Journal of Atomic, Molecular, Condensate & Nano Physics
Vol. 3, No. 1, pp. 1–16, 2016
ISSN 2349-2716 (online); 2349-6088 (print)
Published by RGN Publications

http://www.rgnpublications.com

Study of Lowest Odd Parity Configurations in Ge-I Like Ions

Research Article

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Abstract. Fine structure energy levels, transition probabilities and oscillator strength for terms belonging to the ground configuration, $4s^24p^2$ and the first exited odd parity configurations $4s4p^3$, $4s^24p5s$ and $4s^24p4d$ of Ge-I like ions have been calculated using Hartree-Fock method with relativistic correction incorporating large number of interacting configurations $[4s^24p(4f+5p+5g), 4s4p^2(4d+5s), 4p^3(4d+5s)]$. Experimentally reported levels have been compared with theoretical results establishing energy parameters in the first eleven members of the sequence (Ge I-Mo XI). The configuration $4s^24p4d$ in Rb VI, Sr VII, and $4s4p^3$ except $4s4p^3\ {}^5S_2$ level in Ge-I, are not observed yet. A systematic study of Slater parameters in the isoelectronic sequence enabled us to make precise predictions of the missing energy levels belonging to these configurations.

Keywords. Energy levels; Oscillation strength; ab initio calculations; Isoelectronic sequence; Transition probabilities

PACS. 31.15.A; 31.15.ag; 31.15.aj; 31.15.xr; 32.30.Jc; 33.20.Kf; 33.20.Lg

Received: February 15, 2015 **Accepted:** September 26, 2015

1. Introduction

Highly ionized germanium ions are subject to various investigations in science and technology. Ge-like ions have been widely applied in the laboratory and in astronomical plasmas [1]. Many transition arrays have been studied for the ions GeI-MoXI on the basis of spectrograms observed in laser-produced plasmas, Low-inductance vacuum spark and sliding spark spectra recorded at the N.B.S. spectra obtained at Lund University, St. Francis Xavier University, Antigonish (Canada) and grazing incidence spectrograph at the Zeeman laboratory (Amsterdam) [2–4].

Germanium isoelectronic ions have ground configuration $4s^24p^2$. The ground configuration consists of $^3P_{0,1,2}$, $^1D_2$ and $^1S_0$ levels in increasing order of energy. The recent laser techniques for radiative lifetime measurements, atomic transition probabilities have become much more accurate. The accurate knowledge of theoretical transition probabilities and oscillator strength enables precise investigations of stellar abundances. Energy levels calculation for isoelectronic study contribute atomic structure through the empirical explosion and predictive systemization of predict data [5, 6].

The experimental data for lowest odd configurations $4s4p^3$, $4s^24p5s$ and $4s^24p4d$ of Ge I sequence are still limited, and theoretical calculations are needed [7–9]. Here GeI-MoXI ions for transition probabilities, oscillator strength and energy levels are being calculated using the Cowan code. Because they rely on the availability of experimental data, they can be continually improved by the incorporation of new observations.

2. Theoretical Approximations

In the present paper the energy levels, oscillator strengths, and transition probabilities of GeI like ions are studied theoretically. Moreover, the obtained results are compared with existing data. The theoretical calculations have been performed using the Hartree-Fock method with relativistic corrections included in the Cowan code. The Hamiltonian of an atomic system with N electrons is of the form

$$\begin{aligned} H &= H_{kin} + H_{e\text{-}nuc} + H_{e\text{-}e} \\ &= \sum_i \frac{\hbar}{2m_e}\nabla_i^2 - \sum_i \frac{Ze^2}{r_i} + \sum_{i\neq j}\frac{e_i}{r_{ij}}, \end{aligned} \tag{2.1}$$

where H_{kin}, $H_{e\text{-}nuc}$ and $H_{e\text{-}e}$ refers to the kinetic energy of electrons, the Coulomb potential and the energy of electrostatic interaction of electrons respectively, and r_i is the distance between the i^{th} electron and nucleus, where $r_{ij} = |r_i - r_j|$.

