EAST EUROPEAN JOURNAL OF PHYSICS. 1. 148-155 (2026)
DOI:10.26565/2312-4334-2026-1-13 ISSN 2312-4334

RELATIVISTIC CONFIGURATION-INTERACTION PHOTOIONIZATION DATA FOR Ne-LIKE ISOELECTRONIC SEQUENCE

O. Abu-Haija[1]*, G.A. Alna'washi[2], S.M. Hamasha[2], M.T. Gning[3,4], I. Sakho[3,4], M. Al Shorman[1]
[1]*Applied Physics Department, Tafila Technical University, P. O. Box 179, Tafila 66110, Jordan*
[2]*Department of Physics, Faculty of Science, The Hashemite University, P. O. Box 330127, Zarqa 13133, Jordan*
[3]*Department of Physics Chemistry, UFR Sciences and Technologies, University Iba Der Thiam, Thies, Senegal*
[4]*African Center for Applied Atomic and Nuclear Technologies (CAFTANA), Dakar, Senegal*
**Corresponding Author email: oabuhaija@ttu.edu.jo*
Received October 12, 2025; revised February 4, 2026; accepted February 7, 2026

Photoionization data for the $1s^2\ 2s^2\ 2p^6\ (^1S_0)$ ground state of neon like Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions are reported. The values of ionization threshold limits, resonance energies, quantum defects, transition rates, and oscillator strengths for various Rydberg series are tabulated. The Relativistic configuration-interaction (RCI) approach, implemented in the Flexible Atomic Code (FAC), was used for all calculations. The RCI results for $2s\ 2p^6\ (^2S_{1/2})$ np resonance series show very good agreement with reported values in the literature. In addition, new calculations on K-shell photoexcitations ($1s\ 2s^2\ 2p^6\ (^2S_{1/2})$ np) in these ions are reported. These results would be valuable for high-precision spectral modeling in astrophysical or laboratory plasmas.
Keywords: *Photoexcitation; Resonance energy; Rydberg series; Relativistic configuration-interaction*
PACS: 31.15.ag

1. INTRODUCTION

Since the majority of matter in the Universe exists in an ionic form, the study of photoionization of positive ions is essential for improving our understanding and modeling of both fusion [1] and astrophysics [2] plasmas. In astrophysical nebulae, photoionization is an important process in controlling the ionization balance and, consequently, determining elemental abundances. In particular, the photoionization of Ne-like isoelectronic sequence is of astrophysical importance because the spectra of these ions serve as a key diagnostic tool for probing plasma conditions. Moreover, Ne-like ions of middle and high atomic numbers are found in various plasma environments, including electron-beam ion trap, tokamak, and solar atmosphere [3] [4]. In addition to their astrophysical relevance, these ions have practical significance in X-ray laser research, where photoionization of these ions has been utilized to explain the resonant photo-pumping scheme for driving lasing action [5]. Thus, ions belonging to the Ne isoelectronic sequence have attracted considerable experimental and theoretical studies [6] [7] [8] [9] [10] across a wide range of Z due to their broad application in plasma physics and astrophysics, as well as their stable closed-shell electronic structure. Among these, the neon like Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions are of particular interest. Goyal et al. [11] reported resonance energies and natural widths in the photoionization of Ne-like isoelectronic sequence (Z = 19 to 26) using the Screening Constant by Unit Nuclear Charge (SCUNC) approach. Liang et al. [12] employed the Breit–Pauli Hamiltonian within the R-matrix (B-P R-matrix) method to calculate the photoionization cross sections, resonance positions and widths for Ne-like Ca XI. In addition, the 2s to np autoionizing resonance transitions in various Ne-like ions were studied by Nrisimhamurty et al. [13] using the relativistic multichannel quantum-defect theory (RMQDT) and relativistic random-phase approximation (RRPA). More recently, Alna'washi et al. [14] [15] [16] presented new atomic data identifying 1s → np resonances in Ne and Ne-like ions, based on calculations performed within the relativistic configuration-interaction (RCI) method.

Given that achieving high accuracy for spectral modeling and high-resolution X-ray interpretation remains a significant challenge in astrophysical interest, this work extends our previous study [14] [15] [16] by performing new calculations for the Ne-like Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions. Specifically, the present study focuses on the $1s^2\ 2s\ 2p^6\ (^2S_{1/2})$ np $(^1P_1)$ and $1s\ 2s^2\ 2p^6\ (^2S_{1/2})$ np $(^1P_1)$ resonance series of these ions. To achieve this, the Relativistic Configuration Interaction (RCI) method, as implemented in the Flexible Atomic Code (FAC) [17], was employed for all calculations. The computed quantities include the ionization threshold, resonance energy, oscillator strength, and electric dipole (E1) transition rate corresponding to the 1s to np and 2s to np transitions with principal quantum number ranging from n = 3 to n = 22. Section 2 presents a brief outline of the theoretical framework. Section 3 presents and discusses our results in comparison with available literature data. Finally, we summarize and conclude in section 4.

2. THEORY

The RCI approach, as implemented in the FAC code, has already been extensively detailed in some literatures [14] [15] [16] [17] [18] [19]. Hence, a concise overview is provided here to outline the key aspects relevant to the present study.

Cite as: O. Abu-Haija, G. A. Alna'washi, S. M. Hamasha, M. T. Gning, I. Sakho, M. M. Al Shorman, East Eur. J. Phys. 1, 148 (2026), https://doi.org/10.26565/2312-4334-2026-1-13

2.1. Atomic structure: framework of the Dirac equation

For N electrons atom or ion, the relativistic Hamiltonian (H), expressed in atomic units, can be written as:

$$H = \sum_{i=1}^{N} H_D(i) + \sum_{i<j}^{N} \frac{1}{r_{ij}}, \tag{1}$$

where $H_D(i)$, the one electron Dirac Hamiltonian, is given by:

$$H_D = c\boldsymbol{\alpha}_i \cdot \boldsymbol{\alpha}_j + \beta m_e c^2 - \frac{Z}{r} \tag{2}$$

In Eq. (2), the term $c\boldsymbol{\alpha}_i \cdot \boldsymbol{\alpha}_j$ represents the electron's kinetic energy where $\boldsymbol{\alpha_i}$ and $\boldsymbol{\alpha_j}$ are Dirac matrices. The term $\beta m_e c^2$ denotes the rest-mass energy, and $(-\frac{Z}{r})$ corresponds to the Coulomb potential of the nucleus. The energy levels of any atomic ion can be obtained by diagonalizing the relativistic Hamiltonian (H).

