Canadian Journal of Physics

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Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2018-0335.R1
Manuscript Type:	Article
Date Submitted by the Author:	22-Jun-2018
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Keyword:	MCDHF, energy levels, wavelengths, transition probabilities, line strengths
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Energy levels, wavelengths, transition probabilities and line strengths of Si-like Se ions

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PACS number(s): 31.10.+z, 31.15.ag, 31.30.J-

Abstract

The multi-configuration Dirac-Hartree-Fock (MCDHF) method and the active space approach have been employed to investigate the energy levels, wavelengths, transition probabilities and line strengths of Si-like Se ions. The contributions of Breit interaction (BI), and quantum electrodynamics (QED) correction are taken into consideration. The wavelengths, transition probabilities and line strengths of Si-like Se ions have also been calculated. Compared with other theoretical and experimental values of these parameters, our values are in good agreements with others, and that the number of energy levels we considered is larger than that of any other theoretical calculations.

Key Word: MCDHF, energy levels, wavelengths, transition probabilities, line strengths

1. Introduction

Ions of the silicon isoelectronic sequence have four valence electrons outside a closed $n=2$ core and provide a model for studying the effects of the strong correlation on closely spaced levels in heavy atoms [1]. In order to provide atoms data for atomic data tables, many theoretical and experimental studies have been accomplished for ions of the silicon isoelectronic sequence. And the results of theoretical and experimental studies are important for fundamental physics experiments and that provide data for controlled fusion, industrial applications and space science.

In the experiment, transitions to the $3s^23p^2$ ground configuration from $3s3p^3$ and $3s^23p3d$ were identified in Ge XIX, Se XXI, Sr XXV, Y XXVI and Zr XXVII in the extreme-ultraviolet spectra emitted from linear plasmas that were produced by Ekberg et al. [2] using line-focused laser beams. The measurement of the isoelectronic for Al-like and Si-like intercombination line wavelengths were performed by Bengtsson et al. [3] using the delayed spectroscopy techniques. The lifetime of the $3s^23p^2\ ^3P_2$ level in Si-like Kr and the $3s^23p^2\ ^3P_1 \rightarrow ^3P_2$ transition in Si-like Mo were measured by Träbert et al. [4] using an Electron Beam Ion Trap (EBIT). Later, the electric-dipole (E1) forbidden transitions for Si-like Fe were optically measured by Träbert et al. [5] using a heavy-ion storage ring, observing either near-UV or EUV light. $3s3p^3\ ^5S_2 \rightarrow 3s^23p^2\ ^3P_{1,2}$ transitions for Si-like Rh were investigated by Huang et al. [6] using the techniques of beam foil spectroscopy. In theory, the energy levels and transition probabilities for 27 low-lying levels for transitions in Si-like ions with $Z = 15-106$ were calculated by Huang et al. [7-8] using the MCDF method. Determined transition

parameters for fine structure levels of Si I and Si-like S, Ar, Ca, and Fe were accomplished by Nahar et al. [9-10] using the R-matrix method. Oscillator strengths for $3s^23p^2 \rightarrow 3s^23p3d$ and $3s^23p^2 \rightarrow 3s^23p4s$ transitions in the silicon sequence (from K VI to Xe XLI) were calculated by Charro et al. [11] using the relativistic quantum defect orbital (RQDO) method. Excitation energies, transition probabilities, and lifetimes for Si-like S, Ar, Ca, Ti, Fe, Zn, and Kr were calculated by Kohstall et al. [12] using the MCDF method. The energies of the ground and a number of even and odd parity excited states of silicon isoelectronic sequence were calculated by Vilkas et al. [13-14] through the method of state-averaged. Energy levels, oscillator strengths, and transition probabilities for transitions among the terms belonging to $3s^23p^2$, $3s3p^3$, $3s^23p3d$, $3s^23p4s$, $3s^23p4p$ and $3s^23p4d$ configurations of Si-like P, S, Cl, Ar, K, Zn, Ga, Ge and As were performed by Abou El-Maaref et al. [15-16] using the CIV3 program. The fine structure energy levels, oscillator strengths, line strengths and transition probabilities for Si-like Rb were calculated by Khatri et al. [17] using the MCDF and FAC methods. Energy levels, oscillator strengths, line strengths, and transition probabilities in Si-like ions of La XLIII, Er LIV, Tm LV, and Yb LVI were calculated by Zhan-Bin Chen et al. [18] using the method of MCDF.