On solving the Schrödinger equation in the case of multiple electrons, multiple wave functions obtain. But, due to the appearance of the term of interaction of electrons, an exact solution cannot be obtained. On the other hand, the interaction term is comparable with the Coulomb potential term, so it can by no means be ignored. An approximate solution is to adopt the method of central force field. If it is assumed that every electron moves in the central force field of the nucleus and also in the mean force field produced by other electrons, then we have the following effective Hamiltonian

$$\begin{aligned} H^{eff} &= \sum_{i=1}^{N} H_i^{eff} \\ &= \sum_i^N \left[\frac{1}{2}\frac{P_i^2}{r_i} - V_i^{eff}(r_i)\right]. \end{aligned} \tag{2.2}$$

The Hartree-Fock (HF) approximations assumes that the atomic wave function of N-electron atom be written as the product of N one-electron wave functions, which can be written as Slater

Determinant.

$$\psi(r_1, r_2, \ldots, r_N) = \frac{1}{\sqrt{(N!)}} \begin{pmatrix} \phi_{1(r1)} & \phi_{1(r2)} & \cdots & \phi_{1(rN)} \\ \phi_{2(r1)} & \phi_{2(r2)} & \cdots & \phi_{2(rN)} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{N(r1)} & \phi_{N(r2)} & \cdots & \phi_{N(N)} \end{pmatrix}. \tag{2.3}$$

Cowan developed computer code for HF method to calculate atomic structure. In his method the weighted oscillator strength, gf, is given by Cowan,

$$gf = \frac{8\pi^2 mca_0^2}{3h\lambda} S. \tag{2.4}$$

The transition probability A_{ki} related to oscillator strength (f), by

$$A_{ki} = \frac{2\omega^2 e^2}{mc^3} f, \tag{2.5}$$

where g is the statistical weight of lower level, f is the absorption oscillator strength, h is Planck's constant, c is light velocity, a_0 is Bohr radius, and S is the electric dipole line strength [9, 11, 12].

3. Calculations

The ab initio calculations have been performed for $4s4p^3$, $4s^24p5s$ and $4s^24p4d$ configurations for GeI-MoXI by Hartree-Fock method with relativistic corrections. The Hartree-Fock-Slater method is the most typical method. Cowan revised this method and developed the RCN/RCG program which was used in our study [10]. The program is extreme effective. The energy levels, transition probability and oscillator strength for allowed transitions were yielded. A large number of interacting configurations $[4s^24p(4f + 5p + 5g), 4s4p^2(4d + 5s), 4p^3(4d + 5s)]$ are considered for input. The calculations are semi empirical in the sense that they made use of experimental data to derive scaling factors for the theoretical parameters. The HXR Slater parameters and configuration interaction integral scaled down 100% for Eav and ζ, 85% for Fk and 75% for Gk.

4. Results and Discussions

The energy levels for the ground state configuration $4s^24p2$ and the excited $4s4p^3$, $4s^24p5s$ and $4s^24p4d$ configurations in Germanium and GeI-like As, Se, Br, Kr, Rb, Sr, Y, Zr, Nb, and Mo ions are presented in Table 1. The values calculated by Cowan code are compared with the best observed data available, and found good agreement with it [2, 7, 8, 13–15, 17–25]. The calculated energy levels for $4s4p^3$ configurations except $^5S_2$ are found to be above the ionization limit in Ge-I ion. Although, the $4s^24p4d$ configurations for RbVI and SrVII have to be observed yet experimentally.

Transition probabilities (A_{ki}) and oscillator strength (f) for Ge-I, have been calculated. The calculated weighted transition probability and oscillation strength for $4s4p^3$, $4s^24p5s$ and $4s^24p4d$ configurations are given in Table 2.

The ab initio calculations for transition probability and oscillation strength are reported for Ge-I sequence, would be helpful for line identification in future experimental work.

Table 1. Calculated and observed energy levels for Ge isoelectronic sequence are as follows:

(a) Ge I:

J	E(obs) (cm^{-1}) [13]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	−1.0	1.0	99% 3P
0	16367.3	16348.0	19.3	99% 1S
1	557.1	553.0	4.1	100% 3P
2	1410.0	1387.0	23.0	99% 3P
2	7125.3	7174.0	−48.7	99% 1D
				Excited configurations
0	37451.7	37448.0	3.7	97% 4s2 4p 5s 3P
	51978.2	51912.0	66.2	95% 4s2 4p 4d 3P
1	37702.3	37706.0	−3.7	85% 4s2 4p 5s 3P + 12% 4s2 4p 5s 1P
	40020.6	40019.0	1.6	83% 4s2 4p 5s 1P + 13% 4s2 4p 5s 3P
	48962.8	48967.0	−4.2	87% 4s2 4p 4d 3D
	51705.0	51711.0	−6.0	89% 4s2 4p 4d 3P + 4% 4s2 4p 4d 3D
	52847.2	52929.0	−81.8	57% 4s2 4p 4d 1P + 21% 4s2 4p 6s 1P + 14% 4s2 4p 6s 3P
2	39117.9	39119.0	−1.1	97% 4s2 4p 5s 3P
	41926.7	41926.0	0.7	99% 4s 4p3 5S
	48480.0	48403.0	77.0	77% 4s2 4p 4d 1D + 10% 4s2 4p 4d 3F + 4% 4s2 4p 4d 3P
	48882.3	48911.0	−28.7	62% 4s2 4p 4d 3D + 28% 4s2 4p 4d 3F + 5% 4s2 4p 4d 3P
	50069.0	50075.0	−6.0	59% 4s2 4p 4d 3F + 20% 4s2 4p 4d 3D + 16% 4s2 4p 4d 1D
	51437.8	51429.0	8.8	86% 4s2 4p 4d 3P + 7% 4s2 4p 4d 3D
3	49144.4	49172.0	−27.6	61% 4s2 4p 4d 3D + 29% 4s2 4p 4d 3F
	50323.5	50361.0	−37.5	64% 4s2 4p 4d 3F + 31% 4s2 4p 4d 3D
	52592.2	52567.0	25.2	88% 4s2 4p 4d 1F + 4% 4s2 4p 4d 3F
4	50786.8	50804.0	−17.2	97% 4s2 4p 4d 3F

(b) As II:

J	E(obs) (cm^{-1}) [14–16]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	5.0	−5.0	99% 3P
0	22598.6	22554.0	44.6	99% 1S
1	1063.5	1045.0	18.5	100% 3P
2	2541.3	2485.0	56.3	98% 3P
2	10095.8	10211.0	−115.2	98% 1D
				Excited configurations
0	78730.9	78734.0	−3.1	96% 4s2 4p 5s 3P
	84648.4	84393.0	255.4	62% 4s 4p3 3P + 32% 4s2 4p 4d 3P
	102550.1	102433.0	117.1	63% 4s2 4p 4d 3P + 31% 4s 4p3 3P
1	73749.9	73868.0	−118.1	70% 4s 4p3 3D + 22% 4s2 4p 4d 3D
	79128.3	79131.0	−2.7	81% 4s2 4p 5s 3P+14% 4s2 4p 5s 1P
	82819.2	82819.0	0.2	78% 4s2 4p 5s 1P+13% 4s2 4p 5s 3P
	84636.2	84576.0	60.2	57% 4s 4p3 3P + 31% 4s2 4p 4d 3P
	99066.0	99167.0	−101.0	60% 4s2 4p 4d 3D + 16% 4s 4p3 3D + 11% 4s2 4p 4d 3P
	101488.2	101508.0	−19.8	77% 4s2 4p 4d 1P + 10% 4s 4p3 1P
	102594.9	102538.0	56.9	50% 4s2 4p 4d 3P + 26% 4s 4p3 3P + 9% 4s2 4p 4d 3D + 4% 4s 4p3 3D
	109036.0	109255.0	−219.0	79% 4s 4p3 3S + 7% 4s 4p3 1P
	119014.8	117772.0	1242.8	35% 4s 4p3 1P + 27% 4s2 4p 5d 1P +14% 4s2 4p 6s 1P+9% 4s2 4p 6s 3P
2	54817.1	54470.0	347.1	98% 4s 4p3 5S
	73862.3	73878.0	−15.7	69% 4s 4p3 3D + 21% 4s2 4p 4d 3D + 5% 4s 4p3 3P
	81508.9	81522.0	−13.1	85% 4s2 4p 5s 3P
	83100.8	82800.0	300.8	56% 4s2 4p 4d 1D + 14% 4s 4p3 1D + 9% 4s24p5s 3P+9% 4s 4p3 3P
	85105.9	85715.0	−609.1	40% 4s 4p3 3P + 27% 4s2 4p 4d 3P + 20% 4s2 4p 4d 1D
	88829.1	89011.0	−181.9	95% 4s2 4p 4d 3F
	99548.8	99173.0	375.8	54% 4s2 4p 4d 3D+19% 4s2 4p 4d 3P + 14% 4s 4p3 3D+ 7% 4s 4p3 3P
	102315.4	102688.0	−372.6	40% 4s2 4p 4d 3P + 25% 4s 4p3 3P +18%4s2 4p 4d 3D+8% 4s 4p3 3D
	111531.7	111794.0	−262.3	54% 4s 4p3 1D + 20% 4s2 4p 5d 1D + 17% 4s2 4p 4d 1D
3	74244.4	74825.0	−580.6	74% 4s 4p3 3D + 23% 4s2 4p 4d 3D
	89549.6	89617.0	−67.4	96% 4s2 4p 4d 3F
	100391.1	100288.0	103.1	68% 4s2 4p 4d 3D + 20% 4s 4p3 3D + 5% 4s2 4p 4d 1F
	102487.1	102455.0	32.1	87% 4s2 4p 4d 1F+4% 4s2 4p 4d 3D
4	90927.4	90653.0	274.4	97% 4s2 4p 4d 3F

