282.97	4.52[6]/4.68[6]	210.89	210.73
$1s2s2p^26p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	1.40[6]/1.04[6]	222.79	222.64	3.34[6]/2.65[6]	168.39	168.29
$1s2s2p^27p\ {}^6P^o \rightarrow 1s2p^33p\ {}^6P^e$	8.65[5]/6.15[5]	197.43	197.31	2.10 [6]/1.64[6]	150.26	150.18
$1s2s2p^24s\ {}^6P^e \rightarrow 1s2s2p^23p\ {}^6P^o$	5.91[9]/6.14[9]	257.45	257.44	7.86[9]/7.89[9]	206.08	206.07
$1s2s2p^24p\ {}^6P^o \rightarrow 1s2s2p^24s\ {}^6P^e$	6.29[7]/4.58[7]	4100.39	4102.01	7.23[7]/6.77[7]	3552.61	3554.65

$1s2s2p^25p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	2.79[9]/2.58[9]	487.73	487.75	4.08[9]/3.94[9]	393.44	393.46
$1s2s2p^26p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	1.47[9]/1.65[9]	332.46	332.47	2.62[9]/2.56[9]	267.49	267.50
$1s2s2p^27p\ ^6P^o \rightarrow 1s2s2p^24s\ ^6P^e$	0.98[9] /1.12[9]	278.98	278.99	1.73[9]/1.68[9]	224.47	224.48
$1s2s2p^24d\ ^6P^e \rightarrow 1s2s2p^23p\ ^6P^o$	1.14[10]/1.13[10]	225.43	225.43	1.61[10]/1.64[10]	182.50	182.50
$1s2s2p^24d\ ^6P^e \rightarrow 1s2s2p^24p\ ^6P^o$	7.31[7]/6.45[7]	3249.49	3249.49	8.24[7]/7.73[7]	2894.22	2894.22
$1s2s2p^25p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	7.50[8]/7.61[8]	667.24	667.24	7.49[8]/8.44[8]	522.27	522.27
$1s2s2p^26p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	3.80[8]/3.78[8]	407.12	407.12	4.82[8]/3.92[8]	321.39	321.39
$1s2s2p^27p\ ^6P^o \rightarrow 1s2s2p^24d\ ^6P^e$	2.25[8]/2.20[8]	329.72	329.72	2.81[8]/2.15[8]	261.24	261.24

Table 5. Lifetimes τ (in ps) of the $1s2s2p^23s$, $1s2s2p^23d$, $1s2s2p^24s$, $1s2s2p^24d$, and $1s2p^33p\ ^6P$ states of the boron isoelectronic sequence ($Z=8-13$).

Z	8	9	10	11	12	13
States						
$1s2s2p^23s\ ^6P$	139.28 ^a	70.92 ^a	39.84 ^a	24.39	15.75	10.58
	140.7 ^b , 125 ^c , 99 $\pm$ 12 ^d	71.22 ^b , 64 ^c , 73 $\pm$ 15 ^d	42.48 ^c , 47.70 ^f			
$1s2s2p^23d\ ^6P$	14.94 ^a	6.69 ^a	3.48 ^a	2.00	1.24	0.81
	14.95 ^b , 15.6 ^c , 12 $\pm$ 3 ^d	6.689 ^b , 6.7 ^c , 11 $\pm$ 4 ^d				
$1s2s2p^24s\ ^6P$	238.55	67.89	95.42	59.56	39.48	20.72
$1s2s2p^24d\ ^6P$	31.90	17.96	8.89	5.11	3.05	2.01
$1s2p^33p\ ^6P$	262.88	69.74	33.68	23.32	15.81	11.32
	68.48 ^a	28.74 ^a	16.25 ^a			

^a Ref.[18].

^d Ref. [8]---Experiment

^b Reference [10]---MCHF.

^c Ref. [9]---MCHF

^e Ref.[8]---MCDF

^f Ref. [9]---MCDF

Figure.1 The lifetimes for $1s2s2p^2 3s$, $1s2s2p^2 3d$, $1s2s2p^2 4s$, $1s2s2p^2 4d$, and $1s2p^3 3p \ ^6P^e$ sextet states with $Z= 8-13$.