In FAC, atomic processes are treated with basis state functions generated from a single potential. The basis states (Φ_v), referred as configuration state functions (CSFs), are built as antisymmetric sums of the products of N single-electron Dirac spinors φ_{nkm}.

The approximate atomic state functions are constructed by linearly combining basis states, Φ_v, with same symmetries as follows:

$$\psi = \sum_v b_v \Phi_v \tag{3}$$

where b_v are the mixing coefficients, which can be determined by diagonalizing the total Hamiltonian. The single-electron Dirac spinors are defined as:

$$\varphi_{n\kappa m} = \frac{1}{r}\begin{pmatrix} P_{n\kappa}(r)\chi_{\kappa m}(\theta,\phi,\sigma) \\ iQ_{n\kappa}(r)\chi_{-\kappa m}(\theta,\phi,\sigma) \end{pmatrix}. \tag{4}$$

Here, n denotes the principal quantum number, m represents the z-component of total angular momentum, and $\chi_{\kappa m}$ is the spin-angular function. The relativistic angular quantum number κ is expressed as:

$$\kappa = (l - j)(2j + 1). \tag{5}$$

The functions $P_{n\kappa}$ and $Q_{n\kappa}$ are the Dirac spinor's radial part components. These radial functions are obtained as solutions to the Dirac differential equation for the local central potential $V(r)$ as follows:

$$\left(\frac{d}{dr} + \frac{\kappa}{r}\right) P_{n\kappa} = \alpha \left(\varepsilon_{n\kappa} - V + \frac{2}{\alpha^2}\right) Q_{n\kappa}(r) \tag{6}$$

$$\left(\frac{d}{dr} - \frac{\kappa}{r}\right) Q_{n\kappa} = \alpha(-\varepsilon_{n\kappa} + V) P_{n\kappa}(r). \tag{7}$$

Here, α is the fine-structure constant, and $\varepsilon_{n\kappa}$ represents the energy eigenvalues associated with the corresponding radial functions.

2.2. Radiative transition rates

The electric dipole (E1) transition rates are calculated within the single multipole approximation, which neglects the interference between different multipole orders. The transition rates, A_{fi}^{E1}, is related to the transition line strength, S_{if}, and wavelength of the transition, λ, by the expression:

$$A_{fi}^{E1} = \frac{2.0261\times10^{18}}{(2J+1)\lambda^3} S_{if}^{E1} \tag{8}$$

Here, the generalized line strength of the transition S_{fi} is defined as the squared matrix element $S_{fi} = \left|\langle\varphi_f|O_M^L|\varphi_i\rangle\right|^2$, where O_M^L is the multipole operator, φ_i, and φ_f are the wavefunctions of the initial and final states, respectively. Furthermore, the weighted oscillator strength, gf_{fi}, for different radiative channels is given by:

$$gf_{fi} = \frac{\omega}{L}(\alpha\omega)^{2L-2} S_{fi}, \tag{9}$$

where $\omega = E_f - E_i$ is the energy of transition.

2.3. Resonance energy and quantum defect

The quantum defect concept is introduced in the treatment of highly excited Rydberg states, which in turn accounts for the effects of core polarization and penetration. Within this framework, the revised Rydberg formula gives the energy level of an electron E_n (in eV) as:

$$E_n = E_\infty - \frac{R(Z-N_c)^2}{(n-\delta_n)^2}, \tag{10}$$

In this equation, R is the Rydberg constant, N_c is the number of core electrons, δ_n represents quantum defect, and E_∞ denotes the threshold limit.

2.4. Calculation procedure

Our configuration interaction (CI) expansion includes the ground state configuration ($1s^2\ 2s^2\ 2p^6$) and excited configurations ($1s^2\ 2s\ 2p^6$ np and $1s\ 2s^2\ 2p^6$ np) involving n goes to 22. To ensure convergence, we systematically increased the configuration set and monitored the resonance energies and oscillator strengths. This process guaranteed convergence for energy positions to within approximately 0.02 eV and for line strengths to within 2%. As mentioned in the FAC manual, the estimated uncertainties in the radiative rates and oscillator strengths range from 10 to 20%, while the accuracy within a few (eV) for the calculated energy levels. It is important to point out that the higher-order quantum electrodynamic (QED) effects are excluded from the RCI approach, as their impact is negligible compared to that of electron correlations. Furthermore, within FAC's RCI methodology, autoionizing resonances are treated as bound-like states, neglecting explicit continuum coupling. This approximation eliminates Fano interference and energy-dependent continuum effects, causing systematic shifts in resonance positions.

3. RESULTS AND DISCUSSION

3.1 Threshold limits

The $1s^2\ 2s\ 2p^6$ ($^2S_{1/2}$) and $1s\ 2s^2\ 2p^6$ ($^2S_{1/2}$) series limits for the Ne-like ions with nuclear charge Z = 20 – 24 are listed in Table 1, in addition to other theoretical results obtained by Goyal et al. [11] and Nrisimhamurty et al. [13], as well as tabulated data from the NIST database [20], for comparison.

Table 1. Energy limit E_∞ (eV) of the $1s^22s2p^6(^2S_{1/2})$ and $1s2s^22p^6(^2S_{1/2})$ thresholds of Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{+14} ions.