Although there are so many theoretical and experimental data [19-23] about Si-like ions, the spectra parameter of Si-like Se ions are scarce to date. Our work are motivated by the need for accurate fine-structure data in a variety of scientific applications, which allowing explanation of the existing results and further predictions. And the spectral data of Si-like ions are useful for high temperature plasma diagnosis, the application of light electronics and lighting as well as for understanding of density fluctuations and elementary processes [24]. In the present work, the spectra parameter (energy levels, wavelengths, line strengths, and transition probabilities) of Si-like Se were performed by using the multi-configuration Dirac-Hartree-Fock (MCDHF) method, in which relativistic effects are considered. We believe that the present results not only extended to complete the void in the existing data and provide many new and accurate data for various transitions, but also be useful for the modeling of laboratory and astrophysical plasmas.

2. Theory

In this work, the grasp2K Package has been used, which is based on the MCDHF theory. As we all know, the MCDHF theory has already been described in detail everywhere [25-30], therefore, we only introduce the essential features here.

2.1 MCDHF method

In the MCDHF approach, the wave function for a state labeled γJ , where γ represents the configuration and any other quantum numbers required to specify the state, is approximated by an expansion over configuration state functions (CSFs),

$$\Psi(\gamma J) = \sum_i c_i \Phi_i(\gamma_i J) \quad (1)$$

Where J is the angular quantum numbers, c_i are the mixing coefficients for the configuration state i , and γ_i represents denotes other appropriate labelling of the configuration state functions, for example parity, orbital occupancy and coupling scheme.

For the CSFs, as $\Phi(\gamma J)$, it is an antisymmetrized linear combination of products of relativistic orbitals. One relativistic orbital can be expressed as,

$$\phi(r) = \frac{1}{r} \begin{pmatrix} P_{n\kappa}(r) \chi_{\kappa m}^{\text{V}}(r) \\ i Q_{n\kappa}(r) \chi_{-\kappa m}^{\text{V}}(r) \end{pmatrix} \quad (2)$$

In Eq. (2), κ is the relativistic spherical symmetry quantum, m is the magnetic quantum number, n is the principal quantum number, $P_{n\kappa}(r)$ and $Q_{n\kappa}(r)$ are the large and small component radial wave functions, and $\chi_{\kappa m}^{\text{V}}(r)$ is the spinor spherical harmonic in the lsj coupling scheme.

These relativistic orbitals above can be generated by using an appropriate Hamiltonian. In the MCDHF calculations for an N electron atom, the Dirac-Coulomb Hamiltonian can be described as,

$$\hat{H}^{DC} = \sum_{i=1}^N \hat{H}_D(i) + \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{1}{|\hat{r}_i - \hat{r}_j|} \quad (3)$$

In Eq. (3), $\hat{r}$ is the distance between the electrons and nuclei. The first term describes the electron kinetic energy and the electron-nucleus interaction. And the second term is the two-body Coulomb interactions between the electrons.

Here, we have

$$\hat{H}_D(i) = c \alpha_i \cdot \hat{p}_i + c^2 (\beta_i - 1) + \frac{V(r_i)}{r_i} \quad (4)$$

Where α_i and β_i are the Dirac matrices, $\hat{p}_i$ is the momentum of the electron, and $V(r_i)$ is the nuclear potential at radius r .

Once the atomic state functions (ASFs) are obtained, transition properties between two atomic states and can be expressed according to the reduced transition matrix element

$$\langle \psi(\gamma P J M_J) \| Q_k^{(\lambda)} \| \psi(\gamma' P' J' M_J') \rangle \quad (5)$$

Here $Q_k^{(\lambda)}$ is the transition operator in Coulomb or Babushkin gauge. The type of multipole transition is designated by superscript λ . The two atomic state wave functions that generate transition are described by two independently optimized orbital sets. In order to calculate transition matrix elements between two atomic state functions, we use biorthogonal transformations [31] to make orbital sets biorthogonal, in which case the evaluation of the matrix element was done with standard Racah algebra techniques.

The equation of transition probabilities is

$$A_{\beta \rightarrow \alpha} = [j_{\beta}]^{-1} \sum_{m_{\alpha}, m_{\beta}} 2\pi |M_{\alpha\beta}|^2 \quad (6)$$

In this equation, β , α are Initial and final states, j_{β} is angular momentum, $M_{\alpha\beta}$ is magnetic moment.

2.2 Relativistic configuration interaction

Once a set of radial orbitals like $P_{n\kappa}(r)$ and $Q_{n\kappa}(r)$ has been obtained by self-consistent field procedure, Relativistic configuration interaction (RCI) calculations can be performed.

Some corrections such as Breit interaction (BI), Quantum Electrodynamics (QED), which include vacuum polarization, self-energy and finite nuclear mass corrections,

have also been accounted for. All the calculations are done in the Relativistic Configuration Interaction (RCI) calculations, where optimization is on a weighted sum of energies. In RCI, the total Hamiltonians may include the transverse photon interaction,

$$H_{Breit} = -\sum_{i<j}^N [\alpha_i \alpha_j \frac{\cos(\omega_{ij} r_{ij}/c)}{r_{ij}} + (\alpha_i \cdot \nabla_i)(\alpha_j \cdot \nabla_j) \frac{\cos(\omega_{ij} r_{ij}/c) - 1}{\omega_{ij}^2 r_{ij}/c^2}] \quad (7)$$

Here, ω_{ij} is the photon frequency, the low frequency limit $\omega_{ij} \rightarrow 0$ usually referred to as the Breit interaction.

