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Research Article

Photoionization Study on the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$, Rydberg Series of the Be-like ($Z = 8 - 18$) ions

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Abstract. We report accurate Photoionization energies for the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$ Rydberg series of the Be-like ($Z = 8 - 18$) ions. Calculations are done in the framework of the Screening constant per unit nuclear charge (SCUNC) method. The SCUNC predictions for $n > 8$ may be useful primary source for the NIST database. In addition, the present work enlighten the discrepancies between the MCDF results of Stancalie [*European Physics Journal D*, **67**, 223, (2013)] and the Opacity Project Team (OPT) predictions (the Opacity Project (IOPP, Vol. 1, 1995) especially for the $1s^22s9p\ ^{1,3}D_2$ levels of the Al^{9+} ions. The MCDF calculations are equal to -0.60909 a.u ($1s^22s9p\ ^1D_2$) and -0.60663 a.u ($1s^22s9p\ ^3D_2$). For these states, the OPT data are at -0.61923 a.u ($1s^22s9p\ ^1D_2$) and -0.62020 a.u ($1s^22s9p\ ^3D_2$). The present SCUNC calculations give for these levels -0.6179 a.u ($1s^22s9p\ ^1D_2$) and -0.6205 a.u ($1s^22s9p\ ^3D_2$). Numerous new data are tabulated as useful guideline for investigators focusing their researches on the Photoionisation of Be-like systems as far as the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$ Rydberg series are concerned.s

Keywords. Be-like ions; Screening constant per unit nuclear charge; Rydberg series

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1. Introduction

Beryllium-like systems considered as supra-helium atoms, are attractive candidates for the study of electronic correlation effects in atoms containing two electrons in each of the first

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principal shells. Be-like ions are also among atomic systems of interest for the Opacity Project. On the experimental side, previous measurements have been performed on Be atoms [22] and Be-like ions, such as B^+ [19], C^{2+} [14], N^{3+} and O^{4+} [3]. In addition, calculations on the Be-like sequences with $Z = 6-10$ have been performed [5, 7–12] using a non-iterative variational R-matrix method. The R-matrix approach has also been applied to report resonance energies and widths of the 2pns ^{1}P° and 2pnd^{1}P° Rydberg series of O^{4+} ($n = 6-10$) [6], F^{5+} ($n = 6-10$) [5] and Ne^{6+} ($n = 7-9$) ions [4]. Although many calculations on various Rydberg series of Be-like ions have been performed in the past, very scarce studies are done on the $1s^22snp\ ^1P°$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$, Rydberg series of the Be-like ions. For instance, for n>8, no data are quoted in the NIST data base for the $1s^22snp\ ^1P°$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$ Rydberg series of the Be-like ($Z > 7$) ions. In addition, Stancalie [20] carried out photo-recombination cross section calculations in Be-like C et Al ions applying both Feshbach operator projection (FOP) approximation and the multiconfiguration Dirac-Fock (MCDF) method. For the Rydberg series investigated, discrepancies appear when comparing the MCDF results [20] and the Opacity Project Team (OPT) predictions [21] for some Rydberg series investigated and belonging to the Al^{9+} ions. To illustrate this assertion, one can consider the total energy of the $1s^22s9p\ ^{1,3}D_2$ levels of Al^{9+}. The MCDF calculations are equal to −0.60909,a.u ($1s^22s9p\ ^1D_2$) and −0.60663 a.u ($1s^22s9p\ ^3D_2$). For these, the OPT data are at −0.61923 a.u ($1s^22s9p\ ^1D_2$) and −0.62020 a.u ($1s^22s9p\ ^3D_2$). The energy differences $\Delta E = E^{MCDF} - E^{OPT}$ are 0.010014 a.u ($1s^22s9p\ ^1D_2$) and 0.01357 ($1s^22s9p\ ^3D_2$). It well know that high calculations agreeing each other lead to discrepancies less than 0.001 a.u. Let us underline that, energy difference at 0.01357 a.u is equal to 0.3692 eV. The present work is motivated by two goals: firstly, to provide accurate data for the $1s^22snp\ ^1P°$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$ ($n > 8$) Rydberg series of the Be-like ($Z = 8-18$) ions that may be useful primary source for the NIST database; and secondly, to enlighten the discrepancies between the MCDF results [20] and the Opacity Project Team (OPT) predictions [21] especially for the $1s^22s9p\ ^{1,3}D_2$ levels of the Al^{9+} ions. In our study, we apply the Screening constant by unit nuclear charge (SCUNC) method [1, 15–18]. The SCUNC formalism has been used previously to report precise energy resonances and natural widths on various Be-like ions such as Be [17], B^+ [15], and Be-like ($Z = 8-18$) ions [16]. Large applications the SCUNC formalism on the Photoionisation of various atomic systems such as He-like ions, Li-like ions, Be-like ions, B-like ions, S, Ar^+, Se^+, Se^{2+}, Se^{3+} and Kr^+ are compiled in our very recent book [1]. Section 2 presents a brief description of the methodology adopted in this work. Presentation and the discussion of the results obtained are made in Section 3. We conclude the present study in Section 4.

2. Theory

2.1 Brief description of the SCUNC formalism

In the framework of the Screening Constant per Unit Nuclear Charge formalism, the total energy of the $(Nl, nl')^{2S+1}L^{\pi}$ excited states is expressed in the form (in Rydberg units)

$$E(Nl, nl'; {}^{2S+1}L^{\pi}) = -Z^2\left(\frac{1}{N^2} + \frac{1}{n^2}[1 - \beta(Nl, nl'; {}^{2S+1}L^{\pi}Z)]^2\right). \tag{1}$$

In this equation, the principal quantum numbers N and n are respectively for the inner and the outer electron of the helium-isoelectronic series. The β-parameters are screening constants by unit nuclear charge expanded in inverse powers of Z and given by

$$\beta(Nl\,nl';{}^{2S+1}L^{\pi};Z)=\sum_{k=1}^{q} f_k\left(\frac{1}{Z}\right)^k. \tag{2}$$

where $f_k = f_k(Nl\,nl';{}^{2S+1}L^{\pi})$ are screening constants to be evaluated empirically.

For a given Rydberg series originating from a-${}^{2S+1}\mathrm{L}_J$ state, we obtain

$$E_n = E_\infty - \frac{Z^2}{n^2}\{1-\beta(Z,{}^{2S+1}L_J,n,s,\mu,\nu)\}^2. \tag{3}$$

In eq. (3), ν and μ ($\mu>\nu$) denote the principal quantum numbers of the $({}^{2S+1}L_J)\ nl$ Rydberg series used in the empirical determination of the f_i-screening constants, s represents the spin of the nl-electron ($s=\frac{1}{2}$), E_∞ is the energy value of the series limit, E_n denotes the resonance energy and Z stands for the atomic number. The β-parameters are screening constants by unit nuclear charge expanded in inverse powers of Z and given by

$$\beta(Z,{}^{2S+1}L_J,n,s,\mu,\nu)=\sum_{k=1}^{q} f_k\left(\frac{1}{Z}\right)^k, \tag{4}$$

where $f_k = f_k({}^{2S+1}L_J,n,s,\mu,\nu)$.

The screening constants by unit nuclear charge (4) is in the general form

$$\beta(nl;s,\mu,\nu,{}^{2S+1}L^{\pi};Z)=\frac{f_1(nl;{}^{2S+1}L^{\pi})}{Z}+\frac{f_2({}^{2S+1}L^{\pi})}{Z}\pm\sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'}F(n,\mu,\nu,s)\times\left(\frac{1}{Z}\right)^k. \tag{5}$$

The quantity $\pm\sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'}F(n,\mu,\nu,s)\times\left(\frac{1}{Z}\right)^k$ is a corrective term introduced to stabilize the energy resonances so that quantum defect is constant by varying the principal quantum number n of the nl electron. Practically, precise data are obtained from the SCUNC formalism putting

$$f_1(nl;{}^{2S+1}L^{\pi})=\frac{f_1({}^{2S+1}L^{\pi})}{(n-1)}.$$

So, the energy resonances are written in the general form

$$E_n - E_\infty\frac{Z^2}{n^2}\left\{1-\frac{f_1(nl;{}^{2S+1}L^{\pi})}{Z}+\frac{f_2({}^{2S+1}L^{\pi})}{Z}\pm\sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'}F(n,\mu,\nu,s)\times\left(\frac{1}{Z}\right)^k\right\}^2. \tag{6}$$

Generally, energy resonances are analyzed using the standard quantum-defect expansion formula

$$E_n = E_\infty - \frac{RZ_{\mathrm{core}}^2}{(n-\delta)^2}. \tag{7}$$

In this equation, R is the Rydberg constant, E_∞ denotes the converging limit, Z_{core} represents the electric charge of the core ion, and δ means the quantum defect.

