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Fine Structure Calculation of Energy Levels, Oscillator Strengths and Lifetimes in Se-Like Ions

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Abstract*— Energies of 23 fine-structure levels as well as wavelengths, oscillator strengths and transition probabilities for 33 forbidden transitions (E_2) among the fine-structure levels of the terms belonging to the $4s^2\,4p^4$, $4s\,4p^4\,4d$ and $4s^2\,4p^3\,4f$ configurations for Br II, Sb XVIII and Te XIX, are calculated using extensive configuration-interaction wave functions. The fully relativistic Multiconfiguration Dirac-Fock (MCDF) method taking into account effects in intermediate coupling are incorporated by means of the Breit-Pauli Hamiltonian. Our calculated energy levels are compared with the results of HFR and the available measurements.

***Key words*— Multiconfiguration Dirac-Fock method; energy levels; wavelengths; transition probabilities; collision strengths; lifetimes**

I. INTRODUCTION

The extreme-ultraviolet (EUV) **Br II**, **Sb XVIII** and **Te XIX** lines are useful for electron density diagnostic in the solar atmosphere [1]. The studies of the spectra of sulfur, being one of the most abundant elements in the universe, yield astrophysically interesting quantities [2]. Accurate atomic data such as absorption oscillator strengths and transition probabilities in Se I are required for solar and stellar abundance calculations [3]. Measure the lifetime for the 23 fine-structure levels belonging to the $4s^2 4p^4$, $4s\,4p^4\,4d$ and $4s^2\,4p^3\,4f$ configurations. They also calculated the lifetimes for these levels in a superposition-of-configurations method [4] calculated the oscillator strengths and transition probabilities for some $^3P_{2,1,0}$, $^1D_2$, $^1S_0$ states for $4s^2 4p^4$ and $^1D_2$, $^1P_1$, $^3D_{1,2}$, $^5P_1$, $^3F_{4,3,2}$, $^1F_3$, $^1G_4$ and $^1P_1$ states for $4s\,4p^4\,4d$ and $^3P_{2,1,0}$, $^3F_{4,3,2}$, $^1P_1$, $^1D_2$, $^3D_{1,3}$ and $^3G_3$ states for $4s^2\,4p^3\,4f$ transitions and the lifetimes of the **Se I** is electronic sequence, using the multiconfigurational Hartree-Fock method [5].

The determination of the ionization balance for a given plasma temperature is especially sensitive to the values of the excitation cross sections used to correlate the intensity of a given line to the abundance of the corresponding ion species. Knowing the correct charge state distribution is critical for understanding radiation levels, energy deposition and energy balance of high temperature plasmas [6].

In this study, energy levels, radiative rates and electron impact excitation for fine structure levels of **Br II**, **Sb XVIII** and **Te XIX.** ions are calculated using mcdfgme [7] code (**M**ulti-**C**onfiguration **D**irac-**F**ock and **G**eneral **M**atrix **E**lements). The MCDF calculations were completed with the inclusion of the relativistic two body Breit interaction and the quantum electrodynamics corrections (QED) which arise due to self-energy and vacuum polarization.

Atomic collision processes are important in many fundamental and applied areas of current research [8].

II. METHOD OF CALCULATION

Atomic state wave functions are represented by the J-dependent CI expansions of the form [9].

$$\psi_i(JM_j) = \sum_{j=1}^{K} b_{ij}\phi_j(\alpha_j L_j S_j JM_j), \qquad (1)$$

Where each of the K single-configuration functions ϕ_j is constructed from one-electron functions, and α_j defines the coupling of the orbital L_j and the spin S_j angular momenta to give the total angular momentum J. The mixing coefficients b_{ij} are obtained by diagonalizing the Breit-Pauli Hamiltonian with respect to the basis function ψ_i.

The Breit-Pauli Hamiltonian here consists of the nonrelativistic term plus the one-body mass correction, Darwin term, and spin-orbit, spin-other-orbit, and spin-spin operators. The inclusion of mass correction, Darwin, and spin-spin terms shift the energy of a configuration as a whole, while the spin-orbit and spin-other-orbit terms cause the fine-structure splitting. The radial parts of the one-electron functions are expressed in analytic forms as a sum of Slater-type orbitals

$$P_{nl} = \sum_{i=1}^{K} C_i \left[(2\zeta_i)^{2P_i+1}/(2p_i)!\right]^{\frac{1}{2}} r^{p_i}\exp(-\zeta_i r), \qquad (2)$$

Where n and l, respectively, are the principal and orbital quantum numbers. The parameters C_i, ζ_i, and p_i in equation (2) are the expansion coefficients, exponents, and powers of r, respectively, and are determined variationally [10].

The wave functions given by equation (1) are then used to calculate the excitation energies of the fine-structure levels, length and velocity forms of oscillator strengths, and transition probabilities among the fine-structure levels. The radiative lifetime τ_i of an excited state is calculated from radiative transition probabilities using the relation

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$$\tau_i = 1/\sum_i A_{ji} \qquad (3)$$

Where A_{ji} is the transition probability?