3. Generation of configuration expansions

In this work, all the expanded configurations are generated by the way of active space approach, in which we only consider electrons from the active space and these electrons are excited from the occupied orbitals to the unoccupied ones. The CSFs are increased systematically to guarantee the convergence of the atomic parameters calculated as the increase of the orbital layer. Here, we refer to the $\{1s, 2s, 2p, \dots, 3s, 3p, 3d\}$ set of orbitals as the $n=3$ orbital layer and $\{1s, 2s, 2p, \dots, 4s, 4p, 4d, 4f, \dots\}$ as $n=4$, etc. In order to improve the calculations efficiently and ensure the accuracy of calculated values, we have chosen the active space set with the principal quantum number $n=1-7$ and $l=s-f$. For the studies of Si-like Se, a neon-like core and four outer electrons are used. The active space is defined as follows,

$$AS1 = \{3s, 3p, 3d\} \quad (8)$$

Then the active set was increased as follows,

$$AS(i+1) = AS(i) + \{(i+3)s, (i+3)p, (i+3)d, (i+3)f\} \quad (9)$$

Where $i=(0,1,\dots,4)$, and $n=(i+3)$.

In this way, we only consider the valance-valance correlation, we don't consider the core-valance and core-core correlation because it is relatively unimportant for the energy levels and the transition probabilities^[32]. The core electrons are $1s^2 2s^2 2p^6$, the valance electrons are the $3s^2 3p^2$, we divide the reference configuration into even and odd parity in the calculation which are $3s^2 3p^2$ and $3s 3p^3, 3s^2 3p 3d$ configurations.

4. Result and discussion

The energy levels of the fine structure levels of Si-like Se ions have been tabulated in the table I and arranged in ascending order. And which are calculated step-by-step increase of orbital with $n=3, 4, 5, 6, 7$. The energy levels were calculated as functions of increasing active sets with double (SD) excitations. It is obvious that when the active space has been expanded to $n=7$ the energy levels seem to be reasonably converged, and the greatest difference between the results of $n=6$ and $n=7$ calculation is less than 60 cm^{-1} for all the energy levels listed in the table I.

Table I, energy levels in cm^{-1} for lower states in Si-like Se ions as a function of increase active sets of orbitals.

Key	CSF	Term	n=3	n=4	n=5	n=6	n=7	$\left(\frac{E_{n=7} - E_{n=6}}{E_{n=6}} \right) (\%)$
1	$3s^2 3p^2 (3P)$	3P_0	0	0	0	0	0	0

2	3s ² 3p ² (3 2P)	³ P ₁	48330	48626	48685	48718	48725	0.014366
3	3s ² 3p ² (3 2P)	³ P ₂	72132	71751	71760	71772	71774	0.002787
4	3s ² 3p ² (1 2D)	¹ D ₂	143807	142738	142714	142714	142713	-0.000701
5	3s ² 3p ² (1 0S)	¹ S ₀	210056	208079	207886	207758	207733	-0.012035
6	3s3p ³ (4 3S)	⁵ S ₂	400807	403037	403395	403551	403592	0.010159
7	3s3p ³ (2 3D)	³ D ₁	506389	506238	506343	506390	506397	0.001382
8	3s3p ³ (2 3D)	³ D ₂	510279	510323	510458	510510	510520	0.001959
9	3s3p ³ (2 3D)	³ D ₃	529482	529527	529685	529749	529762	0.002454
10	3s3p ³ (2 1P)	³ P ₀	588503	587876	587877	587857	587853	-0.000680
11	3s3p ³ (2 1P)	³ P ₁	594700	594143	594169	594161	594160	-0.000168
12	3s3p ³ (2 1P)	³ P ₂	595542	594991	595052	595071	595074	0.000504
13	3s ² 3p3d	¹ D ₂	649307	648505	648547	648570	648574	0.000617
14	3s3p ³ (4 3S)	³ S ₁	706783	703872	703615	703565	703546	-0.002701
15	3s ² 3p3d	³ F ₂	707952	704937	704855	704896	704909	0.001844
16	3s ² 3p3d	³ F ₃	731678	728616	728502	728533	728544	0.001510
17	3s ² 3p3d	³ P ₂	794893	791015	790598	790591	790590	-0.000126
18	3s ² 3p3d	³ D ₂	845851	841419	841045	841051	841055	0.000476
19	3s ² 3p3d	³ P ₀	849689	846193	845859	845887	845895	0.000946
20	3s ² 3p3d	³ D ₃	857571	852707	852285	852304	852312	0.000939
21	3s ² 3p3d	³ P ₁	858651	854578	854210	854235	854243	0.000937
22	3s ² 3p3d	¹ F ₃	930709	924633	923918	923900	923897	-0.000325
23	3s ² 3p3d	¹ P ₁	957450	951425	950434	950338	950307	-0.003262
24	3p ⁴	³ P ₂	1014027	1014661	1015081	1015148	1015172	0.002364
25	3s3p ² (3 2P)3d	⁵ F ₁	1043975	1045533	1046101	1046318	1046377	0.005639