In the framework of the SCUNC formalism, eq. (6) can be written in the form of eq. (7) as follows

$$E_n = E_\infty - \frac{RZ^*}{n^2}, \tag{8}$$

where Z^* denotes the effective nuclear charge given by

$$Z^* = Z\left\{1 - \frac{f_1(^{2S+1}L^\pi)}{Z(n-1)} - \frac{f_2(^{2S+1}L^\pi)}{Z} \pm \sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'} F(n,\mu,\nu,s,Z_0) \times \left(\frac{1}{Z}\right)^k\right\}. \tag{9}$$

The screening constant f_2 can be then evaluated theoretically imposing the corrective $\pm \sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'} F(n,\mu,\nu,s,Z_0) \times \left(\frac{1}{Z}\right)^k$ to tend towards zero when the principal quantum number n tends towards infinity, that means

$$\lim_{n\to\infty} \pm \sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'} F(n,\mu,\nu,s,Z_0) \times \left(\frac{1}{Z}\right)^k = 0. \tag{10}$$

That-is-to-say

$$\lim_{n\to\infty} Z^* = \lim_{n\to\infty} Z\left\{1 - \frac{f_1(^{2S+1}L^\pi)}{Z(n-1)} - \frac{f_2(^{2S+1}L^\pi)}{Z} \pm \sum_{k=1}^{q}\sum_{k'=1}^{q'} f_1^{k'} F(n,\mu,\nu,s,Z_0) \times \left(\frac{1}{Z}\right)^k\right\}$$
$$= Z\left\{1 - \frac{f_2(^{2S+1}L^\pi)}{Z}\right\} = Z_{\text{core}}.$$

So

$$f_2 = Z\left\{1 - \frac{Z_{\text{core}}}{Z}\right\} = Z - Z_{\text{core}}. \tag{11}$$

2.2 Energy resonances of the 1s^{2}2s*n*p ^{1}P°, 1s^{2}2s*n*d ^{1,3}D, and 1s^{2}2p*n*d ^{3}D, Rydberg series of the Be-like ions

According to eq. (11), f_2 is theoretically determined and then independent on the ^{2S+1}L spectroscopic term. That means $f_2(^{2S+1}L) = f_2$. So, only one fitting parameter (here f_1) is required in the present calculations. From eq. (6), the energy resonances of the 1s^{2}2snp ^{1}P°, 1s^{2}2snd ^{1,3}D, and 1s^{2}2pnd ^{3}D, Rydberg series of the Be-like ions are given by (in Rydberg units)

$$E_n = E_\infty - \frac{Z^2}{n^2}\left\{1 - \frac{f_1(^{2S+1}L)}{Z(n-1)} - \frac{f_2}{Z} - \frac{f_1(^{2S+1}L)\times(n-\nu)}{Z^2(n+1.5)\times(n+2.5)} - \frac{f_1(^{2S+1}L)\times(n-\nu)}{Z^3(n+1.5)\times(n+2.5)}\right\}^2. \tag{12}$$

Let us first determine f_2 using eq. (11) for the Be-like ions investigated considering their photoionization processes

$$h\nu + N^{3+} \to N^{4+} + e^- \Rightarrow Z_{\text{core}} = 4.0;\ f_2 = 7 - 4 = 3.0.$$
$$h\nu + O^{4+} \to O^{5+} + e^- \Rightarrow Z_{\text{core}} = 5.0;\ f_2 = 8 - 5 = 3.0.$$
$$h\nu + F^{5+} \to F^{6+} + e^- \Rightarrow Z_{\text{core}} = 6.0;\ f_2 = 9 - 6 = 3.0.$$
$$\vdots \qquad\qquad \vdots \qquad\qquad \vdots$$
$$h\nu + Ar^{14+} \to Ar^{15+} + e^- \Rightarrow Z_{\text{core}} = 15.0;\ f_2 = 18 - 15 = 3.0.$$

These results indicate clearly that the f_2-parameter depends not neither on the ^{2S+1}L spectroscopic term nor on the Be-like ion considered. This screening constant depends only on a whole members of a given atomic system and its isoelectronic sequence. For the Be-like ($Z = 7-18$) ions considered here, the screening constant f_1 is evaluated empirically using the NIST data [13] for the lowest member of the isoelectronic sequence N^{3+} ($Z = 7$). For this purpose, we use the resonance energies of the 1s^{2}2s8p ^{1}P°, 1s^{2}2s8d ^{1}D, and 1s^{2}2s8d ^{3}D levels of N^{3+}

respectively equal to (in eV) 73.92817, 74.06185, and 74.02189. These energies are measured with respect to the energy limits of the series at 77.4735(4) for the $1s^22s\ ^2S_{1/2}$ threshold of N^{4+}. For the $1s^22p8d\ ^3D$ level, the energy resonance is at 84.04198 with an energy limit at 87.47357 (average of the $P_{1/2}$ and $P_{3/2}$ symmetries) for the $1s^22s\ ^2P^\circ$ threshold of N^{4+}. Using these NIST data, we find from eq. (12) with $f_2 = 3,0$

- $1s^22s8p\ ^1P^\circ$: $f_1\ (^1P^\circ) = -0.5862 \pm 0.0020$
- $1s^22s8d\ ^1D$: $f_1\ (^1D) = -0.0421 \pm 0.0020$
- $1s^22s8d\ ^3D$: $f_1\ (^3D) = -0.2058 \pm 0.0020$
- $1s^22p8d\ ^3D$: $f_1\ (^3D) = -0.1239 \pm 0.0020$

3. Results and Discussion

Using the values of the screening constant $f_1\ (^{1,3}L)$ above with $f_2 = 3,0$, eq. (11) gives the energy resonances of the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$, Rydberg series of the Be-like ions ($Z = 8-18$) are listed in Tables 1-16. In the framework of the SCUNC formalism, the sign of the quantum defect can be determined via the SCUNC analysis procedure of the energy resonances.

Comparing eqs. (7) and (8), the relationship between the effective charge Z^* and the quantum defect δ is in the form

$$Z^* = \frac{Z_{\text{core}}}{\left(1-\frac{\delta}{n}\right)}. \tag{13}$$

According to eq. (13), each Rydberg series must satisfy the following conditions

$$\begin{cases} Z^* \geq Z_{\text{core}} & \text{if } \delta \geq 0 \\ Z^* \leq Z_{\text{core}} & \text{if } \delta \leq 0 \\ \lim\limits_{n\to\infty} Z^* = Z_{\text{core}} \end{cases} \tag{14}$$

Comparing eqs. (8) and (12), we find the expression of the effective charge Z^*

$$Z^* = Z\left\{1 - \frac{f_1(^{2S+1}L)}{Z(n-1)} - \frac{f_2}{Z} - \frac{f_1(^{2S+1}L)\times(n-\nu)}{Z^2(n+1.5)\times(n+2.5)} - \frac{f_1(^{2S+1}L)\times(n-\nu)}{Z^3(n+1.5)\times(n+2.5)}\right\}. \tag{15}$$

To determine the sign of the quantum defect, one can just calculate Z^* considering the lowest value of the principal quantum n used to evaluate empirically f_1. Here $n = 8$. To illustrate this assertion, let us for instance calculate Z^* for the $1s^22snp\ ^1P^\circ$ Rydberg states of N^{3+} where f_1 $(^1P^\circ) = -0.5862$ and $f_2 = 3.0$. We get from eq. (15) with $n = \nu = 8$ and $Z = 7$

$$Z^* = 7\times\left\{1 + \frac{0.5862}{7\times(8-1)} - \frac{3}{7}\right\} = 4.0837. \tag{16}$$