The wavelengths, transition probabilities for the $4s^2 4p^4$ - $4s\,4p^4 4d$ and $4s^2 4p^4$ - $4s\,4p^3 4f$ forbidden transitions were calculated using the fully relativistic MCDF method are reported in tables (4-6). The calculated MCDF transition probabilities are presented in both length and –velocity gauges, while the oscillator strengths are only shown in length gauge. Exceptions to this are some few transitions; where the agreement. Not only is this overall good agreement highly satisfactory, but it also gives a clear indication of the accuracy of the results. Tables (4-6) present the oscillator strengths (f_L) and the transition probabilities (A) for transitions among n = 4 levels of **Br II**, **Sb XVIII** and **Te XIX** ions**.**

We present in table (7) a comparison between the MCDF, and HFR transition wavelengths (in Å) for the relevant transitions and oscillator strengths.

III. RESULTS AND DISCUSSIONS

Extensive sets of fine structure energy levels and oscillator strengths and transition probabilities for the bound-bound transitions are obtained for some members of Se like ions: **Br II**, **Sb XVIII** and **Te XIX**. The energy levels and bound-bound transitions are discussed separately in the following two sections.

A.FINE STRUCTURE IN ENERGY LEVELS

A total of about 23 fine structure energy levels are obtained for some members of Se-like ions where all levels have been identified. The number of levels obtained far exceed the observed or previously calculated ones. The energy level values obtained using the MCDF and HFR method for the $4s^2\,4p^4$, $4s\,4p^4\,4d$ and $4s^2\,4p^3\,4f$ forbidden transitions in Se -like ions are presented in tables (1- 3). In these tables we present our calculated energies compared with measurements. In general the calculated energies of **Br II**, **Sb XVIII** and Te **XIX** ions are agreeable with the measured values. The tables contain some sets of levels of **Br II**, **Sb XVIII** and **Te XIX** ions. Tables 1-3 show that the agreement between MCDF and HFR energy levels in our members of Se-like ions. Multipliers can be especially confusing.

B. WAVELENGTHS AND TRANSITION PROBABILITIES, OSCILLATOR STRENGTHS

C. RADIATIVE LIFETIMES

The radiative lifetime of an excited state is calculated from radiative transition probability A_{ji} using the relation (3).In tables (8-10), we present the calculated MCDF and HFR radiative lifetime (in sec) of **$4s^2 4p^4$ - $4s\,4p^4 4d$** and **$4s^2 4p^4$ - $4s\,4p^3 4f$.**

Table (1): MCDF and HFR energy levels (in cm^{-1}) of $4s^2 4p^4$,$4s\,4p^4 4d$ and $4s^2 4p^3 4f$ configuration for Br II ion.

	Configuration	J	LS	MCDF (cm^{-1})	HFR (cm^{-1})	Exp (cm^{-1})
1	$4s^2 4p^4$	2	$^3P_2{}^e$	0	0	0
2	$4s^2 4p^4$	1	$^3P_1{}^e$	3080	2966	3 136.4
3	$4s^2 4p^4$	0	$^3P_0{}^e$	3890	3692	3 837.5
4	$4s^2 4p^4$	2	$^1D_2{}^e$	12510	12121	12 089.1
5	$4s^2 4p^4$	0	$^1S_0{}^e$	27900	27735	27 867.1
6	$4s\,4p^4 4d$	2	$^1D_2{}^e$	254370	254998	……….
7	$4s\,4p^4 4d$	1	$^1P_1{}^e$	253770	254279	……….
8	$4s\,4p^4 4d$	4	$^1G_4{}^e$	250080	251032	……….
9	$4s\,4p^4 4d$	2	$^3D_2{}^e$	223320	231295	……….
10	$4s\,4p^4 4d$	1	$^5P_1{}^e$	209170	217991	……….
11	$4s\,4p^4 4d$	4	$^3F_4{}^e$	214600	223000	……….
12	$4s\,4p^4 4d$	3	$^3F_3{}^e$	216130	224515	……….
13	$4s\,4p^4 4d$	2	$^3F_2{}^e$	217270	225768	……….
14	$4s\,4p^4\,4d$	3	$^1F_3{}^e$	256590	257296	……….
15	$4s\,4p^4 4d$	1	$^3D_1{}^e$	230500	230711	……….
16	$4s^2 4p^3 4f$	1	$^1P_1{}^e$	157150	160496	……….

17	$4s^24p^34f$	1	$^3D_1{}^e$	157890	161210	162 395.4
18	$4s^24p^34f$	3	$^3D_3{}^e$	166860	160206	162 342.2
19	$4s^24p^34f$	2	$^1D_2{}^e$	167890	161269	161 894.8
20	$4s^24p^34f$	3	$^3G_3{}^e$	166670	160009	160 881.8
21	$4s^24p^34f$	2	$^3P_2{}^e$	157210	160572	……….
22	$4s^24p^34f$	1	$^3P_1{}^e$	157890	161267	……….
23	$4s^24p^34f$	0	$^3P_0{}^e$	157900	161289	……….

Table (2): MCDF and HFR energy levels (in cm $^{-1}$) of $4s^24p^4$,4s $4p^4$4d and $4s^24p^34f$ configuration for Sb XVIII ion.