In table II, our data for energy levels of Si-like Se ions were compared with the results of NIST [33] and The values of previous calculations presented by Huang et al.[7], regrettably, There is only a small part of the experimental value, This may result in the incorrect order of some of the levels, leaving scope for future amendments[34]. “E” in the table II represent the energy levels calculated when the orbital layer increase to n=7, which was converged. As for the energies of configuration of 3s²3p², we found that from the comparison all the energy levels calculated are close to the values of NIST[33], and the energy levels calculated in this work are more closer to the value of NIST than that were calculated by Huang [7]. For the lower excitation states, the discrepancies of energy levels for lower excited states calculated are within 1% of previous values by Huang[7], except the levels of 3s3p³(4 3S) ³S₁ and 3s²3p3d ³P₁, the difference are about 5%-10%, such differences may be due to the spectrum term is wrong in Huang[15]for the same configuration with the same total angular momentum *J*, which is also pointed out by Khatri et al.[35]. Other lower excited states of 3p⁴, 3s3p²3d, 3p³3d are also calculated and listed in Table II. For these excited states, there are no other theoretical results so far. Which can supplement the atom databases of Si-like Se ions.

In the present calculations, the contributions of Breit interactions and quantum electrodynamics correction are considered. In order to evaluate the BI plus QED effects on the energy levels calculated of Si-like Se ions, the contributions of BI plus

QED effects to the energy level is reflected in Fig. I, we can see that the final calculation changes the energy levels materially as take BI and QED effects into consider in RCI computations, for all the levels list in the table II, the BI plus QED corrections decrease the energy levels by about 0.5%-2.0%, which indicate that the importance of including the relativistic effects for the Si-like Se ions.

Table II, Comparison of the energy levels calculated with other available experimental and theoretical values in Si-like Se ions. $\text{Diff.1} = \frac{|E - \text{Ref.}|}{\text{Ref.}} (\%)$; $\text{Diff.2} = \frac{|E - \text{Exp.}|}{\text{Exp.}} (\%)$; $\text{Diff.3} = \frac{|\text{Ref.} - \text{Exp.}|}{\text{Ref.}} (\%)$, are a relative percentage deviation,

BI+QED represent the Contribution of BI+QED correction to the energy levels.

Key	CSF	Term	E	BI+QED	Refer. ^[7]	Exp. ^[33]	Diff1(%)	Diff.2(%)	Diff.3(%)
1	3s ² 3p ² (3 2P)	³ P ₀	0	0	0	0	0	0	0
2	3s ² 3p ² (3 2P)	³ P ₁	48725	-1137	48507	48956	0.449	0.472	0.917
3	3s ² 3p ² (3 2P)	³ P ₂	71774	-1531	72315	71695	-0.748	-0.110	-0.865
4	3s ² 3p ² (1 2D)	¹ D ₂	142713	-2466	143765	142480	-0.732	-0.164	-0.902
5	3s ² 3p ² (1 0S)	¹ S ₀	207733	-2199	209947	205300	-1.055	-1.185	-2.264
6	3s3p ³ (4 3S)	⁵ S ₂	403592	-2298	402419		0.291		
7	3s3p ³ (2 3D)	³ D ₁	506397	-2017	508127		-0.340		
8	3s3p ³ (2 3D)	³ D ₂	510520	-2413	512124		-0.313		
9	3s3p ³ (2 3D)	³ D ₃	529762	-3250	531188		-0.268		
10	3s3p ³ (2 1P)	³ P ₀	587853	-2619	589871		-0.342		
11	3s3p ³ (2 1P)	³ P ₁	594160	-2955	596249		-0.350		
12	3s3p ³ (2 1P)	³ P ₂	595074	-3114	597314		-0.375		
13	3s ² 3p3d	¹ D ₂	648574	-3840	650990		-0.371		
14	3s3p ³ (4 3S)	³ S ₁	703546	-2371	782123		-10.047		
15	3s ² 3p3d	³ F ₂	704909	-3057	709321		-0.622		
16	3s ² 3p3d	³ F ₃	728544	-3816	733193		-0.634		
17	3s ² 3p3d	³ P ₂	790590	-3185	795847		-0.661		
18	3s ² 3p3d	³ D ₂	841055	-3773	846807		-0.679		
19	3s ² 3p3d	³ P ₀	845895	-3631	849992		-0.482		
20	3s ² 3p3d	³ D ₃	852312	-4379	858381	843900	-0.707	0.985	1.716
21	3s ² 3p3d	³ P ₁	854243	-3951	808979		5.595		
22	3s ² 3p3d	¹ F ₃	923897	-4442	931194		-0.784		
23	3p ⁴	³ P ₂	1015172	-3393					
24	3s3p ² (3 2P)3d	⁵ F ₁	1046377	-3297					
25	3s3p ² (3 2P)3d	⁵ F ₂	1056070	-3691					
26	3s3p ² (3 2P)3d	⁵ F ₃	1070845	-4306					
27	3p ⁴	¹ D ₂	1088180	-4538					
28	3s3p ² (3 2P)3d	⁵ D ₀	1101781	-4013					
29	3s3p ² (3 2P)3d	⁵ D ₁	1105130	-4305					
30	3s3p ² (3 2P)3d	⁵ D ₂	1106567	-4443					
31	3s3p ² (3 2P)3d	⁵ D ₃	1109219	-4698					
32	3s3p ² (1 2D)3d	³ F ₃	1155693	-5257					
33	3s3p ² (3 2P)3d	⁵ P ₃	1181308	-5112					
34	3s3p ² (3 2P)3d	⁵ P ₁	1196720	-4616					
35	3p ⁴	³ P ₂	1232825	-4589					