Ion	Configuration	E_∞^{a}	E_∞^{b}	E_∞^{c}	E_∞^{d}
Ca^{10+}	$1s^2\ 2s\ 2p^6\ (^2S_{1/2})$	679.7839	680.800	679.509	682.642
	$1s\ 2s^2\ 2p^6\ (^2S_{1/2})$	4298.5845			
Sc^{11+}	$1s^2\ 2s\ 2p^6\ (^2S_{1/2})$	781.2269	782.758	782.0369	
	$1s\ 2s^2\ 2p^6\ (^2S_{1/2})$	4794.2941			
Ti^{12+}	$1s^2\ 2s\ 2p^6\ (^2S_{1/2})$	889.6942	891.543	889.3088	
	$1s\ 2s^2\ 2p^6\ (^2S_{1/2})$	5317.9877			
V^{13+}	$1s^2\ 2s\ 2p^6\ (^2S_{1/2})$	1005.2103	1007.146	1004.828	1008.297
	$1s\ 2s^2\ 2p^6\ (^2S_{1/2})$	5869.7555			
Cr^{14+}	$1s^2\ 2s\ 2p^6\ (^2S_{1/2})$	1127.7993	1129.556	1127.871	1130.993
	$1s\ 2s^2\ 2p^6\ (^2S_{1/2})$	6449.6768			

[a] : Present work.
[b] : Goyal et al. [11].
[c] : National Institute of Standards and Technology (NIST) [20].
[d] : Nrisimhamurty et al. [13].

For these ions, it can be seen that the present results for the $1s^2\ 2s\ 2p^6$ ($^2S_{1/2}$) limit are in good agreement with the results reported in the literature. The computed RCI energy limits show excellent agreement with the NIST data but lie approximately 1–1.8 eV below the values obtained using SCUNC method. In contrast, the results from RMQDT by Nrisimhamurty et al. [13] are slightly higher than the present RCI, SCUNC and NIST data for Ca^{10+}, V^{13+}, and Cr^{14+} ions. This discrepancy is likely attributed to omission of electron correlation effects in their RMQDT calculations. To the best of our knowledge, the threshold limits of the $1s\ 2s^2\ 2p^6$ ($^2S_{1/2}$) series have not been previously published for these five neon-like ions (Ca, Sc, Ti, V and Cr). Consequently, the calculated RCI $1s\ 2s^2\ 2p^6$ ($^2S_{1/2}$) series limits presented here may provide new findings for these K-shell excitations and may guide future theoretical and experimental studies.

3.2 The $1s^22s2p^6(^2S_{1/2})$ np ($^1P_1$) series

Following the determination of the energy thresholds, we investigate the resonance series associated with E1 transitions from the ground state to the $1s^2\ 2s\ 2p^6$ ($^2S_{1/2}$) np ($^1P_1$) excited states of the Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions. For these resonances, we present RCI-calculated resonance energies (E_n), transition rates (A_{fi}^{E1}), weighted oscillator strengths (gf_{ij}), and the quantum defects (δ_n) obtained from Eq. (10) using the corresponding computed RCI series limits. A comparison of our RCI results for the $2s\ 2p^6$ ($^2S_{1/2}$) np Rydberg series with those from Goyal et al. [11] is provided in Tables 2–6 for all five ions. For Ne-like Ca^{10+} ion, Table 2 also includes reference values from the (B-P R-matrix) method [12]. The B-P R-matrix resonance energies for Ca^{10+} ion show excellent agreement with our results for $n = 5 - 15$, with energy differences ranging from 0.08 eV to 0.42 eV. For all five ions, one can see from Tables 2–6 that our RCI-calculated resonance energy values for the $2s\ 2p^6$ ($^2S_{1/2}$) np ($^1P_1$) series agree well with the SCUNC data with energy differences remaining below 1.9 eV. In addition, the RCI and SCUNC resonance energies converge to nearly identical series limits with remarkably small differences of 1.02 eV, 1.53 eV, 1.85 eV, 1.94 eV, and 1.76 eV for Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions, respectively. This close agreement confirms the reliability of the present RCI predictions, particularly for higher states. Based on the preceding comparisons, the absolute uncertainties in the resonance energies are estimated as follows: ± 1.0 eV, ± 1.5 eV, ± 1.9 eV, ± 1.9 eV, and ± 1.8 eV for Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+}, and Cr^{14+} ions, respectively.

Table 2. Calculated Spectroscopic Parameters: Resonance energies (E_n), quantum defects (δ_n), transition rates (A_{fi}^{E1}), and oscillator strengths (gf_{ij}) for $1s^2 2s 2p^6$ np ($^1P_1$) resonances in Ca^{10+}

n	E_n^a (eV)	δ_n^a	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^b (eV)	δ_n^b	E_n^c (eV)
3	460.7453	0.25847	1.2562×10^{12}	4.091×10^{-1}			
4	562.8209	0.24829	5.3983×10^{11}	1.178×10^{-1}			
5	606.9299	0.24636	2.7276×10^{11}	5.119×10^{-2}			607.3513
6	630.0417	0.24705	1.5547×10^{11}	2.708×10^{-2}	630.92	0.255	630.2552
7	643.6609	0.24911	9.6801×10^{10}	1.615×10^{-2}	644.62	0.254	643.8187
8	652.3546	0.25278	6.4248×10^{10}	1.044×10^{-2}	653.37	0.253	652.4828
9	658.2414	0.25812	4.4782×10^{10}	7.146×10^{-3}	659.29	0.252	658.3523
10	662.4117	0.26523	3.2439×10^{10}	5.111×10^{-3}	663.48	0.252	662.5115
11	665.4738	0.27415	2.4241×10^{10}	3.784×10^{-3}	666.55	0.251	665.5660
12	667.7881	0.28511	1.8584×10^{10}	2.881×10^{-3}	668.87	0.251	667.8749
13	669.5799	0.29813	1.4559×10^{10}	2.245×10^{-3}	670.67	0.251	669.6641
14	670.9954	0.31340	1.1618×10^{10}	1.784×10^{-3}	672.09	0.250	671.0763
15	672.1331	0.33103	9.4165×10^{9}	1.441×10^{-3}	673.23	0.250	672.2124
16	673.0612	0.35120	7.7381×10^{9}	9.800×10^{-4}	674.16	0.250	
17	673.8283	0.37391	6.4359×10^{9}	8.223×10^{-4}	674.93	0.250	
18	674.4695	0.39947	5.4102×10^{9}	8.549×10^{-4}	675.57	0.250	
19	675.0110	0.42787	4.5914×10^{9}	6.967×10^{-4}	676.12	0.250	
20	675.4724	0.45936	3.9298×10^{9}	5.955×10^{-4}	676.58	0.250	
21	675.8688	0.49397	3.3895×10^{9}	5.130×10^{-4}	676.98	0.250	
22	676.2118	0.53202	2.9439×10^{9}	4.451×10^{-4}	677.32	0.250	
⋮							
∞	679.7839				680.800		

[a] : Present RCI results.
[b] : SCUNC calculations of Goyal et al. [11].
[c] : B-P R-matrix code calculations of Liang et al. [12].