	Configuration	J	LS	MCDF (cm^{-1})	HFR (cm^{-1})
1	$4s^24p^4$	2	$^3P_2$	0	0
2	$4s^24p^4$	1	$^3P_1$	82308	82616
3	$4s^24p^4$	0	$^3P_0$	36386	37537
4	$4s^24p^4$	2	$^1D_2$	106871	103187
5	$4s^24p^4$	0	$^1S_0$	211424	209114
6	$4s\,4p^4\,4d$	2	$^1D_2$	1253294	1253255
7	$4s\,4p^4\,4d$	1	$^1P_1$	1186674	1188837
8	$4s\,4p^4\,4d$	4	$^1G_4$	1227451	1231551
9	$4s\,4p^4\,4d$	2	$^3D_2$	1118553	1132185
10	$4s\,4p^4\,4d$	3	$^1F_3$	1263968	1279763
11	$4s\,4p^4\,4d$	1	$^5P_1$	1056473	1077969
12	$4s\,4p^4\,4d$	4	$^3F_4$	1105179	1121879
13	$4s\,4p^4\,4d$	3	$^3F_3$	1114126	1127939
14	$4s\,4p^4\,4d$	2	$^3F_2$	1150189	1159806
15	$4s\,4p^4\,4d$	1	$^3D_1$	1117166	1132392
16	$4s^24p^34f$	1	$^3D_1$	1429851	1429348
17	$4s^24p^34f$	3	$^3D_3$	1404079	1407964
18	$4s^24p^34f$	2	$^1D_2$	1439687	1440119
19	$4s^24p^34f$	3	$^3G_3$	1381538	1387777
20	$4s^24p^34f$	1	$^1P_1$	1398978	1401381
21	$4s^24p^34f$	0	$^3P_0$	1445203	1443447
22	$4s^24p^34f$	1	$^3P_1$	1440336	1439737

23	$4s^24p^34f$	2	$^3P_2$	1418421	1419522

Table (3): MCDF and HFR energy levels (in cm^{-1}) of $4s^24p^4$, $4s\,4p^44d$ and $4s^24p^34f$ configuration for Te XIX ion.

	Configuration	J	LS	MCDF (cm^{-1})	HFR (cm^{-1})
1	$4s^24p^4$	2	$^3P_2$	0	0
2	$4s^24p^4$	1	$^3P_1$	94300	93926
3	$4s^24p^4$	0	$^3P_0$	40400	39457
4	$4s^24p^4$	2	$^1D_2$	119500	115069
5	$4s^24p^4$	0	$^1S_0$	232462	228542
6	$4s\,4p^4\,4d$	2	$^1D_2$	1326200	1325467
7	$4s\,4p^4\,4d$	1	$^1P_1$	1335700	1337766
8	$4s\,4p^4\,4d$	4	$^1G_4$	1300454	………
9	$4s\,4p^4\,4d$	2	$^3D_2$	1183119	1195789
10	$4s\,4p^4\,4d$	3	$^1F_3$	1336651	1354004
11	$4s\,4p^4\,4d$	1	$^5P_1$	1117836	1138685
12	$4s\,4p^4\,4d$	4	$^3F_4$	1170195	1186483
13	$4s\,4p^4\,4d$	3	$^3F_3$	1235289	1246385
14	$4s\,4p^4\,4d$	2	$^3F_2$	1216433	1224497
15	$4s\,4p^4\,4d$	1	$^3D_1$	1182341	1197451
16	$4s^24p^34f$	1	$^3D_1$	1509400	1508323
17	$4s^24p^34f$	3	$^3D_3$	1482902	1486324
18	$4s^24p^34f$	2	$^1D_2$	1520159	1519950
19	$4s^24p^34f$	3	$^3G_3$	1459016	1464960
20	$4s^24p^34f$	1	$^1P_1$	1476390	1478437
21	$4s^24p^34f$	0	$^3P_0$	1525453	1519334
22	$4s^24p^34f$	1	$^3P_1$	1520641	1519334
23	$4s^24p^34f$	2	$^3P_2$	1497091	1497796

Table (4) :MCDF Transition wavelengths (in Å), Transition probabilities velocity (in sec^{-1}) and Oscillator strength f_L for lines of Br II Forbidden transitions (E2).

Lower	Upper	λ	A_V	f_L
$4s^24p^4$ ($^3P_0$)	$4s4p^44d$ ($^1D_2$)	402.082	7.2621421E+03	1.22E-06
	$4s4p^44d$ ($^3D_2$)	456.052	7.1297252E+04	1.26E-05
	$4s4p^44d$ ($^3F_2$)	468.997	4.7836343E+04	7.88E-06