36	3s3p ² (3 2P)3d	³ D ₁	1276380	-4775
37	3s3p ² (1 2D)3d	³ D ₁	1310673	-4405
38	3p ³ (2 3D)3d	³ F ₂	1634040	-4856
39	3p ³ (2 3D)3d	¹ S ₀	1646941	-5321
40	3p ³ (2 3D)3d	³ F ₃	1647029	-5449
41	3p ³ (4 3S)3d	⁵ D ₁	1666088	-4928
42	3p ³ (2 3D)3d	³ D ₂	1672003	-5785
43	3p ³ (4 3S)3d	⁵ D ₀	1673043	-5455
44	3p ³ (2 3D)3d	³ D ₁	1679729	-5916
45	3p ³ (2 1P)3d	³ D ₁	1759928	-5321

Fig. 1. BI and QED contributions to the excited energy levels for Si-like Se ions. All energies are relative to the ground state.

Wavelengths, transition probabilities, line strengths for E1 transitions of the Si-like Se ions were calculated and listed in Table III, and other theoretical results [7] were also displayed to illustrate the accuracy of the calculated results, due to the length form is more stable than the velocity form, so we only show the calculated results in length gauge. As from the table III, for the wavelengths, transition probabilities, line strengths we can see that the difference is less than 0.8% between the results present calculated and the values of Huang et al. [7] for all the E1 transitions except for the transitions that involve 3s3p³(4 3S) ³S₁, 3s²3p3d ³P₁, and the difference are about 10%-15%, and the maximum difference of line strengths is about 38%, which due to the difference of energy levels above are large. Since the experimental measurements of compiled data by NIST are not available, the comparison will be limited only to the energy levels.

Table III. Wavelengths, transition probabilities, line strengths for E1 transitions of the Si-like Se ions.

Lower state	Upper state	$\lambda(\text{\AA})$			$A(s^{-1})$		$S(a.u.)$	
		MCDHF	Ref.[7]	Exp.[2]	MCDHF	Ref.[7]	MCDHF	Ref.[7]
3s ² 3p ² (3 2P) ³ P ₀	3s3p ³ (2 3D) ³ D ₁	197.47	196.80	197.26	5.369E+09	5.316E+09	6.122E-02	5.999E-02
3s ² 3p ² (3 2P) ³ P ₀	3s3p ³ (2 1P) ³ P ₁	168.30	167.71	168.54	2.806E+09	2.805E+09	1.981E-02	1.959E-02