As for N^{3+}, $Z_{\text{core}} = 4$, eq. (16) shows clearly that $Z^* = 4.0837 > Z_{\text{core}} = 4$. So, according to the SCUNC conditions (14), the quantum defect is positive for all the members of the $1s^22snp$ $^1P^\circ$ series of N^{3+}. Similar calculations indicate that the quantum defects of the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$, Rydberg series of the Be-like ions ($Z = 7-18$) are all positive as shown by the values quoted in Tables 1-16. This important result illustrate the utility of the SCUNC analysis procedure (14) of the energy resonances who permits to know the sign of the quantum defect of a given series before measuring or calculating it. In addition, in can be observed that quantum defects are practically constant along all the series of the Be-like ions ($Z = 7-18$) investigated and decrease with increasing Z. Table 1 compares the present SCUNC results for the energy resonances with only available NIST data [13] for the 2snp ^{1}P° and 2pnd ^{3}D Rydberg series of the Be-like N^{3+} ions. Good agreements are obtained. Except for the 2s9p ^{1}P° and 2s10 p ^{1}P° levels, the maximum energy difference with respect to the NIST data $|\Delta E| = |E^{SCUNC} - E^{NIST}| < 0.008$ eV. Table 2 shows a comparison between the present SCUNC calculations of energy resonances of the 2snd ^{1,3}D Rydberg series of the Be-like N^{3+} ions with the data quoted in NIST [13]. Here again, the agreements are very good as the energy difference with respect to the NIST data $|\Delta E| = |E^{SCUNC} - E^{NIST}| < 0.008$ eV up to $n = 15$. For $n > 15$, no data are quoted in NIST and our predictions may be good benchmarked values for both 2snp ^{1}P°, 2pnd ^{3}D, and 2snd ^{1,3}D Rydberg series of the Be-like N^{3+} ions. Tables 3-16 list the SCUNC predictions of the 1s^{2}2snp ^{1}P°, 1s^{2}2snd ^{1,3}D, and 1s^{2}2pnd ^{3}D, Rydberg series of the Be-like ions ($Z = 8-18$). Here, very scarce data are quoted in the NIST database [13]. Only data for $n = 8$ are available for O^{4+} and Ne^{6+}. In Table 3, the SCUNC data for the 2s8p ^{1}P° level of O^{4+} at 108.405 eV is seen to agree with the NIST data at 108.418 eV. In addition, in Table 4, for the 2s8d ^{3}D level of O^{4+} the SCUNC data at 108.522 eV agrees with the NIST data at 108.506 eV. In Table 8, the SCUNC data for the 2s8d ^{3}D and 2s9d ^{3}D levels of Ne^{6+} respectively 196.766 eV and 198.979 eV compare satisfactory with the NIST data at 196.783 eV and 198.700 eV respectively. It should be underlined the large discrepancy between the SCUNC and the NIST data for the 2s9d ^{3}D level of Ne^{6+}. Here, the energy difference is at 0.279 eV. For the 2s8d ^{3}D and 2s9d ^{3}D levels, the SCUNC quantum defects as quoted in Table 8 are constant and equal to 0.033. For the same levels, the corresponding NIST quantum defects evaluated from the standard formula (7) are equal to 0.027 for 2s8d ^{3}D and 0.180 for 2s9d ^{3}D. If the NIST data $0.027 \approx 0.030$ agrees well with the SCUNC value at 0.033, the NIST quantum defect at 0.180 for the 2s9d ^{3}D level is somewhat surprising. Although the SUCNC formalism a very simple, the NIST value at 198.700 eV may be probably lower than the precise data for the 2s9d ^{3}D level of Ne^{6+}. The SCUNC prediction at 198.979 eV may then be preferable. For the other Be-like ions, no data are available in the NIST database [13] for $n > 8$. The good quantum defects obtained may indicate the accuracy of the present calculations. But, we can enlighten the precision of the present SCUNC predictions by calculating the energy resonances for the lowest states $n = 3-7$ for which NIST data are listed. For this purpose, we have quoted in Tables 17-20 energy resonances of the 2snp ^{1}P°, 2pnd ^{3}D, and 2snd ^{1,3}D ($n = 3-7$) Rydberg series of the Be-like ($Z = 8-18$) ions using eq. (12). Actually, eq. (12) is rigorously applicable for the resonance with $n > 8$ (reminding that f_1 has been evaluated for $n = \nu = 8$). So, the results obtained from eq. (12) for $n = 3-7$ are only estimated SCUNC values. Although eq. (12) is established for $n > 8$, the estimated SCUCN results for $n = 3-7$ are seen to agree well with the NIST values [2]. These very satisfactory agreements may enlighten the accuracy of the present SCUNC calculations for the 2snp ^{1}P°, 2pnd ^{3}D, and 2snd ^{1,3}D ($n = 8-30$) Rydberg series of the Be-like ($Z = 8-18$) investigated in this paper. Table 21 presents total energy ($-E$) of the 2snp ^{1}P°, and 2snd ^{1,3}D Rydberg series of the Be-like Al^{9+} ions.

Table 1. Energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P°$ and $2pnd\ ^3D$ Rydberg series of the Be-like N^{3+} ions. The energies are expressed in eV. The energy difference with respect to the NIST data is $|\Delta E| = |E^{SCUNC} - E^{NIST}|$

	$2snp\ ^1P°$				$2pnd\ ^3D$			
	SCUNC		NIST*	$\lvert\Delta E\rvert$	SCUNC		NIST*	$\lvert\Delta E\rvert$
n	E	δ	E		E	δ		
8	73.928	0.164	73.928	0.000	84.042	0.035	84.042	0.000
9	74.686	0.164	74.714	0.028	84.765	0.035	84.767	0.002
10	75.224	0.163	75.236	0.012	85.281	0.035	85.286	0.005
11	75.620	0.163	75.624	0.004	85.663	0.035	85.670	0.007
12	75.920	0.163	75.919	0.001	85.953	0.035	-	-
13	76.152	0.164	76.150	0.002	86.178	0.035	86.184	0.006
14	76.336	0.164			86.357	0.035		
15	76.484	0.164			86.502	0.035		
16	76.605	0.164			86.619	0.035		
17	76.705	0.164			86.717	0.035		
18	76.789	0.164			86.799	0.035		
19	76.860	0.165			86.868	0.035		
20	76.920	0.165			86.927	0.035		
21	76.972	0.165			86.978	0.035		
22	77.017	0.165			87.022	0.035		
23	77.056	0.165			87.061	0.035		
24	77.090	0.165			87.095	0.035		
25	77.121	0.166			87.124	0.035		
26	77.147	0.166			87.151	0.035		
27	77.171	0.166			87.174	0.035		
28	77.193	0.166			87.195	0.035		
29	77.212	0.166			87.214	0.035		
30	77.229	0.166			87.231	0.035		
...	...	...			...	...		
∞	77.473		77.473		87.474		77.474	

*: A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (ver. 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD.