Table 3. Calculated Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for $1s^2 2s\ 2p^6$ np ($^1P_1$) resonances in Sc^{11+}.

n	E_n^a (eV)	δ_n^a	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^b (eV)	δ_n^b
3	523.5293	0.24269	1.6887×10^{12}	4.260×10^{-1}		
4	643.1629	0.23295	7.2497×10^{11}	1.213×10^{-1}		
5	695.0858	0.23090	3.6641×10^{11}	5.243×10^{-2}		
6	722.3511	0.23136	2.089×10^{11}	2.768×10^{-2}	723.75	0.238
7	738.4419	0.23301	1.3014×10^{11}	1.650×10^{-2}	739.91	0.238
8	748.7241	0.23608	8.6406×10^{10}	1.066×10^{-2}	750.25	0.237
9	755.6920	0.24060	6.0251×10^{10}	7.294×10^{-3}	757.25	0.237
10	760.6314	0.24662	4.3653×10^{10}	5.216×10^{-3}	762.21	0.236
11	764.2599	0.25419	3.2632×10^{10}	3.863×10^{-3}	765.85	0.236
12	767.0035	0.26347	2.5021×10^{10}	2.941×10^{-3}	768.60	0.236
13	769.1282	0.27458	1.9606×10^{10}	2.291×10^{-3}	770.73	0.236
14	770.8072	0.28759	1.5647×10^{10}	1.821×10^{-3}	772.42	0.236
15	772.1571	0.30253	1.2684×10^{10}	1.471×10^{-3}	773.77	0.235
16	773.2585	0.31964	1.0422×10^{10}	1.205×10^{-3}	774.87	0.235
17	774.1689	0.33901	8.6718×10^{9}	1.000×10^{-3}	775.79	0.235
18	774.9301	0.36069	7.2907×10^{9}	8.394×10^{-4}	776.55	0.235
19	775.5730	0.38481	6.1879×10^{9}	7.112×10^{-4}	777.19	0.235
20	776.1209	0.41150	5.2967×10^{9}	6.079×10^{-4}	777.74	0.235
21	776.5916	0.44097	4.5687×10^{9}	5.237×10^{-4}	778.21	0.235
22	776.9990	0.47321	3.9685×10^{9}	4.545×10^{-4}	778.62	0.235
⋮						
∞	781.2269				782.758	

[a] : Present RCI results.
[b] : SCUNC calculations of Goyal et al. [11].

Table 4. Calculated Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for $1s^2 2s\ 2p^6$ np ($^1P_1$) resonances in Ti^{12+}.

n	E_n^a (eV)	δ_n^a	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^b (eV)	δ_n^b
3	590.2818	0.22879	2.2147×10^{12}	4.3945×10^{-1}		
4	728.8120	0.21950	9.4955×10^{11}	1.236×10^{-1}		
5	789.1685	0.21739	4.7996×10^{11}	2.808×10^{-2}		
6	820.9233	0.21769	2.7370×10^{11}	2.708×10^{-2}	822.64	0.223
7	839.6881	0.21902	1.7058×10^{11}	1.673×10^{-2}	841.47	0.224
8	851.6902	0.22162	1.1329×10^{11}	1.080×10^{-2}	853.52	0.223
9	859.8293	0.22549	7.9025×10^{10}	7.390×10^{-3}	861.69	0.223
10	865.6021	0.23064	5.7265×10^{10}	5.284×10^{-3}	867.49	0.223
11	869.8445	0.23717	4.2818×10^{10}	3.913×10^{-3}	871.75	0.223
12	873.0535	0.24513	3.2840×10^{10}	2.979×10^{-3}	874.97	0.223
13	875.5393	0.25469	2.5735×10^{10}	2.321×10^{-3}	877.46	0.223
14	877.5042	0.26585	2.0541×10^{10}	1.844×10^{-3}	879.43	0.223
15	879.0842	0.27871	1.6655×10^{10}	1.490×10^{-3}	881.01	0.222
16	880.3736	0.29342	1.3689×10^{10}	1.221×10^{-3}	882.31	0.223

n	E_n^{a} (eV)	δ_n^{a}	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^{b} (eV)	δ_n^{b}
17	881.4396	0.31003	1.1388×10^{10}	1.013×10^{-3}	883.37	0.223
18	882.3310	0.32863	9.5759×10^{9}	8.504×10^{-4}	884.27	0.223
19	883.0839	0.34939	8.1282×10^{9}	7.206×10^{-4}	885.02	0.223
20	883.7256	0.37239	6.9583×10^{9}	6.160×10^{-4}	885.66	0.223
21	884.2770	0.39768	6.002×10^{9}	5.307×10^{-4}	886.22	0.223
22	884.7542	0.42553	5.2142×10^{9}	4.605×10^{-4}	886.69	0.223
⋮						
∞	889.6942				891.543	

[a] : Present RCI results.
[b] : SCUNC calculations of Goyal et al. [11].