$3s^23p^2(3$	$3s3p^3(4\ 3S)$	142.14	127.86	143.39	1.524E+10	1.099E+10	6.480E-02	3.400E-02
$2P)^3P_0$	3S_1							
$3s^23p^2(3$	$3s^23p3d\ ^3P_1$	117.06	123.61		5.788E+08	9.333E+10	1.375E-03	2.610E-01
$2P)^3P_0$								
$3s^23p^2(3$	$3s^23p3d\ ^1P_1$	105.23	104.42		1.338E+09	1.414E+09	2.308E-03	2.385E-03
$2P)^3P_0$								
$3s^23p^2(3$	$3s3p^3(2\ 1P)$	185.48	184.72		1.047E+10	1.025E+10	3.297E-02	3.188E-02
$2P)^3P_1$	3P_0							
$3s^23p^2(3$	$3s^23p3d\ ^3P_0$	125.44	124.77	126.15	8.912E+10	8.962E+10	8.683E-02	8.591E-02
$2P)^3P_1$								
$3s^23p^2(3$	$3s3p^3(2\ 3D)$	218.50	217.57	218.36	1.116E+08	1.085E+08	1.723E-03	1.654E-03
$2P)^3P_1$	3D_1							
$3s^23p^2(3$	$3s3p^3(2\ 1P)$	183.34	182.57	183.71	7.970E+09	7.953E+09	7.273E-02	7.166E-02
$2P)^3P_1$	3P_1							
$3s^23p^2(3$	$3s3p^3(4\ 3S)$	152.71	136.31	154.23	2.613E+10	1.830E+10	1.378E-01	6.864E-02
$2P)^3P_1$	3S_1							
$3s^23p^2(3$	$3s^23p3d\ ^3P_1$	124.14	131.49	124.95	5.755E+10	1.946E+10	1.630E-01	6.551E-02
$2P)^3P_1$								
$3s^23p^2(3$	$3s^23p3d\ ^1P_1$	110.92	109.99		9.206E+08	9.663E+10	1.860E-03	1.904E-03
$2P)^3P_1$								
$3s^23p^2(3$	$3s3p^3(4\ 3S)$	281.80	282.56		1.357E+08	1.308E+08	7.493E-03	7.284E-03
$2P)^3P_1$	5S_2							
$3s^23p^2(3$	$3s3p^3(2\ 3D)$	216.55	215.70	216.71	3.833E+09	3.791E+09	9.606E-02	9.388E-02
$2P)^3P_1$	3D_2							
$3s^23p^2(3$	$3s3p^3(2\ 1P)$	183.03	182.21		4.786E+07	5.421E+07	7.242E-04	8.094E-04
$2P)^3P_1$	3P_2							
$3s^23p^2(3$	$3s^23p3d\ ^1D_2$	166.71	165.98		5.090E+08	4.900E+08	5.820E-03	5.529E-03
$2P)^3P_1$								
$3s^23p^2(3$	$3s^23p3d\ ^3F_2$	152.40	151.33		1.284E+09	1.265E+09	1.122E-02	1.082E-02
$2P)^3P_1$								
$3s^23p^2(3$	$3s^23p3d\ ^3P_2$	134.80	133.81	135.77	5.007E+10	5.096E+10	3.026E-01	3.013E-01
$2P)^3P_1$								
$3s^23p^2(3$	$3s^23p3d\ ^3D_2$	126.21	125.27	127.21	4.728E+10	4.888E+10	2.346E-01	2.371E-01
$2P)^3P_1$								
$3s^23p^2(3$	$3s3p^3(2$	230.08	229.46		2.463E+08	2.469E+08	4.441E-03	4.417E-03
$2P)^3P_2$	$3D)^3D_1$							
$3s^23p^2(3$	$3s3p^3(2\ 1P)$	191.43	190.86		8.144E+08	7.525E+08	8.459E-03	7.747E-03
$2P)^3P_2$	3P_1							
$3s^23p^2(3$	$3s3p^3(4\ 3S)$	158.28	140.88	159.84	6.681E+10	2.175E+08	3.923E-01	9.007E-04
$2P)^3P_2$	3S_1							
$3s^23p^2(3$	$3s^23p3d\ ^3P_1$	127.80	135.75	128.61	2.428E+10	3.390E+09	7.505E-02	1.256E-02
$2P)^3P_2$								
$3s^23p^2(3$	$3s^23p3d\ ^1P_1$	113.83	112.94		2.877E+07	1.938E+03	6.283E-05	4.134E-09
$2P)^3P_2$								