Table 2. Energy resonances (E) and quantum defect (δ) of the $2snd\ ^{1,3}$D Rydberg series of the Be-like N^{3+} ions. The energies are expressed in eV. The energy difference with respect to the NIST data is $|\Delta E| = |E^{SCUNC} - E^{NIST}|$

	$2snp\ ^1$D				$2pnd\ ^3$D			
	SCUNC		NIST*	$\|\Delta E\|$	SCUNC		NIST*	$\|\Delta E\|$
n	E	δ	E		E	δ		
8	74.062	0.012	74.062	0.000	74.022	0.058	74.022	0.000
9	74.779	0.012	74.776	0.003	74.751	0.058	74.746	0.005
10	75.291	0.012	75.288	0.003	75.271	0.058	75.266	0.005
11	75.671	0.012	75.666	0.004	75.655	0.058	75.651	0.004
12	75.959	0.012	75.955	0.004	75.947	0.058	75.943	0.004
13	76.183	0.012	76.185	0.002	76.174	0.058	76.173	0.001
14	76.361	0.012			76.354	0.058	76.361	0.007
15	76.504	0.012			76.498	0.058	76.503	0.005
16	76.622	0.012			76.617	0.058		
17	76.719	0.012			76.715	0.058		
18	76.801	0.012			76.797	0.058		
19	76.870	0.012			76.867	0.058		
20	76.929	0.012			76.926	0.058		
21	76.979	0.012			76.977	0.058		
22	77.023	0.012			77.021	0.058		
23	77.062	0.012			77.060	0.058		
24	77.095	0.012			77.094	0.058		
25	77.125	0.012			77.124	0.058		
26	77.151	0.012			77.150	0.058		
27	77.175	0.012			77.174	0.058		
28	77.196	0.012			77.195	0.058		
29	77.214	0.012			77.214	0.058		
30	77.231	0.012			77.231	0.059		
...	...	...			...	...		
∞	77.473		77.473		77.473		77.473	

*: A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (ver. 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology. Gaithersburg, MD.

Table 3. Energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P°$ and $2pnd\ ^3D$ Rydberg series of the Be-like O^{4+} ions. The energies are expressed in eV. The energy difference with respect to the NIST data is $|\Delta E| = |E^{\mathrm{SCUNC}} - E^{\mathrm{NIST}}$

	$2snp\ ^1D$				$2pnd\ ^3D$			
	SCUNC		NIST*	$\|\Delta E\|$	SCUNC		NIST*	$\|\Delta E\|$
n	E	δ	E		E	δ		
8	108.405	0.132	108.418	0.013	120.545	0.028		
9	109.575	0.131			121.671	0.028		
10	110.407	0.131			122.477	0.028		
11	111.020	0.131			123.072	0.028		
12	111.485	0.131			123.524	0.028		
13	111.845	0.130			123.876	0.028		
14	112.131	0.130			124.155	0.028		
15	112.361	0.130			124.380	0.028		
16	112.548	0.131			124.564	0.028		
17	112.704	0.131			124.716	0.028		
18	112.834	0.131			124.844	0.028		
19	112.944	0.131			124.952	0.028		
20	113.037	0.131			125.044	0.028		
21	113.118	0.131			125.124	0.028		
22	113.188	0.131			125.193	0.028		
23	113.249	0.131			125.253	0.028		
24	113.302	0.131			125.305	0.028		
25	113.349	0.131			125.352	0.028		
26	113.391	0.131			125.393	0.028		
27	113.428	0.131			125.430	0.028		
28	113.461	0.131			125.462	0.028		
29	113.491	0.131			125.492	0.028		
30	113.518	0.131			125.518	0.028		
...	...	...			...	...		
∞	113.899		113.899		125.897		125.897	

*: A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (ver. 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 4. Energy resonances (E) and quantum defect (δ) of the $2snd\ ^{1,3}$D Rydberg series of the Be-like O^{4+} ions. The energies are expressed in eV. The energy difference with respect to the NIST data is $|\Delta E| = |E^{\text{SCUNC}} - E^{\text{NIST}}$

	$2snp\ ^1$D				$2pnd\ ^3$D			
	SCUNC		NIST*	$\|\Delta E\|$	SCUNC		NIST*	$\|\Delta E\|$
n	E	δ	E		E	δ		
8	108.571	0.010			108.522	0.046	108.506	0.016
9	109.691	0.010			109.656	0.046		
10	110.491	0.009			110.466	0.046		
11	111.083	0.009			111.064	0.046		
12	111.533	0.009			111.519	0.046		
13	111.883	0.009			111.872	0.046		
14	112.161	0.009			112.152	0.046		
15	112.385	0.009			112.378	0.046		
16	112.569	0.009			112.563	0.046		
17	112.721	0.009			112.716	0.046		
18	112.848	0.009			112.844	0.046		
19	112.956	0.009			112.952	0.046		
20	113.048	0.009			113.045	0.046		
21	113.127	0.009			113.124	0.046		
22	113.196	0.009			113.193	0.046		
23	113.255	0.009			113.253	0.046		
24	113.308	0.009			113.306	0.046		
25	113.354	0.009			113.353	0.046		
26	113.395	0.009			113.394	0.046		
27	113.432	0.009			113.431	0.046		
28	113.465	0.009			113.464	0.046		
29	113.494	0.009			113.493	0.046		
30	113.521	0.010			113.520	0.047		
...	...	...			...	...		
∞	113.899			113.899	113.899		113.899	

*: A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 5. Energy resonances (E) and quantum defect (δ) of the $2snp$ $^1P°$ and $2pnd$ ^3D Rydberg series of the Be-like F^{5+} ions. The energies are expressed in eV

	$2pnd$ ^1D		$2pnd$ ^3D	
	SCUNC		SCUNC	
n	E	δ	E	δ
8	149.295	0.110	163.474	0.024
9	150.966	0.109	165.094	0.023
10	152.156	0.109	166.251	0.023
11	153.034	0.109	167.107	0.023
12	153.699	0.109	167.758	0.023
13	154.216	0.108	168.264	0.023
14	154.625	0.108	168.665	0.023
15	154.954	0.108	168.989	0.023
16	155.224	0.108	169.254	0.023
17	155.446	0.108	169.473	0.023
18	155.633	0.108	169.657	0.023
19	155.791	0.108	169.812	0.023
20	155.925	0.108	169.945	0.023
21	156.041	0.108	170.059	0.023
22	156.141	0.108	170.158	0.023
23	156.228	0.108	170.245	0.023
24	156.305	0.108	170.320	0.023
25	156.373	0.108	170.387	0.023
26	156.432	0.108	170.447	0.023
27	156.486	0.108	170.499	0.023
28	156.533	0.108	170.547	0.023
29	156.576	0.108	170.589	0.023
30	156.615	0.108	170.627	0.023
...	...	...	...	...
∞	157.163		171.172	

Table 6. Energy resonances (E) and quantum defect (δ) of the $2snd\ ^{1,3}$D Rydberg series of the Be-like F^{5+} ions. The energies are expressed in eV

	$2pnd\ ^1$D		$2pnd\ ^3$D	
	SCUNC		SCUNC	
n	E	δ	E	δ
8	149.495	0.008	149.435	0.039
9	151.105	0.008	151.064	0.039
10	152.257	0.008	152.227	0.039
11	153.109	0.008	153.087	0.038
12	153.757	0.008	153.740	0.038
13	154.261	0.008	154.248	0.038
14	154.661	0.008	154.650	0.038
15	154.984	0.008	154.975	0.038
16	155.248	0.008	155.241	0.038
17	155.467	0.008	155.461	0.038
18	155.650	0.008	155.645	0.038
19	155.805	0.008	155.801	0.038
20	155.938	0.008	155.934	0.038
21	156.052	0.008	156.048	0.038
22	156.150	0.008	156.148	0.038
23	156.237	0.008	156.234	0.038
24	156.312	0.008	156.310	0.038
25	156.379	0.008	156.377	0.038
26	156.438	0.008	156.436	0.038
27	156.491	0.008	156.489	0.038
28	156.538	0.008	156.537	0.038
29	156.580	0.008	156.579	0.038
30	156.619	0.008	156.617	0.038
...	...	...	...	...
∞	157.163		157.163	

Table 7. Energy resonances (E) and quantum defect (δ) of the $2snp$ $^1P°$ and $2pnd$ ^3D Rydberg series of the Be-like Ne^{6+} ions. The energies are expressed in eV

	$2snd$ ^1D		$2pnd$ ^3D	
	SCUNC		SCUNC	
n	E	δ	E	δ
8	196.603	0.095	212.844	0.020
9	198.866	0.094	215.046	0.020
10	200.478	0.093	216.620	0.020
11	201.667	0.093	217.783	0.020
12	202.569	0.093	218.668	0.020
13	203.269	0.093	219.356	0.020
14	203.824	0.093	219.902	0.020
15	204.271	0.093	220.342	0.020
16	204.636	0.092	220.703	0.020
17	204.939	0.092	221.001	0.020
18	205.192	0.092	221.251	0.020
19	205.406	0.092	221.463	0.020
20	205.589	0.092	221.643	0.020
21	205.746	0.092	221.799	0.020
22	205.882	0.092	221.933	0.020
23	206.001	0.092	222.051	0.020
24	206.105	0.092	222.154	0.020
25	206.196	0.092	222.245	0.020
26	206.278	0.092	222.325	0.020
27	206.350	0.092	222.397	0.020
28	206.415	0.092	222.462	0.020
29	206.473	0.092	222.519	0.020
30	206.526	0.092	222.571	0.020
...	...	...	...	...
∞	207.271	223.313		