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	$4s^24p^34f$ ($^3P_2$)	652.139	2.8104748E+03	1.04E-06
$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	398.200	4.9970408E+02	1.97E-08
	$4s\,4p^44d$ ($^1P_1$)	399.144	6.6613117E+03	2.28E-07
	$4s\,4p^44d$ ($^1F_3$)	394.695	7.1700921E+02	3.90E-08
	$4s\,4p^44d$ ($^3D_2$)	454.367	3.9601371E+04	2.04E-06
	$4s\,4p^44d$ ($^3F_2$)	467.216	6.2236775E+04	3.39E-06
	$4s\,4p^44d$ ($^3F_3$)	469.731	6.3692509E+04	5.12E-06
	$4s^24p^34f$ ($^3D_1$)	646.028	5.3862301E+03	3.37E-07
	$4s^24p^34f$ ($^3P_2$)	648.701	4.9424619E+03	5.19E-07
	$4s^24p^34f$ ($^3G_3$)	650.986	1.3865594E+03	2.05E-07
	$4s^24p^34f$ ($^3D_3$)	650.150	4.0382323E+03	5.97E-07
$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	393.377	3.5467424E+04	8.22E-07
	$4s\,4p^44d$ ($^1P_1$)	396.805	2.4349889E+04	5.01E-07
	$4s\,4p^44d$ ($^1F_3$)	389.957	1.4758940E+03	4.71E-08
	$4s\,4p^44d$ ($^1G_4$)	400.115	6.7892182E+03	2.93E-07
	$4s\,4p^44d$ ($^3D_1$)	448.099	2.7889880E+03	8.39E-08
	$4s\,4p^44d$ ($^3F_2$)	460.591	2.0532027E+04	6.53E-07
	$4s\,4p^44d$ ($^3F_3$)	463.034	6.7594539E+04	3.04E-06
	$4s\,4p^44d$ ($^3F_4$)	4.66333	1.3214295E+05	7.75E-06
	$4s^24p^34f$ ($^3D_2$)	633.429	4.9029149E+02	1.76E-08
	$4s^24p^34f$ ($^3G_3$)	638.195	3.5532829E+02	3.03E-08
	$4s^24p^34f$ ($^3P_2$)	635.998	1.7575246E+03	1.06E-07
	$4s^24p^34f$ ($^3D_3$)	637.392	4.0060922E+03	3.41E-07
$4s^24p^4$ ($^1D_2$)	$4s\,4p^44d$ ($^1D_2$)	417.235	1.1120127E+05	3.82E-06
	$4s\,4p^44d$ ($^1G_4$)	424.823	2.8453154E+05	1.72E-05
	$4s\,4p^44d$ ($^1F_3$)	413.349	2.6542722E+05	1.28E-05
	$4s\,4p^44d$ ($^1P_1$)	418.271	1.7078716E+05	3.51E-06
	$4s^24p^34f$ ($^3D_1$)	697.551	1.0129862E+03	4.43E-08
$4s^24p^4$ ($^1S_0$)	$4s\,4p^44d$ ($^1D_2$)	451.857	4.3841820E+03	6.70E-07
	$4s\,4p^44d$ ($^3D_2$)	520.583	2.2281652E+02	4.61E-08

Table (5): MCDF Transition wavelengths (in Å), Transition probabilities velocity (in sec^{-1}) and Oscillator strength f_L for lines of Sb XVII Forbidden transitions (E2).

Lower	Upper	λ	A_V	f_L
$4s^24p^4$ ($^3P_0$)	$4s4p^44d$ ($^1D_2$)	82.3969	4.6592677E+06	2.37E-05
	$4s4p^44d$ ($^3D_2$)	92.5852	3.4887892E+04	2.24E-07
	$4s4p^44d$ ($^3F_2$)	89.9490	1.1411881E+07	6.92E-05
	$4s^24p^34f$ ($^3P_2$)	72.3556	4.7591897E+05	1.86E-06
$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	85.5515	3.0485570E+06	5.57E-06
	$4s\,4p^44d$ ($^1P_1$)	90.7262	1.7029383E+06	2.10E-06
	$4s\,4p^44d$ ($^1F_3$)	84.7793	4.9474922E+06	1.24E-05
	$4s\,4p^44d$ ($^3F_2$)	93.8284	2.9657579E+06	6.52E-06
	$4s\,4p^44d$ ($^3F_3$)	97.1152	7.6072009E+05	2.51E-06
	$4s^24p^34f$ ($^3D_1$)	74.2098	3.2931966E+07	2.71E-05
	$4s^24p^34f$ ($^3D_3$)	75.6567	1.7897599E+07	3.58E-05
	$4s^24p^34f$ ($^3P_2$)	74.8448	6.0502961E+06	8.46E-06
	$4s^24p^34f$ ($^3G_3$)	76.9697	8.2940167E+05	1.71E-06
$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	79.920	6.4694769E+04	6.19E-08
	$4s\,4p^44d$ ($^1P_1$)	84.418	1.4063527E+07	9.01E-06
	$4s\,4p^44d$ ($^1F_3$)	79.246	6.1815887E+05	8.14E-07
	$4s\,4p^44d$ ($^1G_4$)	81.605	6.1217169E+05	1.10E-06
	$4s\,4p^44d$ ($^3D_1$)	89.678	1.0207614E+06	7.38E-07
	$4s\,4p^44d$ ($^3F_2$)	87.098	1.6473538E+05	1.87E-07
	$4s\,4p^44d$ ($^3F_3$)	89.923	1.0188047E+07	1.72E-05
	$4s\,4p^44d$ ($^3F_4$)	90.651	1.3913689E+07	3.08E-05
	$4s^24p^34f$ ($^3D_2$)	69.935	8.3550086E+06	3.67E-06
	$4s^24p^34f$ ($^3G_3$)	72.381	1.0095195E+07	1.11E-05
	$4s^24p^34f$ ($^3P_2$)	70.499	4.5694100E+07	3.40E-05
	$4s^24p^34f$ ($^3D_3$)	71.219	2.5149081E+07	2.67E-05