3s ² 3p ² (3 2P) ³ P ₂	3s3p ³ (4 3S) ⁵ S ₂	301.37	302.94		1.157E+08	1.122E+08	7.812E-03	7.697E-03
3s ² 3p ² (3 2P) ³ P ₂	3s3p ³ (2 3D) ³ D ₂	227.92	227.37		3.982E+07	3.966E+07	1.163E-03	1.150E-03
3s ² 3p ² (3 2P) ³ P ₂	3s3p ³ (2 1P) ³ P ₂	191.09	190.48		8.930E+09	8.846E+09	1.538E-01	1.509E-01
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ¹ D ₂	173.37	172.81		1.922E+06	1.139E+06	2.471E-05	1.451E-05
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ³ F ₂	157.94	156.98		2.493E+09	2.484E+09	2.424E-02	2.371E-02
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ³ P ₂	139.12	138.21	140.10	3.258E+10	3.251E+10	2.164E-01	2.118E-01
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ³ D ₂	129.99	129.12	131.00	5.023E+10	4.996E+10	2.723E-01	2.654E-01
3s ² 3p ² (3 2P) ³ P ₂	3s3p ³ (2 3D) ³ D ₃	218.35	217.93		2.222E+09	2.230E+09	7.990E-02	7.973E-02
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ³ F ₃	152.26	151.31		3.612E+09	3.576E+09	4.405E-02	4.281E-02
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ³ D ₃	128.12	127.22	128.97	9.980E+10	1.023E+11	7.251E-01	7.277E-01
3s ² 3p ² (3 2P) ³ P ₂	3s ² 3p3d ¹ F ₃	117.35	116.43	118.29	1.931E+10	1.823E+10	1.078E-01	9.940E-02
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (2 3D) ³ D ₁	274.96	274.45		2.226E+08	2.237E+08	6.850E-03	6.848E-03
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (2 1P) ³ P ₁	221.51	221.00		5.740E+07	5.077E+07	9.237E-04	8.115E-04
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (4 3S) ³ S ₁	178.31	156.65		1.247E+07	5.460E+10	1.047E-04	3.108E-01
3s ² 3p ² (1 2D) ¹ D ₂	3s ² 3p3d ³ P ₁	140.54	150.33	141.47	1.830E+10	6.396E+09	7.523E-02	3.217E-02
3s ² 3p ² (1 2D) ¹ D ₂	3s ² 3p3d ¹ P ₁	123.82	122.86	124.87	1.084E+09	6.730E+08	3.047E-03	1.848E-03
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (4 3S) ⁵ S ₂	383.32	386.62		8.145E+06	7.192E+06	1.132E-03	1.026E-03
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (2 3D) ³ D ₂	271.88	271.47		4.062E+07	4.292E+07	2.014E-03	2.119E-03
3s ² 3p ² (1 2D) ¹ D ₂	3s3p ³ (2 1P) ³ P ₂	221.06	220.48		2.768E+08	3.251E+08	7.380E-03	8.600E-03
3s ² 3p ² (1 2D) ¹ D ₂	3s ² 3p3d ¹ D ₂	197.68	197.15		7.153E+09	7.187E+09	1.364E-01	1.359E-01
3s ² 3p ² (1 2D) ¹ D ₂	3s ² 3p3d ³ F ₂	177.87	176.82		2.374E+09	2.470E+09	3.297E-02	3.370E-02
3s ² 3p ² (1 2D) ¹ D ₂	3s ² 3p3d ³ P ₂	154.35	153.37	155.50	6.919E+09	7.235E+09	6.278E-02	6.440E-02

$3s^23p^2(1$	$3s^23p3d\ ^3D_2$	143.20	142.24	144.37	2.644E+10	2.720E+10	1.916E-01	1.932E-01
$2D)^1D_2$								
$3s^23p^2(1$	$3s3p^3(2$	258.37	258.12		8.096E+08	7.693E+08	4.824E-02	4.571E-02
$2D)^1D_2$	$3D)^3D_3$							
$3s^23p^2(1$	$3s^23p3d\ ^3F_3$	170.70	169.66		2.975E+06	1.498E+06	5.113E-05	2.527E-05
$2D)^1D_2$								
$3s^23p^2(1$	$3s^23p3d\ ^3D_3$	140.92	139.94	141.90	1.347E+10	1.295E+10	1.302E-01	1.226E-01
$2D)^1D_2$								
$3s^23p^2(1$	$3s^23p3d\ ^1F_3$	128.01	127.00	129.08	9.734E+10	9.991E+10	7.054E-01	7.070E-01
$2D)^1D_2$								
$3s^23p^2(1$	$3s3p^3(2$	334.82	335.37		1.953E+07	1.736E+07	1.085E-03	9.698E-04
$0S)^1S_0$	$3D)^3D_1$							
$3s^23p^2(1$	$3s3p^3(2\ 1P)^3P_1$	258.78	258.86		1.985E+08	1.963E+08	5.092E-03	5.041E-03
$0S)^1S_0$								
$3s^23p^2(1$	$3s3p^3(4\ 3S)$	201.69	174.77	203.83	1.136E+09	8.966E+09	1.380E-02	7.087E-02
$0S)^1S_0$	3S_1							
$3s^23p^2(1$	$3s^23p3d\ ^3P_1$	154.68	166.94		7.441E+07	2.558E+07	4.077E-04	1.762E-04
$0S)^1S_0$								
$3s^23p^2(1$	$3s^23p3d\ ^1P_1$	134.67	133.73	135.77	9.611E+10	9.719E+10	3.475E-01	3.442E-01
$0S)^1S_0$								

5. Conclusions

In this work, the energy levels, transition probabilities and line strengths for transitions between the levels belonging to $3s^23p^2$, $3s3p^3$, $3s^23p3d$, $3s3p^23d$, $3p^4$ and $3p^33d$ configurations of Si-like Se ions. The results of calculations of energy levels show good agreement with the experimental data and other theoretical calculations, also wavelengths, transition probabilities and line strengths we calculated. In conclusion, we have achieved some new and previously unpublished energy levels, transition probabilities and line strengths for the Si-like Se ions. The calculations of this work not only provide many additional and accurate data, but also might be useful in thermonuclear fusion research and astrophysical plasmas.