Table 8. Energy resonances (E) and quantum defect (δ) of the $2snd\ ^{1,3}$D Rydberg series of the Be-like Ne^{6+} ions. The energies are expressed in eV. The energy difference with respect to the NIST data is $|\Delta E| = |E|^{SCUNC} - E^{NIST}$

	$2snd\ ^1$D				$2snd\ ^3$D			
	SCUNC		NIST*	$\|\Delta E\|$	SCUNC		NIST*	$\|\Delta E\|$
n	E	δ	E		E	δ		
8	196.836	0.007	196.783	0.053	196.766	0.033	196.783	0.017
9	199.028	0.007			198.979	0.033	198.700	0.279
10	200.595	0.007			200.560	0.033		
11	201.754	0.007			201.728	0.033		
12	202.636	0.007			202.616	0.033		
13	203.322	0.007			203.306	0.033		
14	203.866	0.007			203.854	0.033		
15	204.305	0.007			204.295	0.033		
16	204.665	0.007			204.656	0.033		
17	204.962	0.007			204.955	0.033		
18	205.212	0.007			205.206	0.033		
19	205.423	0.007			205.418	0.033		
20	205.603	0.007			205.599	0.032		
21	205.758	0.007			205.755	0.032		
22	205.893	0.007			205.889	0.032		
23	206.010	0.007			206.007	0.032		
24	206.113	0.007			206.110	0.032		
25	206.204	0.007			206.202	0.032		
26	206.284	0.007			206.282	0.032		
27	206.356	0.007			206.354	0.032		
28	206.420	0.007			206.419	0.032		
29	206.478	0.007			206.477	0.032		
30	206.530	0.007			206.529	0.032		
...	...	...			...	...		
∞	207.271		207.271		207.271		207.271	

*: A. Kramida, Yu.Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 9. Present screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P°$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like Na^{7+} ions. The energies are expressed in eV

	$2snp\ ^1P°$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	250.300	0.083	268.632	0.018	250.566	0.006	250.486	0.029
9	253.243	0.082	271.505	0.018	253.428	0.006	253.372	0.029
10	255.340	0.082	273.560	0.017	255.474	0.006	255.434	0.029
11	256.888	0.081	275.078	0.017	256.988	0.006	256.958	0.029
12	258.062	0.081	276.233	0.017	258.139	0.006	258.116	0.029
13	258.975	0.081	277.131	0.017	259.035	0.006	259.017	0.029
14	259.698	0.081	277.844	0.017	259.746	0.006	259.731	0.028
15	260.280	0.081	278.419	0.017	260.319	0.006	260.307	0.028
16	260.756	0.081	278.889	0.017	260.788	0.006	260.778	0.028
17	261.150	0.081	279.278	0.017	261.177	0.006	261.169	0.028
18	261.480	0.080	279.605	0.017	261.503	0.006	261.496	0.028
19	261.759	0.080	279.881	0.017	261.778	0.006	261.773	0.028
20	261.997	0.080	280.117	0.017	262.014	0.006	262.009	0.028
21	262.202	0.080	280.320	0.017	262.216	0.006	262.212	0.028
22	262.380	0.080	280.496	0.017	262.392	0.006	262.388	0.028
23	262.534	0.080	280.649	0.017	262.545	0.006	262.542	0.028
24	262.670	0.080	280.784	0.017	262.680	0.006	262.677	0.028
25	262.790	0.080	280.902	0.017	262.798	0.006	262.796	0.028
26	262.896	0.080	281.008	0.017	262.903	0.006	262.901	0.028
27	262.990	0.080	281.102	0.017	262.997	0.006	262.995	0.028
28	263.075	0.080	281.186	0.017	263.081	0.006	263.079	0.028
29	263.151	0.080	281.261	0.017	263.156	0.006	263.155	0.028
30	263.219	0.080	281.329	0.017	263.224	0.006	263.223	0.028
...	...	...	...	...	...	...	...	...
∞	264.192		282.298		264.192		264.192	

Table 10. Present Screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp$ $^1P°$, $2pnd$ ^3D, and $2snd$ $^{1,3}D$ Rydberg series of the Be-like Mg^{8+} ions. The energies are expressed in eV

	$2snp$ $^1P°$		$2pnd$ ^3D		$2snd$ ^1D		$2snd$ ^3D	
n	E	δ	E	δ	E	δ	E	δ
8	310.448	0.074	420.911	0.016	310.747	0.005	310.658	0.026
9	314.161	0.073	424.546	0.016	314.368	0.005	314.306	0.026
10	316.807	0.073	427.144	0.015	316.958	0.005	316.913	0.026
11	318.761	0.072	429.065	0.015	318.873	0.005	318.840	0.025
12	320.244	0.072	430.526	0.015	320.330	0.005	320.304	0.025
13	321.396	0.072	431.662	0.015	321.464	0.005	321.443	0.025
14	322.309	0.072	432.564	0.015	322.363	0.005	322.347	0.025
15	323.045	0.072	433.291	0.015	323.089	0.005	323.075	0.025
16	323.646	0.071	433.886	0.015	323.682	0.005	323.671	0.025
17	324.144	0.071	434.379	0.015	324.174	0.005	324.165	0.025
18	324.561	0.071	434.792	0.015	324.587	0.005	324.579	0.025
19	324.914	0.071	435.141	0.015	324.936	0.005	324.929	0.025
20	325.215	0.071	435.439	0.015	325.233	0.005	325.228	0.025
21	325.474	0.071	435.696	0.015	325.490	0.005	325.485	0.025
22	325.698	0.071	435.919	0.015	325.712	0.005	325.708	0.025
23	325.894	0.071	436.113	0.015	325.906	0.005	325.902	0.025
24	326.065	0.071	436.283	0.015	326.076	0.005	326.073	0.025
25	326.217	0.071	436.433	0.015	326.226	0.005	326.223	0.025
26	326.351	0.071	436.567	0.015	326.359	0.005	326.357	0.025
27	326.470	0.071	436.685	0.015	326.478	0.005	326.475	0.025
28	326.577	0.071	436.792	0.015	326.584	0.005	326.582	0.025
29	326.673	0.071	436.887	0.015	326.679	0.005	326.677	0.025
30	326.760	0.071	436.973	0.015	326.765	0.005	326.763	0.025
...	...	...	...	...	...	...	...	...
∞	327.990		438.199		327.990		327.990	

Table 11. Present Screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P^\circ$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like Al^{9+} ions. The energies are expressed in eV

	$2snp\ ^1P^\circ$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	377.034	0.066	399.678	0.014	377.366	0.005	377.266	0.023
9	381.604	0.066	404.162	0.014	381.835	0.005	381.766	0.023
10	384.865	0.065	407.368	0.014	385.031	0.005	384.981	0.023
11	387.271	0.065	409.739	0.014	387.396	0.005	387.359	0.023
12	389.099	0.065	411.542	0.014	389.194	0.005	389.166	0.023
13	390.519	0.065	412.944	0.014	390.594	0.005	390.571	0.023
14	391.644	0.064	414.057	0.014	391.704	0.005	391.686	0.023
15	392.551	0.064	414.954	0.014	392.599	0.005	392.585	0.023
16	393.292	0.064	415.688	0.014	393.332	0.005	393.320	0.023
17	393.906	0.064	416.297	0.014	393.940	0.005	393.930	0.023
18	394.421	0.064	416.806	0.014	394.449	0.005	394.440	0.023
19	394.856	0.064	417.238	0.014	394.879	0.005	394.872	0.022
20	395.227	0.064	417.606	0.014	395.247	0.005	395.241	0.022
21	395.546	0.064	417.923	0.014	395.563	0.005	395.558	0.022
22	395.823	0.064	418.197	0.014	395.838	0.005	395.833	0.022
23	396.064	0.064	418.437	0.014	396.077	0.005	396.073	0.022
24	396.275	0.064	418.647	0.014	396.287	0.005	396.283	0.022
25	396.462	0.064	418.833	0.014	396.472	0.005	396.469	0.022
26	396.627	0.064	418.997	0.014	396.637	0.005	396.634	0.022
27	396.775	0.064	419.144	0.014	396.783	0.005	396.781	0.022
28	396.907	0.064	419.275	0.014	396.914	0.005	396.912	0.022
29	397.025	0.064	419.393	0.014	397.032	0.005	397.030	0.022
30	397.132	0.064	419.499	0.014	397.138	0.005	397.136	0.023
...	...	...	...	...	...	...	...	...
∞	398.650		421.012		398.650		398.650	