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$4s^24p^4$ ($^1D_2$)	$4s\,4p^44d$ ($^1D_2$)	87.387	1.6301967E+07	1.86E-05
	$4s\,4p^44d$ ($^1G_4$)	89.406	1.3453389E+07	2.90E-05
	$4s\,4p^44d$ ($^1F_3$)	86.603	1.2646926E+07	1.99E-05
	$4s\,4p^44d$ ($^1P_1$)	92.794	2.3497580E+06	1.82E-06
	$4s\,4p^44d$ ($^3D_2$)	99.053	4.3436111E+04	6.38E-08
	$4s^24p^34f$ ($^3D_1$)	75.587	4.3818398E+05	2.25E-07
$4s^24p^4$ ($^1S_0$)	$4s\,4p^44d$ ($^1D_2$)	96.179	4.9090943E+04	3.40E-07
	$4s\,4p^44d$ ($^3D_2$)	110.502	1.3664846E+04	1.25E-07

Table (6) :MCDF Transition wavelengths (in Å), Transition probabilities velocity (in sec^{-1}) and Oscillator strength f_L for lines of Te XIX Forbidden transitions (E2).

Lower	Upper	λ	A_V	f_L
$4s^24p^4$ ($^3P_0$)	$4s4p^44d$ ($^1D_2$)	77.905	4.8379723E+06	2.20E-05
	$4s4p^44d$ ($^3D_2$)	87.589	5.7184456E+04	3.28E-07
	$4s4p^44d$ ($^3F_2$)	85.104	9.6131245E+06	5.21E-05
	$4s^24p^34f$ ($^3P_2$)	68.587	3.9704410E+05	1.40E-06
$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	81.325	4.4195286E+06	7.30E-06
	$4s\,4p^44d$ ($^1P_1$)	80.702	7.8298325E+05	7.64E-07
	$4s\,4p^44d$ ($^1F_3$)	80.643	6.7234161E+06	1.52E-05
	$4s\,4p^44d$ ($^3F_2$)	89.299	3.8315559E+06	7.63E-06
	$4s\,4p^44d$ ($^3F_3$)	87.821	5.2314494E+06	1.41E-05
	$4s^24p^34f$ ($^3D_1$)	70.665	3.4889514E+07	2.61E-05
	$4s^24p^34f$ ($^3D_3$)	72.014	1.9052222E+07	3.45E-05
	$4s^24p^34f$ ($^3P_2$)	71.286	7.5992626E+06	9.64E-06
	$4s^24p^34f$ ($^3G_3$)	73.275	9.1970071E+05	1.72E-06
$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	75.531	1.0996544E+05	9.40E-08
	$4s\,4p^44d$ ($^1P_1$)	74.994	4.4742440E+05	2.26E-07
	$4s\,4p^44d$ ($^1F_3$)	74.943	5.5039586E+05	6.48E-07
	$4s\,4p^44d$ ($^1G_4$)	77.030	6.0864520E+05	9.74E-07
	$4s\,4p^44d$ ($^3D_1$)	84.742	1.4120653E+06	9.12E-07
	$4s\,4p^44d$ ($^3F_2$)	82.362	7.4085497E+04	7.53E-08
	$4s\,4p^44d$ ($^3F_3$)	81.103	3.0194907E+04	4.16E-08
	$4s\,4p^44d$ ($^3F_4$)	85.622	1.6005894E+07	3.16E-05
	$4s^24p^34f$ ($^3D_2$)	66.250	9.8209160E+06	3.87E-06
	$4s^24p^34f$ ($^3G_3$)	68.538	1.0651982E+07	1.05E-05
	$4s^24p^34f$ ($^3P_2$)	66.795	4.7750597E+07	3.19E-05
	$4s^24p^34f$ ($^3D_3$)	67.433	2.6992770E+07	2.57E-05
$4s^24p^4$ ($^1D_2$)	$4s\,4p^44d$ ($^1D_2$)	83.028	1.7007860E+07	1.75E-05
	$4s\,4p^44d$ ($^1G_4$)	84.843	1.4523453E+07	2.82E-05
	$4s\,4p^44d$ ($^1F_3$)	82.318	1.2416111E+07	1.76E-05
	$4s\,4p^44d$ ($^1P_1$)	82.379	1.7473469E+07	1.06E-05
	$4s\,4p^44d$ ($^3D_2$)	94.227	3.2532548E+04	4.33E-08
	$4s^24p^34f$ ($^3D_1$)	71.948	6.3935964E+05	2.97E-07
$4s^24p^4$ ($^1S_0$)	$4s\,4p^44d$ ($^1D_2$)	77.831	4.8497151E+06	2.20E-05
	$4s\,4p^44d$ ($^3D_2$)	87.589	5.7184457E+04	3.28E-07

Table (7): Comparison between MCDF and HFR Transition wavelengths (in Å) and oscillator strengths for Se -like ions.