Table 5. Calculated Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for $1s^22s\ 2p^6$ np ($^1P_1$) resonances in V^{13+}

n	E_n^{a} (eV)	δ_n^{a}	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^{b} (eV)	δ_n^{b}
3	661.0276	0.21648	2.8432×10^{12}	4.499×10^{-1}		
4	819.7928	0.20761	1.2174×10^{12}	1.252×10^{-1}		
5	889.2021	0.20549	6.1534×10^{11}	5.381×10^{-2}		
6	925.7824	0.20569	3.5104×10^{11}	2.832×10^{-2}	927.60	0.210
7	947.4239	0.20678	2.1882×10^{11}	1.685×10^{-2}	949.29	0.211
8	961.2773	0.20901	1.4538×10^{11}	1.088×10^{-2}	963.19	0.211
9	970.6776	0.21234	1.0142×10^{11}	7.442×10^{-3}	972.62	0.211
10	977.3480	0.21682	7.3513×10^{10}	5.321×10^{-3}	979.32	0.211
11	982.2519	0.22251	5.4977×10^{10}	3.940×10^{-3}	984.24	0.211
12	985.9625	0.22942	4.2174×10^{10}	2.999×10^{-3}	987.96	0.211
13	988.8376	0.23772	3.3054×10^{10}	2.337×10^{-3}	990.84	0.211
14	991.1106	0.24745	2.6385×10^{10}	1.857×10^{-3}	993.12	0.211
15	992.9387	0.25863	2.1397×10^{10}	1.500×10^{-3}	994.95	0.211
16	994.4308	0.27144	1.7589×10^{10}	1.230×10^{-3}	996.45	0.211
17	995.6646	0.28584	1.4634×10^{10}	1.021×10^{-3}	997.69	0.211
18	996.6964	0.30201	1.2305×10^{10}	8.564×10^{-4}	998.72	0.211
19	997.5679	0.32015	1.0446×10^{10}	7.257×10^{-4}	999.59	0.211
20	998.3109	0.34004	8.9434×10^{9}	6.204×10^{-4}	1000.34	0.211
21	998.9493	0.36205	7.7156×10^{9}	5.346×10^{-4}	1000.98	0.211
22	999.5019	0.38620	6.7026×10^{9}	4.639×10^{-4}	1001.53	0.211
⋮						
∞	1005.2103				1007.146	

[a] : Present RCI results.
[b] : SCUNC calculations of Goyal et al. [11].

Table 6. Calculated Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for $1s^22s\ 2p^6$ np ($^1P_1$) resonances in Cr^{14+}.

n	E_n^{a} (eV)	δ_n^{a}	A_{fi}^{E1} (s^{-1})	gf_{ij}	E_n^{b} (eV)	δ_n^{b}
3	735.7920	0.20550	3.5833×10^{12}	4.576×10^{-1}		
4	916.1298	0.19703	1.5323×10^{12}	1.262×10^{-1}		
5	995.2111	0.19494	7.7450×10^{11}	5.406×10^{-2}		
6	1036.9528	0.19506	4.4200×10^{11}	2.842×10^{-2}	1038.60	0.199
7	1061.6735	0.19597	2.7559×10^{11}	1.690×10^{-2}	1063.35	0.200
8	1077.5096	0.19789	1.8314×10^{11}	1.091×10^{-2}	1079.24	0.200
9	1088.2609	0.20082	1.2779×10^{11}	7.460×10^{-3}	1090.02	0.200
10	1095.8933	0.20475	9.2648×10^{10}	5.333×10^{-3}	1097.68	0.200
11	1101.5063	0.20975	6.9296×10^{10}	3.949×10^{-3}	1103.31	0.200
12	1105.7546	0.21582	5.3168×10^{10}	3.006×10^{-3}	1107.57	0.200
13	1109.0471	0.22310	4.1676×10^{10}	2.343×10^{-3}	1110.87	0.200
14	1111.6506	0.23162	3.3272×10^{10}	1.861×10^{-3}	1113.48	0.200
15	1113.7448	0.24144	2.6984×10^{10}	1.504×10^{-3}	1115.58	0.201
16	1115.4543	0.2527	2.2185×10^{10}	1.233×10^{-3}	1117.29	0.201
17	1116.8680	0.26539	1.8459×10^{10}	1.023×10^{-3}	1118.71	0.201
18	1118.0504	0.27959	1.5523×10^{10}	8.585×10^{-4}	1119.89	0.201
19	1119.0493	0.29544	1.3179×10^{10}	7.256×10^{-4}	1120.89	0.201
20	1119.9008	0.31301	1.1283×10^{10}	6.220×10^{-4}	1121.75	0.201
21	1120.6326	0.33231	9.7348×10^{9}	5.359×10^{-4}	1122.48	0.201
22	1121.2661	0.35346	8.4571×10^{9}	4.651×10^{-4}	1123.11	0.201
⋮						
∞	1127.7993				1129.556	

[a] : Present RCI results.
[b] : SCUNC calculations of Goyal et al. [11].

The quantum defects calculated for Ne-like isoelectronic sequence reveal a noticeable increase with the principal quantum number n. This behavior indicates the growing dominance of the core polarization effect as n increases. In contrast, $\delta_n^{\mathrm{SCUNC}}$ values for all ions exhibit no noticeable change across $n = 6 - 22$. As expected for high-n Rydberg states, the transition rate values for all studied ions drop by at least two orders of magnitude. Meanwhile, the oscillator strength values exhibit an even more pronounced decline of over three orders of magnitude, indicating the reduced overlap associated with the state wavefunctions.

3.3 The $1s2s^22p^6(^2S_{1/2})$ np ($^1P_1$) series

Tables 7-11 present the RCI-calculated resonance parameters for the inner shell 1s → np excitations ($n = 3 - 22$) for Ne-like ions with $10 \leq Z \leq 14$, respectively. It can be seen that the calculated energies demonstrate a clear convergence trend toward their respective series limits with increasing n. In addition, the quantum defect values display minimal variation, with average values of 0.27 for Ca^{10+}, 0.25 for Sc^{11+}, 0.24 for Ti^{12+}, 0.22 for V^{13+}, and 0.21 for Cr^{14+}. The stability of δ_n indicates that the core polarization effect is largely independent of n. Both the transition rates and oscillator strengths follow similar decreasing trend with increasing the principal quantum number. The behavior of the transition rates is in accordance with that of electric dipole-allowed transitions in Rydberg series, whereas the trend of the oscillator strengths can be attributed to the reduced overlap between the initial and final states.