Table 12. Present screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P°$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like Si^{10+} ions. The energies are expressed in eV

	$2snp\ ^1P°$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	450.064	0.060	474.947	0.013	450.429	0.004	450.319	0.021
9	455.582	0.060	480.371	0.013	455.836	0.004	455.760	0.021
10	459.520	0.059	484.248	0.013	459.703	0.004	459.648	0.021
11	462.427	0.059	487.116	0.013	462.564	0.004	462.523	0.021
12	464.634	0.059	489.296	0.013	464.739	0.004	464.708	0.021
13	466.350	0.059	490.993	0.012	466.432	0.004	466.408	0.021
14	467.710	0.058	492.339	0.012	467.776	0.004	467.756	0.021
15	468.806	0.058	493.424	0.012	468.859	0.004	468.843	0.021
16	469.702	0.058	494.312	0.012	469.746	0.004	469.733	0.020
17	470.444	0.058	495.048	0.012	470.481	0.004	470.470	0.020
18	471.066	0.058	495.665	0.012	471.097	0.004	471.087	0.020
19	471.592	0.058	496.187	0.012	471.618	0.004	471.610	0.020
20	472.040	0.058	496.632	0.012	472.063	0.004	472.056	0.020
21	472.426	0.058	497.015	0.012	472.445	0.004	472.440	0.020
22	472.761	0.058	497.348	0.012	472.777	0.004	472.772	0.020
23	473.052	0.058	497.637	0.012	473.067	0.004	473.062	0.020
24	473.308	0.058	497.892	0.012	473.321	0.004	473.317	0.020
25	473.534	0.058	498.116	0.012	473.545	0.004	473.542	0.020
26	473.734	0.058	498.315	0.012	473.744	0.004	473.741	0.020
27	473.912	0.058	498.493	0.012	473.921	0.004	473.918	0.020
28	474.071	0.058	498.651	0.012	474.080	0.004	474.077	0.020
29	474.215	0.058	498.794	0.012	474.222	0.004	474.220	0.020
30	474.344	0.058	498.922	0.012	474.350	0.004	474.348	0.020
...	...	...	...	...	...	...	...	...
∞	476.180		500.753		476.180		476.180	

Table 13. Present screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp$ $^1P°$, $2pnd$ ^3D, and $2snd$ $^{1,3}D$ Rydberg series of the Be-like P^{11+} ions. The energies are expressed in eV

	$2snp$ $^1P°$		$2pnd$ ^3D		$2snd$ ^1D		$2snd$ ^3D	
n	E	δ	E	δ	E	δ	E	δ
8	529.578	0.055	556.775	0.012	529.977	0.004	529.857	0.020
9	536.134	0.055	563.227	0.012	536.411	0.004	536.328	0.019
10	540.813	0.054	567.840	0.012	541.012	0.004	540.952	0.019
11	544.268	0.054	571.252	0.012	544.417	0.004	544.372	0.019
12	546.891	0.054	573.846	0.011	547.005	0.004	546.971	0.019
13	548.931	0.054	575.865	0.011	549.020	0.004	548.993	0.019
14	550.547	0.054	577.466	0.011	550.618	0.004	550.597	0.019
15	551.850	0.053	578.757	0.011	551.908	0.004	551.890	0.019
16	552.916	0.053	579.814	0.011	552.963	0.004	552.949	0.019
17	553.798	0.053	580.690	0.011	553.838	0.004	553.826	0.019
18	554.537	0.053	581.423	0.011	554.570	0.004	554.560	0.019
19	555.162	0.053	582.044	0.011	555.191	0.004	555.182	0.019
20	555.696	0.053	582.574	0.011	555.720	0.004	555.713	0.019
21	556.155	0.053	583.031	0.011	556.176	0.004	556.169	0.019
22	556.552	0.053	583.426	0.011	556.571	0.004	556.565	0.019
23	556.899	0.053	583.771	0.011	556.915	0.004	556.910	0.019
24	557.204	0.053	584.073	0.011	557.217	0.004	557.213	0.019
25	557.472	0.053	584.340	0.011	557.484	0.004	557.481	0.019
26	557.710	0.053	584.577	0.011	557.721	0.004	557.718	0.019
27	557.922	0.053	584.788	0.011	557.932	0.004	557.929	0.019
28	558.112	0.053	584.977	0.011	558.120	0.004	558.118	0.019
29	558.282	0.053	585.147	0.011	558.290	0.004	558.287	0.019
30	558.435	0.053	585.299	0.011	558.443	0.004	558.440	0.019
...	...	...	...	...	...	...	...	...
∞	560.620		587.478		560.620		560.620	

Table 14. Present screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P^\circ$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like S^{12+} ions. The energies are expressed in eV

	$2snp\ ^1P^\circ$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	615.568	0.051	643.653	0.011	615.999	0.004	615.870	0.018
9	623.250	0.051	651.223	0.011	623.550	0.004	623.460	0.018
10	628.733	0.050	656.636	0.011	628.950	0.004	628.885	0.018
11	632.783	0.050	660.639	0.011	632.945	0.004	632.896	0.018
12	635.859	0.050	663.683	0.011	635.983	0.004	635.946	0.018
13	638.250	0.050	666.051	0.011	638.347	0.004	638.318	0.017
14	640.145	0.049	667.929	0.010	640.223	0.004	640.199	0.017
15	641.673	0.049	669.445	0.010	641.736	0.004	641.717	0.017
16	642.923	0.049	670.685	0.010	642.974	0.004	642.959	0.017
17	643.958	0.049	671.712	0.010	644.000	0.004	643.988	0.017
18	644.824	0.049	672.573	0.010	644.860	0.004	644.850	0.017
19	645.558	0.049	673.302	0.010	645.588	0.004	645.579	0.017
20	646.183	0.049	673.924	0.010	646.210	0.004	646.202	0.017
21	646.722	0.049	674.459	0.010	646.744	0.004	646.738	0.017
22	647.188	0.049	674.923	0.010	647.208	0.004	647.202	0.017
23	647.595	0.049	675.328	0.010	647.612	0.004	647.607	0.017
24	647.952	0.049	675.683	0.010	647.967	0.004	647.962	0.017
25	648.267	0.049	675.996	0.010	648.280	0.003	648.276	0.017
26	648.546	0.049	676.274	0.010	648.558	0.003	648.554	0.017
27	648.794	0.049	676.522	0.010	648.805	0.003	648.802	0.017
28	649.017	0.049	676.743	0.010	649.026	0.003	649.024	0.017
29	649.217	0.049	676.942	0.010	649.225	0.003	649.223	0.017
30	649.397	0.048	677.122	0.010	649.405	0.003	649.402	0.017
...	...	...	...	...	...	...	...	...
∞	651.960			651.960		651.960		

Table 15. Present screening constant per unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P^\circ$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like Cl^{13+} ions. The energies are expressed in eV