Z	Initial	Final	MCDF		HFR	
			λ	f_L	λ	f_L
35	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	398.20	1.9E-08	396.75	3.1E-08
	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1P_1$)	399.14	2.2E-07	397.88	2.2E-07
	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1F_3$)	394.69	3.9E-08	393.16	3.2E-08
	$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	393.37	8.2E-07	396.81	1.0E-06
	$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1P_1$)	396.80	5.0E-07	392.16	4.1E-07
	$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1F_3$)	389.95	2.9E-07	388.65	3.2E-07
	$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^3D_1$)	448.09	8.3E-08	448.42	5.7E-07
	$4s^24p^4$ ($^1D_2$)	$4s\,4p^44d$ ($^1D_2$)	417.23	3.8E-06	411.70	7.7E-06
51	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	90.15	3.8E-06	90.01	7.6E-06
	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1P_1$)	95.31	2.1E-06	94.96	2.3E-06
	$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1F_3$)	89.29	9.6E-05	88.06	8.7E-06
	$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	79.92	6.1E-08	79.79	2.2E-07

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	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^1P_1)$	84.41	9.0E-06	84.11	1.0E-05
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^1F_3)$	79.24	8.1E-07	78.13	2.4E-09
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^3D_1)$	89.67	7.3E-07	88.30	1.0E-06
	$4s^24p^4\ (^1D_2)$	$4s\,4p^44d\ (^1D_2)$	87.38	1.8E-05	86.95	2.0E-05
	$4s^24p^4\ (^3P_1)$	$4s\,4p^44d\ (^1D_2)$	89.40	2.9E-05	88.62	2.9E-05
	$4s^24p^4\ (^3P_1)$	$4s\,4p^44d\ (^1P_1)$	92.79	1.8E-06	92.11	1.6E-06
52	$4s^24p^4\ (^3P_1)$	$4s\,4p^44d\ (^1D_2)$	81.32	7.3E-06	81.19	1.1E-05
	$4s^24p^4\ (^3P_1)$	$4s\,4p^44d\ (^1P_1)$	80.70	7.6E-07	86.21	2.1E-06
	$4s^24p^4\ (^3P_1)$	$4s\,4p^44d\ (^1F_3)$	80.64	1.5E-05	79.36	5.8E-06
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^1D_2)$	75.53	9.4E-08	75.44	2.2E-07
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^1P_1)$	74.99	2.2E-07	74.75	4.5E-07
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^1F_3)$	74.94	6.4E-07	73.85	1.5E-08
	$4s^24p^4\ (^3P_2)$	$4s\,4p^44d\ (^3D_1)$	84.74	9.1E-07	83.51	1.3E-06
	$4s^24p^4\ (^1D_2)$	$4s\,4p^44d\ (^1D_2)$	83.02	1.7E-05	82.61	1.9E-05

Table (8): MCDF and HFR radiative lifetime τ (in sec) of $4s^24p^4$, $4s\,4p^44d$ and $4s^24p^34f$ configuration for Br II ion.

Lower	Upper	Lifetime length Gauge (MCDF)	Lifetime velocity Gauge (MCDF)	Lifetime (HFR)
$4s^24p^4\ (^3P_0)$	**$4s\,4p^44d\ (^1D_2)$**	9.8E-05	1.3E-04	4.2E-04
	$4s\,4p^44d\ (^3D_2)$	1.5E-05	1.8E-05	1.5E-06
	$4s\,4p^44d\ (^3F_2)$	2.5E-05	2.8E-05	2.5E-06
	$4s^24p^34f\ (^3P_2)$	3.09E-04	3.5E-04	6.4E-05
$4s^24p^4\ (^3P_1)$	**$4s\,4p^44d\ (^1D_2)$**	1.3E-03	2.0E-03	7.4E-04
	$4s\,4p^44d\ (^1P_1)$	1.0E-04	1.5E-04	1.0E-04
	$4s\,4p^44d\ (^1F_3)$	9.4E-04	1.4E-03	7.0E-05
	$4s\,4p^44d\ (^3F_2)$	1.5E-05	1.6E-05	6.3E-06
	$4s\,4p^44d\ (^3F_3)$	1.5E-05	1.5E-05	4.1E-06
	$4s\,4p^44d\ (^3D_2)$	2.1E-05	2.5E-05	1.2E-05
	$4s^24p^34f\ (^3D_1)$	1.6E-04	1.8E-04	9.5E-05
	$4s^24p^34f\ (^3P_2)$	1.7E-04	2.0E-04	9.0E-05
	$4s^24p^34f\ (^3G_3)$	6.2E-04	7.2E-04	2.6E-04
	$4s^24p^34f\ (^3D_3)$	2.2E-04	2.4E-04	6.5E-05
$4s^24p^4\ (^1S_0)$	**$4s\,4p^44d\ (^1D_2)$**	2.0E-04	2.2E-04	1.8E-05
	$4s\,4p^44d\ (^3D_2)$	5.2E-03	4.4E-03	2.1E-03
$4s^24p^4\ (^3P_2)$	**$4s\,4p^44d\ (^1D_2)$**	1.9E-05	2.8E-05	2.2E-05
	$4s\,4p^44d\ (^1P_1)$	2.8E-05	4.1E-05	5.5E-05
	$4s\,4p^44d\ (^1F_3)$	4.4E-04	6.7E-04	1.7E-04
	$4s\,4p^44d\ (^1G_4)$	1.0E-04	1.4E-04	7.2E-05
	$4s\,4p^44d\ (^3D_2)$	3.0E-04	3.5E-04	4.8E-05
	$4s\,4p^44d\ (^3F_2)$	4.4E-05	4.8E-05	2.48E-05
	$4s\,4p^44d\ (^3F_3)$	1.3E-05	1.4E-05	6.6E-06
	$4s\,4p^44d\ (^3F_4)$	7.2E-06	7.5E-06	2.5E-06
	$4s^24p^34f\ (^3G_3)$	2.5E-03	2.8E-03	7.7E-04
	$4s^24p^34f\ (^3P_1)$	8.4E-05	9.9E-05	1.2E-04
	$4s^24p^34f\ (^3P_2)$	4.8E-04	5.6E-04	5.7E-04
	$4s^24p^34f\ (^3D_1)$	1.7E-03	2.0E-03	7.7E-04
	$4s^24p^34f\ (^3D_2)$	1.7E-04	2.0E-04	4.0E-04
	$4s^24p^34f\ (^3D_3)$	2.17E-04	2.4E-04	8.0E-05
$4s^24p^4\ (^1D_2)$	**$4s\,4p^44d\ (^1D_2)$**	6.8E-06	8.9E-06	3.2E-06
	$4s\,4p^44d\ (^1G_4)$	2.8E-06	3.5E-06	1.5E-06
	$4s\,4p^44d\ (^1F_3)$	2.7E-06	3.7E-06	1.81E-06
	$4s\,4p^44d\ (^1P_1)$	4.4E-06	5.8E-06	4.3E-06
	$4s\,4p^44d\ (^3D_2)$	1.5E-01	1.6E-01	5.8E-06
	$4s^24p^34f\ (^3D_1)$	1.0E-03	9.8E-04	5.3E-04