6. Acknowledgements

The authors wish to thank P. Jönsson for providing the GRASP2K package for free. This work was supported by the Anhui Province Natural Science Foundation of China. (Grant Nos. KJ2018A0588)

Reference

- [1] F. Hu, J. Yang, C. Wang, et al. Phys. Rev. A, 84, 1460(2011)
- [2] L. Sturesson, P. Jönsson, and C.F. Fischer. Comput. Phys. Commun. 177, 539(2007).
- [3] P. Bengtsson, K. Ando, T. Kambara, Y. Awaya, R. Hutton, Phys. Scr. T73, 81 (1997)
- [4] E. Träbert, P. Beiersdorfer, S.B. Utter, J.R. Crespo López-Urrutia, Phys. Scr. 58, 599. (1998)
- [5] E. Träbert, A.G. Calamai, G. Gwinner, et al. J. Phys. B 36, 1129 (2003).
- [6] M. Huang, R. Hutton, et al. Methods Phys. Res. B 205, 119 (2003)
- [7] K. Huang, At. Data Nucl. Data Tables 32, 503 (1985).
- [8] K. Huang, Nucl. Instrum. Methods Phys. Res. B 9, 498 (1985)
- [9] S.N. Nahar, A.K. Pradhan, J. Phys. B 26, 1109 (1993).

- [10] S.N. Nahar, Phys. Scr. 48, 297 (1993).
- [11] E. Charro, I. Martin, C. Lavin, Astron. Astrophys. Suppl. Ser. 124, 397 (1997).
- [12] C. Kohstall, S. Fritzsche, B. Fricke, W.D. Sepp, At. Data Nucl. Data Tables 70, 63 (1998).
- [13] M.J. Vilkas, Y. Ishikawa, J. Phys. B 37, 1803 (2004).
- [14] M.J. Vilkas, Y. Ishikawa¹, E. Träbert, J. Phys. B 39, 2195 (2006).
- [15] A. Abou El-Maaref, et al. At. Data Nucl. Data Tables 98, 589 (2012).
- [16] A. Abou El-Maaref, et al. At. Data Nucl. Data Tables 100, 155 (2014).
- [17] I. Khatri, A. Goyalal, S. Aggarwal, A.K. Singhb, M. Mohana, Chin. Phys. B 24, 103202 (2015).
- [18] Z B Chen, K Ma, H J Wang, et al. Atomic Data & Nuclear Data Tables, 113,258 (2017).
- [19] E. Landi, A.K. Bhatia, Astrophys. J. 589, 1075 (2003).
- [20] S.S. Tayal, Astrophys. J. Suppl. Ser. 146 459 (2003).
- [21] A.G. Trigueiros, et al. Quant. Spectrosc. Radiat. Transfer 97, 29 (2006).
- [22] C.F. Fischer, G. Tachiev, A. Irimia, At. Data Nucl. Data Tables 92, 607 (2006).
- [23] G.P. Gupta, A.Z. Msezane, Phys. Scr. 86, 015303 (2012).
- [24] D.A. Liedahl, P. Beiersdorfer, et al. Laboratory Space Science Workshop (1–3 April), NASA, Washington, p. 85. (1998)
- [25] I.P. Grant. Springer Science & Business Media, New York. 2007.
- [26] P. Jönsson, X. He, C.F. Fischer, and I.P. Grant. Comput. Phys. Commun. 177, 597 (2007).
- [27] I.P. Grant. Comput. Phys. Commun. 84, 59 (1994).
- [28] L. Sturesson, P. Jönsson, and C.F. Fischer. Comput. Phys. Commun. 177, 539(2007).
- [29] F. Peng, S. Song, and G. Jiang. Phys. Scr. 76, 501 (2007).
- [30] F. Hu, G. Jiang, W. Hong, and L.H. Hao. Eur. Phys. J. D, 49, 293 (2008).
- [31] J. Olsen, M.R. Godefroid, P. Jönsson, P.Å. Malmqvist, and C.F. Fischer. Phys.Rev. E, 52, 4499 (1995).
- [32] M Wu, G Bian, X F Li, et al. Canadian Journal of Physics, 94, 359(2015).
- [33] <https://physics.nist.gov/cgi-bin/ASD/energy1.pl>
- [34] K.M. Aggarwal, Astrophys. J. Suppl. Series 118 (1998) 589
- [35] K.M. Aggarwal, F.P. Keenan, A.Z. Msezane, Astron. Astrophys. 401, 377 (2003)