	$2snp\ ^1P^\circ$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	708.063	0.048	740.136	0.010	708.527	0.003	708.387	0.017
9	716.961	0.047	748.913	0.010	717.283	0.003	717.186	0.017
10	723.312	0.047	755.189	0.010	723.545	0.003	723.475	0.016
11	728.004	0.046	759.830	0.010	728.178	0.003	728.125	0.016
12	731.568	0.046	763.360	0.010	731.701	0.003	731.661	0.016
13	734.338	0.046	766.106	0.010	734.443	0.003	734.411	0.016
14	736.535	0.046	768.284	0.010	736.618	0.003	736.593	0.016
15	738.305	0.046	770.041	0.010	738.373	0.003	738.353	0.016
16	739.754	0.046	771.479	0.010	739.809	0.003	739.792	0.016
17	740.953	0.045	772.671	0.010	740.999	0.003	740.985	0.016
18	741.958	0.045	773.669	0.010	741.996	0.003	741.985	0.016
19	742.808	0.045	774.514	0.010	742.840	0.003	742.831	0.016
20	743.533	0.045	775.236	0.010	743.561	0.003	743.553	0.016
21	744.157	0.045	775.856	0.010	744.181	0.003	744.174	0.016
22	744.698	0.045	776.394	0.010	744.719	0.003	744.712	0.016
23	745.169	0.045	776.864	0.010	745.188	0.003	745.182	0.016
24	745.583	0.045	777.275	0.010	745.599	0.003	745.594	0.016
25	745.948	0.045	777.639	0.010	745.962	0.003	745.958	0.016
26	746.271	0.045	777.961	0.010	746.284	0.003	746.280	0.016
27	746.560	0.045	778.248	0.010	746.571	0.003	746.568	0.016
28	746.818	0.045	778.505	0.010	746.828	0.003	746.825	0.016
29	747.049	0.045	778.736	0.010	747.058	0.003	747.056	0.016
30	747.258	0.045	778.944	0.010	747.266	0.003	747.264	0.016
...	...	...	...	...	...	...	...	...
∞	750.230		781.909		750.230		750.230	

Table 16. Present screening constant by unit nuclear charge calculations of energy resonances (E) and quantum defect (δ) of the $2snp\ ^1P^\circ$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ Rydberg series of the Be-like Ar^{14+} ions. The energies are expressed in eV

	$2snp\ ^1P^\circ$		$2pnd\ ^3D$		$2snd\ ^1D$		$2snd\ ^3D$	
n	E	δ	E	δ	E	δ	E	δ
8	807.102	0.044	841.770	0.009	807.599	0.003	807.450	0.016
9	817.305	0.044	851.843	0.009	817.650	0.003	817.546	0.015
10	824.589	0.044	859.046	0.009	824.838	0.003	824.763	0.015
11	829.970	0.043	864.373	0.009	830.156	0.003	830.100	0.015
12	834.058	0.043	868.424	0.009	834.200	0.003	834.157	0.015
13	837.236	0.043	871.576	0.009	837.347	0.003	837.314	0.015
14	839.755	0.043	874.076	0.009	839.844	0.003	839.818	0.015
15	841.787	0.043	876.093	0.009	841.859	0.003	841.837	0.015
16	843.448	0.042	877.744	0.009	843.507	0.003	843.490	0.015
17	844.824	0.042	879.112	0.009	844.874	0.003	844.859	0.015
18	845.977	0.042	880.258	0.009	846.018	0.003	846.006	0.015
19	846.952	0.042	881.227	0.009	846.987	0.003	846.977	0.015
20	847.784	0.042	882.055	0.009	847.814	0.003	847.805	0.015
21	848.500	0.042	882.768	0.009	848.526	0.003	848.519	0.015
22	849.121	0.042	883.385	0.009	849.143	0.003	849.137	0.015
23	849.662	0.042	883.924	0.009	849.682	0.003	849.676	0.015
24	850.137	0.042	884.397	0.009	850.154	0.003	850.149	0.015
25	850.555	0.042	884.814	0.009	850.571	0.003	850.566	0.015
26	850.927	0.042	885.184	0.009	850.940	0.003	850.936	0.015
27	851.258	0.042	885.513	0.009	851.270	0.003	851.266	0.015
28	851.554	0.042	885.808	0.009	851.564	0.003	851.561	0.015
29	851.819	0.042	886.073	0.009	851.829	0.003	851.826	0.015
30	852.059	0.042	886.312	0.009	852.068	0.003	852.065	0.015
...	...	...	...	...	...	...	...	...
∞	855.470		889.715		855.470		855.470	

Table 17. Energy resonances (E) of the 2snp ^{1}P°, 2pnd ^{3}D, and 2snd ^{1,3}D ($n = 3-7$) Rydberg series of the Be-like O^{4+}, F^{5+}, and Ne^{6+} ions. The energies are expressed in eV

	O^{4+}		F^{5+}		Ne^{6+}	
	SCUNC	NIST	SCUNC	NIST	SCUNC	NIST
2snp ^{1}P°						
2s3p ^{1}P°	71.811	72.013	97.571	97.680	127.149	127.161
2s4p ^{1}P°	91.027	91.485	124.609	124.959	163.333	163.646
2s5p ^{1}P°	99.512	99.493	136.632	136.308	179.506	179.840
2s6p ^{1}P°	104.012	104.099	143.031	143.131	188.138	188.280
2s7p ^{1}P°	106.686	106.736	146.842	146.855	193.286	193.255
2pnd ^{3}D						
2p3d ^{3}D	87.235		115.704		148.009	
2p4d ^{3}D	104.307		140.161		181.178	
2p5d ^{3}D	112.129		151.386		196.418	
2p6d ^{3}D	116.357		157.457	157.425	204.666	
2p7d ^{3}D	118.899	118.902	161.108	161.087	209.628	
2snd ^{1}D						
2s3d ^{1}D	75.805	75.955	102.377	102.515	132.769	132.900
2s4d ^{1}D	92.526	92.526	126.413	126.385	165.443	165.383
2s5d ^{1}D	100.238	100.223	137.504	137.469	180.526	180.447
2s6d ^{1}D	104.419	104.405	143.520	143.495	188.708	188.687
2s7d ^{1}D	106.938		147.144	147.119	193.638	193.680
2snd ^{3}D						
2s3d ^{3}D	74.624	74.486	100.952	125.771	131.100	130.727
2s4d ^{3}D	92.081	92.026	125.876	140.143	164.813	164.686
2s5d ^{3}D	100.022	99.987	137.244	137.173	180.221	180.162
2s6d ^{3}D	104.298	104.275	143.374	133.436	188.538	188.502
2s7d ^{3}D	106.863	106.848	147.054	147.026	193.533	193.540

NIST, A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 18. Energy resonances (E) of the $2snp\ ^1P°$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ ($n = 3-7$) Rydberg series of the Be-like Na^{7+}, Mg^{8+}, and Al^{9+} ions. The energies are expressed in eV

	Na^{7+}		Mg^{8+}		Al^{9+}	
	SCUNC	NIST	SCUNC	NIST	SCUNC	NIST
$2snp\ ^1P°$						
$2s3p\ ^1P°$	160.515	160.464	197.733	197.581	238.789	238.527
$2s4p\ ^1P°$	207.169	207.474	256.180	256.484	310.353	
$2s5p\ ^1P°$	228.105	227.996	282.493	282.792	342.653	
$2s6p\ ^1P°$	239.301	239.402	296.586	296.591	359.977	
$2s7p\ ^1P°$	245.988		305.011	305.094	370.341	
$2pnd\ ^3D$						
$2p3d\ ^3D$	184.133		314.149		268.054	
$2p4d\ ^3D$	227.338		368.713		335.300	
$2p5d\ ^3D$	247.206		393.821		366.261	
$2p6d\ ^3D$	257.963		407.420		383.034	
$2p7d\ ^3D$	264.436		415.605		393.131	
$2snd\ ^1D$						
$2s3d\ ^1D$	166.951	167.098	204.986	205.142	246.860	247.019
$2s4d\ ^1D$	209.585	209.530	258.903	258.865	313.382	313.377?
$2s5d\ ^1D$	229.272	229.242	283.807	283.723	344.115	343.988?
$2s6d\ ^1D$	239.954	239.938	297.321	297.251	360.794	
$2s7d\ ^1D$	246.390		305.464	305.372	370.845	
$2snd\ ^3D$						
$2s3d\ ^3D$	165.036	164.567	202.826	202.246	244.454	243.772
$2s4d\ ^3D$	208.863	207.711	258.089	257.888	312.476	
$2s5d\ ^3D$	228.923	229.206?	283.413	283.294	343.677	
$2s6d\ ^3D$	239.758	239.715?	297.100	296.978	360.549	
$2s7d\ ^3D$	246.270		305.328	305.286	370.694	