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Table (9): MCDF and HFR radiative lifetime τ (in sec) of $4s^24p^4$, $4s\,4p^44d$ and $4s^24p^34f$ configuration for Sb XVIII ion.

Lower	Upper	Lifetime length Gauge (MCDF)	Lifetime velocity Gauge (MCDF)	Lifetime (HFR)
$4s^24p^4$ ($^3P_0$)	$4s\,4p^44d$ ($^1D_2$)	1.6E-07	2.1E-07	4.2E-08
	$4s\,4p^44d$ ($^3D_2$)	2.9E-05	2.8E-05	4.1E-06
	$4s\,4p^44d$ ($^3F_2$)	8.2E-08	8.7E-08	1.1E-08
	$4s^24p^34f$ ($^3P_2$)	1.4E-06	2.1E-06	9.6E-07
$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	2.7E-07	3.2E-07	1.1E-07
	$4s\,4p^44d$ ($^1P_1$)	5.6E-07	5.8E-07	5.5E-07
	$4s\,4p^44d$ ($^1F_3$)	1.6E-07	2.0E-07	1.5E-07
	$4s\,4p^44d$ ($^3F_2$)	3.4E-07	3.3E-07	5.4E-07
	$4s\,4p^44d$ ($^3F_3$)	1.4E-06	1.3E-06	8.9E-07
	$4s^24p^34f$ ($^3D_1$)	2.8E-08	3.0E-08	2.9E-08
	$4s^24p^34f$ ($^3P_2$)	1.4E-07	1.6E-07	8.1E-08
	$4s^24p^34f$ ($^3G_3$)	1.1E-06	1.2E-06	5.2E-07
	$4s^24p^34f$ ($^3D_3$)	5.2E-08	5.5E-08	2.3E-08
$4s^24p^4$ ($^1S_0$)	$4s\,4p^44d$ ($^1D_2$)	2.0E-05	2.0E-05	2.8E-05
	$4s\,4p^44d$ ($^3D_2$)	9.2E-05	7.3E-05	8.4E-06
$4s^24p^4$ ($^3P_2$)	$4s\,4p^44d$ ($^1D_2$)	1.1E-05	1.5E-05	4.1E-06
	$4s\,4p^44d$ ($^1P_1$)	5.7E-08	7.1E-08	9.7E-08
	$4s\,4p^44d$ ($^1F_3$)	1.1E-06	1.6E-06	3.7E-04
	$4s\,4p^44d$ ($^1G_4$)	1.2E-06	1.6E-06	7.2E-07
	$4s\,4p^44d$ ($^3D_1$)	9.4E-07	9.7E-07	1.1E-06
	$4s\,4p^44d$ ($^3F_2$)	5.6E-06	6.07E-06	4.8E-06
	$4s\,4p^44d$ ($^3F_3$)	9.2E-08	9.8E-08	6.1E-08
	$4s\,4p^44d$ ($^3F_4$)	6.8E-08	7.2E-08	3.4E-08
	$4s^24p^34f$ ($^3G_3$)	9.1E-08	9.9E-08	6.7E-08
	$4s^24p^34f$ ($^3P_1$)	1.7E-08	1.9E-08	2.9E-08
	$4s^24p^34f$ ($^3P_2$)	1.9E-08	2.2E-08	1.9E-08
	$4s^24p^34f$ ($^3D_1$)	1.2E-07	1.1E-07	1.3E-07
	$4s^24p^34f$ ($^3D_3$)	3.6E-08	3.9E-08	2.6E-08
$4s^24p^4$ ($^1D_2$)	$4s\,4p^44d$ ($^1D_2$)	5.4E-08	6.1E-08	5.5E-08
	$4s\,4p^44d$ ($^1G_4$)	6.8E-08	7.4E-08	4.0E-08
	$4s\,4p^44d$ ($^1F_3$)	6.7E-08	7.9E-08	4.5E-08
	$4s\,4p^44d$ ($^1P_1$)	4.2E-07	4.2E-07	7.5E-07
	$4s\,4p^44d$ ($^3D_2$)	3.1E-05	2.3E-05	1.4E-04
	$4s^24p^34f$ ($^3D_1$)	2.2E-06	2.2E-06	3.9E-06

Table (10): MCDF and HFR radiative lifetime τ (in sec) of $4s^24p^4$, $4s\,4p^44d$ and $4s^24p^34f$ configuration for Te XIX ion.