Table 7. Present RCI Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for the $1s2s^22p^6$ ($^2S_{1/2}$) np ($^1P_1$) series in Ca^{10+} ion.

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
3	4075.7419	0.28197	2.1720×10^{13}	9.040×10^{-2}
4	4180.3278	0.26887	8.3378×10^{12}	3.299×10^{-2}
5	4225.1686	0.26459	4.0696×10^{12}	1.576×10^{-2}
6	4248.5758	0.26240	2.2961×10^{12}	8.795×10^{-3}
7	4262.3341	0.26098	1.4173×10^{12}	5.394×10^{-3}
8	4271.1030	0.26015	9.3575×10^{11}	3.546×10^{-3}
9	4277.0341	0.25972	6.4991×10^{11}	2.456×10^{-3}
10	4281.2325	0.25957	4.6963×10^{11}	1.771×10^{-3}
11	4284.3130	0.25966	3.5035×10^{11}	1.320×10^{-3}
12	4286.6401	0.25993	2.6830×10^{11}	1.009×10^{-3}
13	4288.4409	0.26037	2.0998×10^{11}	7.894×10^{-4}
14	4289.8630	0.26093	1.6741×10^{11}	6.289×10^{-4}
15	4291.0057	0.26152	1.3561×10^{11}	5.092×10^{-4}
16	4291.9376	0.26222	1.1139×10^{11}	4.181×10^{-4}
17	4292.7076	0.26295	9.2608×10^{10}	3.475×10^{-4}
18	4293.3511	0.26378	7.7824×10^{10}	2.919×10^{-4}
19	4293.8945	0.26445	6.6026×10^{10}	2.476×10^{-4}
20	4294.3574	0.26525	5.6500×10^{10}	2.118×10^{-4}
21	4294.7550	0.26606	4.8722×10^{10}	1.826×10^{-4}
22	4295.0990	0.26696	4.2308×10^{10}	1.586×10^{-4}
⋮				
∞	4298.5845			

Table 8. Present RCI Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for the $1s2s^22p^6$ ($^2S_{1/2}$) np ($^1P_1$) series in Sc^{11+} ion.

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
3	4532.3767	0.26499	2.7733×10^{13}	9.334×10^{-2}
4	4654.7836	0.25253	1.0695×10^{13}	3.299×10^{-2}
5	4707.5176	0.24839	5.2325×10^{12}	1.632×10^{-2}
6	4735.1112	0.24635	2.9595×10^{12}	9.126×10^{-3}
7	4751.3567	0.24503	1.8287×10^{12}	5.600×10^{-3}
8	4761.7228	0.24425	1.2083×10^{12}	3.684×10^{-3}
9	4768.7402	0.24386	8.3970×10^{11}	2.553×10^{-3}
10	4773.7109	0.24370	6.0710×10^{11}	1.842×10^{-3}
11	4777.3599	0.24379	4.5304×10^{11}	1.372×10^{-3}
12	4780.1176	0.24407	3.4705×10^{11}	1.050×10^{-3}
13	4782.2526	0.24439	2.7170×10^{11}	8.214×10^{-4}
14	4783.9390	0.24488	2.1667×10^{11}	6.546×10^{-4}
15	4785.2944	0.24540	1.7555×10^{11}	5.300×10^{-4}
16	4786.4000	0.24602	1.4422×10^{11}	4.352×10^{-4}
17	4787.3137	0.24666	1.1992×10^{11}	3.618×10^{-4}
18	4788.0775	0.24727	1.0079×10^{11}	3.040×10^{-4}
19	4788.7224	0.24800	8.5524×10^{10}	2.578×10^{-4}
20	4789.2720	0.24856	7.3192×10^{10}	2.206×10^{-4}
21	4789.7441	0.24915	6.3122×10^{10}	1.902×10^{-4}
22	4790.1526	0.24983	5.4818×10^{10}	1.652×10^{-4}
⋮				
∞	4794.2941			

Table 9. Present RCI Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for the $1s2s^22p^6$ ($^2S_{1/2}$) np ($^1P_1$) series in Ti^{12+} ion.

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
3	5013.9358	0.25002	3.4800×10^{13}	9.571×10^{-2}
4	5155.5039	0.23817	1.3474×10^{13}	3.505×10^{-2}
5	5216.7516	0.23420	6.6055×10^{12}	1.678×10^{-2}
6	5248.8680	0.23230	3.7449×10^{12}	9.398×10^{-3}
7	5267.8036	0.23106	2.3161×10^{12}	5.770×10^{-3}

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
8	5279.8982	0.23036	1.5313×10^{12}	3.798×10^{-3}
9	5288.0921	0.22999	1.0647×10^{12}	2.632×10^{-3}
10	5293.8994	0.22987	7.7015×10^{11}	1.900×10^{-3}
11	5298.1646	0.22995	5.7489×10^{11}	1.416×10^{-3}
12	5301.3892	0.23020	4.4050×10^{11}	1.084×10^{-3}
13	5303.8863	0.23054	3.4495×10^{11}	8.478×10^{-4}
14	5305.8594	0.23096	2.7514×10^{11}	6.757×10^{-4}
15	5307.4454	0.23151	2.2298×10^{11}	5.473×10^{-4}
16	5308.7395	0.23206	1.8320×10^{11}	4.494×10^{-4}
17	5309.8091	0.23266	1.5235×10^{11}	3.736×10^{-4}
18	5310.7034	0.23318	1.2806×10^{11}	3.139×10^{-4}
19	5311.4586	0.23377	1.0868×10^{11}	2.663×10^{-4}
20	5312.1022	0.23431	9.3018×10^{10}	2.279×10^{-4}
21	5312.6551	0.23489	8.0228×10^{10}	1.965×10^{-4}
22	5313.1336	0.23547	6.9679×10^{10}	1.707×10^{-4}
⋮				
∞	5317.9877			