NIST, A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 19. Energy resonances (E) of the $2snp\ ^1P^\circ$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ ($n = 3-7$) Rydberg series of the Be-like Si^{10+}, P^{11+}, and S^{12+} ions. The energies are expressed in eV

	Si^{10+}		P^{11+}		S^{12+}	
	SCUNC	NIST	SCUNC	NIST	SCUNC	NIST
$2snp\ ^1P^\circ$						
$2s3p\ ^1P^\circ$	283.690	283.309	332.478	332.00	385.141	384.54
$2s4p\ ^1P^\circ$	369.695	369.937?	434.245	434.32	503.995	504.21
$2s5p\ ^1P^\circ$	408.596		480.359	480.79?	557.934	
$2s6p\ ^1P^\circ$	429.482		505.141		586.944	
$2s7p\ ^1P^\circ$	441.986		519.986		604.330	
$2pnd\ ^3D$						
$2p3d\ ^3D$	315.863		367.632		421.853	
$2p4d\ ^3D$	397.114		464.211		535.083	
$2p5d\ ^3D$	434.539		508.714		587.275	
$2p6d\ ^3D$	454.820		532.833		615.567	
$2p7d\ ^3D$	467.030		547.357		632.604	
$2snd\ ^1D$						
$2s3d\ ^1D$	292.580	292.763	342.187	342.38	395.670	395.92
$2s4d\ ^1D$	373.031	372.916	437.889	437.81?	507.946	507.7
$2s5d\ ^1D$	410.205	410.172	482.116		559.839	
$2s6d\ ^1D$	430.381		506.122		588.007	
$2s7d\ ^1D$	442.540		520.589		604.984	
$2snd\ ^3D$						
$2s3d\ ^3D$	289.928	289.172	339.288	338.345	392.524	391.543
$2s4d\ ^3D$	372.033	371.760	436.798	436.595	506.763	506.54
$2s5d\ ^3D$	409.723	409.693	481.590	481.73	559.268	
$2s6d\ ^3D$	430.111		505.827		587.688	
$2s7d\ ^3D$	442.374		520.408		604.788	

NIST, A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 20. Energy resonances (E) of the $2snp\ ^1P°$, $2pnd\ ^3D$, and $2snd\ ^{1,3}D$ ($n = 3-7$) Rydberg series of the Be-like Cl^{13+}, and Ar^{14+} ions. The energies are expressed in eV

	Cl^{13+}		Ar^{14+}	
	SCUNC	NIST	SCUNC	NIST
$2snp\ ^1P°$				
$2s3p\ ^1P°$	441.711	441.024	502.226	501.15
$2s4p\ ^1P°$	578.974		659.222	
$2s5p\ ^1P°$	641.351		730.649	
$2s6p\ ^1P°$	674.921		769.112	
$2s7p\ ^1P°$	695.049		792.182	
$2pnd\ ^3D$				
$2p3d\ ^3D$	483.080		546.859	
$2p4d\ ^3D$	614.283		697.360	
$2p5d\ ^3D$	674.777		766.768	
$2p6d\ ^3D$	707.574		804.402	
$2p7d\ ^3D$	727.326		827.069	
$2snd\ ^1D$				
$2s3d\ ^1D$	453.059	453.373	514.395	514.52
$2s4d\ ^1D$	583.233		663.789	663.74
$2s5d\ ^1D$	643.403		732.849	
$2s6d\ ^1D$	676.066		770.340	
$2s7d\ ^1D$	695.753		792.937	
$2snd\ ^3D$				
$2s3d\ ^3D$	449.667	448.622	510.756	509.688
$2s4d\ ^3D$	581.957		662.421	
$2s5d\ ^3D$	642.788		732.190	
$2s6d\ ^3D$	675.723		769.971	
$2s7d\ ^3D$	695.541		792.710	

NIST, A. Kramida, Yu. Ralchenko, J. Reader and NIST ASD Team (2015), *NIST Atomic Spectra Database* (version 5.3), available online: `http://physics.nist.gov/asd` [2016, December 24], National Institute of Standards and Technology, Gaithersburg, MD

Table 21. Total energy ($-E$) of the $2snp\ ^1P°$, and $2snd\ ^{1,3}D$ Rydberg series of the Al^{9+}. The present screening constant per unit nuclear charge (SCUNC) calculations are compared with the Feshbach operator projection approximation and multiconfiguration Dirac Fock (MCDF) computations of Stancalie [20] and with the data from the Opacity Project Team (OPT) [21] as quoted in Stancalie [20]. The energies are expressed in atomic units (a.u)

	$2snp\ ^1P°$		$2snd\ ^1D$			$2snd\ ^3D$		
n	SCUNC	FPO	SCUNC	OPT	MCDF	SCUNC	OPT	MCDF
8	0.7944		0.7822		0.7859			
9	0.6264	0.6226	0.6179	0.6192	0.6091	0.6205	0.6202	0.6066
10	0.5066	0.5056	0.5005		0.5023			
11	0.4182	0.4175	0.4136		0.4150			
12	0.3510	0.3505	0.3475		0.3485			
13	0.2988	0.2984	0.2961		0.2969			
14	0.2575	0.2572	0.2553		0.2559			
15	0.2241	0.2238	0.2224		0.2229			
16	0.1969		0.1954		0.1959			
17	0.1743		0.1731		0.1735			
18	0.1554		0.1544		0.1547			
19	0.1394		0.1386		0.1388			
20	0.1258		0.1251		0.1253			
21	0.1141		0.1134		0.1136			
22	0.1039		0.1033		0.1035			
23	0.0950		0.0946		0.0947			
24	0.0873		0.0868		0.0870			
25	0.0804		0.0800		0.0801			

The present Screening constant by unit nuclear charge (SCUNC) calculations are compared with the Feshbach operator projection approximation and multiconfiguration Dirac Fock (MCDF) computations of Stancalie [20] and with the data from the Opacity Project Team (OPT) [21] as quoted in Stancalie [20]. For the $2snp\ ^1P°$ levels, the agreements between the SCUNC and OPT [21] predictions are seen to agree well each other up to $n = 15$ where the relative energy difference is at 0.0003 a.u. For the $2snd\ ^{1,3}D$, only the data for the $2s9d\ ^{1,3}D$ levels are available. For the $2snd\ ^1D$, the SCUNC prediction at 0.6179 a.u is seen to match more with the OPT data at 0.6192 a.u than with the MCDF value at 0.6091 a.u. In the same way, for the $2snd\ ^3D$, the SCUNC prediction at 0.6205 a.u is seen to match again more with the OPT data at 0.6202 a.u than with the MCDF value at 0.6066 a.u. These agreements indicate that the SCUNC results for the $2snd\ ^{1,3}D$ series of the Be-like Al^{9+} ions may be good references data for the Opacity project Team.

4. Conclusion

Photoionization study of the Be-like ($Z = 8-18$) ions has been carried out in this paper. Calculations of energies resonances of the $1s^22snp\ ^1P^\circ$, $1s^22snd\ ^{1,3}D$, and $1s^22pnd\ ^3D$ ($n = 3-30$) Rydberg series of the Be-like ($Z = 8-18$) ions are done in the framework of the Screening constant by unit nuclear charge (SCUNC) method. In general, the present SCUNC prediction agree well with the existing NIST data and the SCUNC prediction for $n > 8$ may be useful primary source for the NIST database. In addition, more accurate SCUNC total energy than the MCDF results of Stancalie [20] are obtained and they may be good reference data for the Opacity Project Team (OPT). Besides, the present study demonstrate the possibility to use the SCUNC method for enlightening discrepancies between computational works and to report again high lying energy resonances up to $n = 30$.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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