Lower	Upper	Lifetime length Gauge (MCDF)	Lifetime velocity Gauge (MCDF)	Lifetime (HFR)
$4s^24p^4$ ($^3P_0$)	$4s\,4p^44d$ ($^1D_2$)	1.6E-07	2.1E-07	4.2E-08
	$4s\,4p^44d$ ($^3D_2$)	2.9E-05	2.8E-05	4.1E-06
	$4s\,4p^44d$ ($^3F_2$)	8.2E-08	8.7E-08	1.1E-08
	$4s^24p^34f$ ($^3P_2$)	1.4E-06	2.1E-06	9.E-07
$4s^24p^4$ ($^3P_1$)	$4s\,4p^44d$ ($^1D_2$)	2.7E-07	3.2E-07	1.1E-07
	$4s\,4p^44d$ ($^1P_1$)	5.6E-07	5.8E-07	5.5E-07
	$4s\,4p^44d$ ($^1F_3$)	1.6E-07	2.0E-07	1.5E-07
	$4s\,4p^44d$ ($^3F_2$)	3.4E-07	3.3E-07	5.4E-07
	$4s\,4p^44d$ ($^3F_3$)	1.4E-06	1.3E-06	8.9E-07
	$4s^24p^34f$ ($^3D_1$)	2.8E-08	3.0E-08	2.9E-08
	$4s^24p^34f$ ($^3P_2$)	1.4E-07	1.6E-07	8.1E-08
	$4s^24p^34f$ ($^3G_3$)	1.1E-06	1.2E-06	5.2E-07
	$4s^24p^34f$ ($^3D_3$)	5.2E-08	5.5E-08	2.3E-08
$4s^24p^4$ ($^1S_0$)	$4s\,4p^44d$ ($^1D_2$)	2.1E-05	2.0E-05	2.8E-05
	$4s\,4p^44d$ ($^3D_2$)	9.2E-05	7.3E-05	8.4E-06

$4s^24p^4$ $(^3P_2)$	$4s4p^44d\ (^1D_2)$	1.1E-05	1.5E-05	4.1E-06
	$4s4p^44d\ (^1P_1)$	5.7E-08	7.1E-08	9.7E-08
	$4s4p^44d\ (^1F_3)$	1.1E-06	1.6E-06	3.7E-04
	$4s4p^44d\ (^1G_4)$	1.2E-06	1.6E-06	7.1E-07
	$4s4p^44d\ (^3D_1)$	9.4E-07	9.8E-07	1.1E-06
	$4s4p^44d\ (^3F_2)$	5.6E-06	6.0E-06	6.8E-06
	$4s4p^44d\ (^3F_3)$	9.2E-08	9.8E-08	6.0E-08
	$4s4p^44d\ (^3F_4)$	6.8E-08	7.2E-08	3.4E-08
	$4s^24p^34f\ (^3G_3)$	9.2E-08	9.9E-08	6.7E-08
	$4s^24p^34f\ (^3P_1)$	1.7E-08	1.9E-08	2.9E-08
	$4s^24p^34f\ (^3P_2)$	1.9E-08	2.2E-08	1.9E-08
	$4s^24p^34f\ (^3D_1)$	1.2E-07	1.2E-07	1.2E-07
	$4s^24p^34f\ (^3D_3)$	3.6E-08	3.9E-08	2.5E-08
$4s^24p^4$ $(^1D_2)$	$4s4p^44d\ (^1D_2)$	5.4E-08	6.1E-08	5.5E-08
	$4s4p^44d\ (^1G_4)$	6.8E-08	7.4E-08	4.0E-08
	$4s4p^44d\ (^1F_3)$	6.7E-08	7.9E-08	4.5E-08
	$4s4p^44d\ (^1P_1)$	4.2E-07	4.2E-07	7.5E-07
	$4s4p^44d\ (^3D_2)$	3.2E-05	2.3E-05	1.4E-04
	$4s^24p^34f\ (^3D_1)$	2.2E-06	2.2E-06	3.9E-06

III. CONCLUSION

Accurate and large-scale calculations have been carried out for the set of fine structure energy levels and transition probabilities for **Br II**, **Sb XVIII** and **Te XIX** ions. The set of results far exceeds the currently available experimental and theoretical data. We report energy levels and radiative rates for forbidden transitions with the fully relativistic mutliconfiguration Dirac-Fock method.

The results are obtained in intermediate coupling including relativistic effects using the Breit Pauli R-matrix method (BPRM) in the close coupling approximation. Both the energies and the transition probabilities show very good agreement, within 1-10%, with almost all accurate calculated and measured values available. This indicates that for these highly charged ions the higher order relativistic and the quantum electrodynamics corrections QED effects omitted in the BPRM calculations may lead to an error not exceeding the estimated uncertainty.

The results from the present work should be particularly useful in the analysis of X-ray and Extreme Ultraviolet spectra from astrophysical and laboratory sources where non-local thermodynamic equilibrium (NLTE) atomic models with many excited levels are needed.

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