Table 10. Present RCI Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for the $1s2s^22p^6$ ($^2S_{1/2}$) np ($^1P_1$) series in V^{13+} ion

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
3	5520.5112	0.23673	4.3008×10^{13}	9.757×10^{-2}
4	5682.5795	0.22547	1.6709×10^{13}	3.577×10^{-2}
5	5752.9610	0.22166	8.2062×10^{12}	1.714×10^{-2}
6	5789.9367	0.2199	4.6630×10^{12}	9.617×10^{-3}
7	5811.7652	0.21874	2.8860×10^{12}	5.907×10^{-3}
8	5825.7200	0.21808	1.9092×10^{12}	3.889×10^{-3}
9	5835.1804	0.21773	1.3282×10^{12}	2.697×10^{-3}
10	5841.8886	0.21763	9.6104×10^{11}	1.947×10^{-3}
11	5846.8176	0.2177	7.1759×10^{11}	1.451×10^{-3}
12	5850.5453	0.21791	5.4996×10^{11}	1.111×10^{-3}
13	5853.4327	0.21823	4.3076×10^{11}	8.692×10^{-4}
14	5855.7148	0.21858	3.4366×10^{11}	6.929×10^{-4}
15	5857.5496	0.21901	2.7854×10^{11}	5.613×10^{-4}
16	5859.0468	0.21953	2.2888×10^{11}	4.610×10^{-4}
17	5860.2846	0.21997	1.9037×10^{11}	3.832×10^{-4}
18	5861.3195	0.22048	1.6004×10^{11}	3.221×10^{-4}
19	5862.1936	0.22098	1.3583×10^{11}	2.733×10^{-4}
20	5862.9386	0.22143	1.1626×10^{11}	2.338×10^{-4}
21	5863.5787	0.22187	1.0029×10^{11}	2.017×10^{-4}
22	5864.1326	0.22249	8.7106×10^{10}	1.751×10^{-4}
⋮				
∞	5869.7555			

Table 11. Present RCI Spectroscopic Parameters: E_n, δ_n, A_{fi}^{E1} and gf_{ij} for the $1s2s^22p^6$ ($^2S_{1/2}$) np ($^1P_1$) series in Cr^{14+} ion.

n	E_n (eV)	δ_n	A_{fi}^{E1} (s^{-1})	gf_{ij}
3	6052.1823	0.22485	5.2439×10^{13}	9.898×10^{-2}
4	6236.0900	0.21414	2.0435×10^{13}	3.633×10^{-2}
5	6316.2251	0.21051	1.0051×10^{13}	1.742×10^{-2}
6	6358.3963	0.20888	5.7238×10^{12}	9.788×10^{-3}
7	6383.3321	0.20721	3.5450×10^{12}	6.015×10^{-3}
8	6399.2671	0.20718	2.3464×10^{12}	3.961×10^{-3}
9	6410.0840	0.20687	1.6329×10^{12}	2.748×10^{-3}
10	6417.7575	0.20679	1.1819×10^{12}	1.984×10^{-3}
11	6423.3979	0.20686	8.8278×10^{11}	1.479×10^{-3}
12	6427.6648	0.20707	6.7668×10^{11}	1.132×10^{-3}
13	6430.9708	0.20733	5.3010×10^{11}	8.862×10^{-4}
14	6433.5841	0.20769	4.2298×10^{11}	7.065×10^{-4}
15	6435.6856	0.20810	3.4291×10^{11}	5.724×10^{-4}
16	6437.4008	0.20851	2.8181×10^{11}	4.702×10^{-4}
17	6438.8188	0.20900	2.3440×10^{11}	3.909×10^{-4}
18	6440.0047	0.20938	1.9708×10^{11}	3.285×10^{-4}
19	6441.0063	0.20988	1.6727×10^{11}	2.788×10^{-4}
20	6441.8601	0.21027	1.4319×10^{11}	2.386×10^{-4}
21	6442.5937	0.21070	1.2352×10^{11}	2.057×10^{-4}
22	6443.2287	0.21108	1.0729×10^{11}	1.787×10^{-4}
⋮				
∞	6449.6768			

To the best of our knowledge, no experimental and/or theoretical data exists for the K-shell excitations of the studied ions. Consequently, the results presented here may provide a valuable benchmark for future studies. In the absence of benchmark data, estimating the uncertainty for these 1s excitations is challenging. We therefore base our uncertainty estimate of approximately ± 2.0 eV on our recent work for neutral neon [14], where the electronic configuration is the same.

4. CONCLUSIONS

The 1s → np and 2s → np resonances for several members of the neon isoelectronic sequence have been investigated using the RCI approach within the FAC code. The RCI calculations show good agreement with available theoretical data, confirming the accuracy and reliability of the present results. This study has reported new data for K-shell transitions to the 1s $2s^2$ $2p^6$ ($^2S_{1/2}$) np ($^1P_1$) excited states in all studied ions, thereby addressing a longstanding gap in the atomic data. The present results constitute important data for advancing spectral modeling of high-resolution X-ray emissions in both astrophysical and laboratory plasmas.

ORCID

O. Abu-Haija, https://orcid.org/0009-0005-4702-8080; **G.A. Alna'washi,** https://orcid.org/0000-0003-2860-7552;
S.M. Hamasha, https://orcid.org/0000-0001-5472-7801; **M.T. Gning,** https://orcid.org/0000-0003-3456-2717;
I. Sakho, https://orcid.org/0000-0003-2983-1396; **M.M. Al Shorman,** https://orcid.org/0009-0005-7760-7681

REFERENCES

[1] H.E. Mason, and B.C. Monsignori-Fossi, Astron. Astrophys. Rev. **6**, 123 (1994). https://doi.org/10.1007/bf01208253
[2] H.P. Summers, Adv. Atom. Mol. Opt. Phys. **33**, 275 (1994). https://doi.org/10.1016/S1049-250X(08)60039-7
[3] P. Beiersdorfor, M.H. Chen, R.E. Marrs, and M.A. Levine, Phys. Rev. A, **41**, 3453 (1990). https://doi.org/10.1103/physreva.41.3453
[4] D.D. Dietrich, A. Simionovici, M.H. Chen, G. Chandler, C.J. Hailey, P.O. Egan, P.H. Mokler, *et al.*, Phys. Rev. A, **41**, 1450 (1990). https://doi.org/10.1103/PhysRevA.41.1450
[5] J. Nilsen, J. Quant. Spectrosc. Radiat. Transf. **47**, 171 (1992). https://doi.org/10.1016/0022-4073(92)90026-Z
[6] J.A. Santana, J.K. Lepson, E. Trabert, and P.Beiersdorfer, Phys. Rev. A, **91**, 012502 (2015). https://doi.org/10.1103/PhysRevA.91.012502
[7] M.C. Simon, M. Schwarz, S.W. Epp, C. Beilmann, B.L. Schmitt, Z. Harman, T.M. Baumann, *et al.*, J. Phys. B: At. Mol. Opt. Phys. **43**, 065003 (2010). https://doi.org/10.1088/0953-4075/43/6/065003
[8] K. Schulz, M. Domke, R. Püttner, A. Gutiérrez, G. Kaindl, G. Miecznik, and C.H. Greene, Phys. Rev. A, **54**, 3095 (1996). https://doi.org/10.1103/PhysRevA.54.3095
[9] L.C. Gao, D.H. Zhang, L.Y. Xie, J.G. Wang, Y.L. Shi, and C.Z. Dong, J. Phys. B, **46**, 175402 (2013). https://doi.org/10.1088/0953-4075/46/17/175402
[10] I. Sakho, J. Electron Spectrosc. & Relat. Phenom. **222**, 40 (2018). https://doi.org/10.1016/j.elspec.2017.09.011
[11] A. Goyal, I. Khatri, M. Sow, I. Sakho, S. Aggarwal, A.K. Singh, and M. Mohan, Rad. Phys. Chem. **125**, 50 (2016). https://doi.org/10.1016/j.radphyschem.2016.03.017
[12] L. Liang, W.-J. Gao., and C. Zhou, Phys. Scr. **87**, 015301 (2013). https://doi.org/10.1088/0031-8949/87/01/015301
[13] M. Nrisimhamurty, G. Aravind, P.C. Deshmukh, and S.T. Manson, Phys. Rev. A, **91**, 13404 (2015). https://doi.org/10.1103/PhysRevA.91.013404
[14] G. A. Alna'washi, S.M. Hamasha, and O. Abu-Haija, Chem. Phys. Impact, **11**, 100926 (2025). https://doi.org/10.1016/j.chphi.2025.100926
[15] G. A. Alna'washi, O. Abu-Haija, and S.M. Hamasha, Phys. Open, **25**, 100317 (2025). https://doi.org/10.2139/ssrn.5744890
[16] G. A. Alna'washi, O. Abu-Haija, and S.M. Hamasha, J. Electron Spectrosc. & Relat. Phenom. **283**, 147574 (2025). https://doi.org/10.1016/j.elspec.2025.147574.
[17] M.F. Gu, Can. J. Phys. **86**, 675 (2008). https://doi.org/10.1139/p07-197
[18] A. Goyal, R. Sharma, A. Singh, and M. Mohan, Can. J. Phys. **95**, 10 (2017). https://doi.org/10.1139/cjp-2016-0812
[19] M.J. Seaton, Rep. Prog. Phys. **46**, 167 (1983). https://doi.org/10.1088/0034-4885/46/2/002
[20] A.E. Kramida, Yu. Ralchenko, and J. Reader, "NIST Atomic Spectra Database, version 5.2, (NIST ASD Team, 2024). https://www.nist.gov/pml/atomic-spectra-database

ДАНІ ФОТОНІЗАЦІЇ РЕЛЯТИВІСТСЬКОЇ КОНФІГУРАЦІЙНОЇ ВЗАЄМОДІЇ ДЛЯ Ne-ПОДІБНОЇ ІЗОЕЛЕКТРОННОЇ ПОСЛІДОВНОСТІ

О. Абу-Хайджа[1], Г.А. Ална'ваші[2], С.М. Хамаша[2], М.Т. Гнінг[3,4], І. Сахо[3,4], М. Аль Шорман[1]

[1]Кафедра прикладної фізики, Технічний університет Тафіли, а/с 179, Тафіла 66110, Йорданія
[2]Кафедра фізики, Факультет природничих наук, Хашимітський університет, а/с 330127, Зарка 13133, Йорданія
[3]Кафедра фізики та хімії, Університет УФР, Університет Іба Дер Тіам, Тієс, Сенегал
[4]Африканський центр прикладних атомних та ядерних технологій (CAFTANA), Дакар, Сенегал

Наведено дані фотоіонізації для основного стану $1s^2$ $2s^2$ $2p^6$ ($^1S_0$) неону, такого як іони Ca^{10+}, Sc^{11+}, Ti^{12+}, V^{13+} та Cr^{14+}. Значення порогових меж іонізації, резонансних енергій, квантових дефектів, швидкостей переходів та сил осциляторів для різних серій Ридберга наведено в таблиці. Для всіх розрахунків було використано підхід релятивістської конфігураційної взаємодії (RCI), реалізований у Гнучкому атомному коді (FAC). Результати RCI для резонансних серій 2s $2p^6$ ($^2S_{1/2}$) np демонструють дуже добру відповідність зі значеннями, наведеними в літературі. Крім того, повідомляється про нові розрахунки фотозбудження K-оболонки (1s $2s^2$ $2p^6$ ($^2S_{1/2}$) np) у цих іонах. Ці результати будуть цінними для високоточного спектрального моделювання в астрофізичній або лабораторній плазмі.

Ключові слова: *фотозбудження; резонансна енергія; серії Ридберга; релятивістська конфігураційна взаємодія*