(c) Se III:

J	E(obs) (cm^{-1}) [17]	E(LSF)	Differ.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	15.0	−15.0	98% 3P
	28128.7	28074.0	54.7	98% 1S
1	1742.4	1714.0	28.4	100% 3P
2	3936.0	3862.0	74.0	96% 3P
	13032.0	13174.0	−142.0	96% 1D
				Excited configurations
0	106482.4	106216.0	266.4	84% 4s 4p3 3P + 14% 4s2 4p 4d 3P
	126280.0	126270.0	10.0	97% 4s2 4p 5s 3P
	142315.1	142311.0	4.1	83% 4s2 4p 4d 3P + 13% 4s 4p3 3P
1	92611.2	93311.0	−699.8	83% 4s 4p3 3D + 13% 4s2 4p 4d 3D
	106593.4	106308.0	285.4	82% 4s 4p3 3P + 14% 4s2 4p 4d 3P
	126780.2	126792.0	−11.8	81% 4s2 4p 5s 3P + 16% 4s2 4p 5s 1P
	131654.7	131654.0	0.7	70% 4s2 4p 5s 1P + 16% 4s2 4p 5s 3P + 8% 4s2 4p 4d 1P
	136944.8	136571.0	373.8	70% 4s 4p3 3S + 17% 4s 4p3 1P + 4% 4s2 4p 4d 1P
	140639.7	139722.0	917.7	47% 4s2 4p 4d 3D + 20% 4s2 4p 4d 3P + 8% 4s 4p3 3D + 8% 4s2 4p 4d 1P
	139216.0	140668.0	−1452.0	33% 4s 4p3 1P + 21% 4s2 4p 4d 3D + 20% 4s 4p3 3S + 17% 4s2 4p 4d 1P
	142758.2	142669.0	89.2	61% 4s2 4p 4d 3P + 13% 4s2 4p 4d 3D + 11% 4s 4p3 3P
	157851.8	156695.0	1156.8	54% 4s2 4p 4d 1P + 34% 4s 4p3 1P
2	68502.7	68011.0	491.7	99% 4s 4p3 5S
	92726.3	93325.0	−598.7	82% 4s 4p3 3D + 13% 4s2 4p 4d 3D
	106515.1	106260.0	255.1	76% 4s 4p3 3P + 14% 4s2 4p 4d 3P
	112565.4	112921.0	−355.6	59% 4s2 4p 4d 1D + 32% 4s 4p3 1D + 4% 4s 4p3 3P
	124050.6	124510.0	−459.4	96% 4s2 4p 4d 3F
	130389.2	130393.0	−3.8	97% 4s2 4p 5s 3P
	139410.2	139530.0	−119.8	41% 4s2 4p 4d 3P + 40% 4s2 4p 4d 3D + 7% 4s 4p3 3P + 6% 4s 4p3 3D
	142705.2	142352.0	353.2	43% 4s2 4p 4d 3D + 37% 4s2 4p 4d 3P + 7% 4s 4p3 3P
	147828.9	147208.0	620.9	57% 4s 4p3 1D + 34% 4s2 4p 4d 1D
3	93289.6	93856.0	−566.4	85% 4s 4p3 3D + 13% 4s2 4p 4d 3D
	125310.5	125577.0	−266.5	97% 4s2 4p 4d 3F
	142014.7	141498.0	516.7	82% 4s2 4p 4d 3D + 12% 4s 4p3 3D
	148680.9	149547.0	−866.1	93% 4s2 4p 4d 1F
4	127409.5	127270.0	139.5	97% 4s2 4p 4d 3F

(d) Br IV:

J	E(obs) (cm^{-1}) [18, 19]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^24p^2$
0	0	33	−33	98% 3P
0	33576.3	33506	70.3	98% 1S
1	2625.6	2580	45.6	100% 3P
2	5616.3	5513	103.3	94% 3P
2	16139.1	16326	−186.9	94% 1D
				Excited configurations
0	127226.0	127103.0	123.0	88% 4s 4p3 3P + 11% 4s2 4p 4d 3P
	178741.7	178765.0	−23.3	70%4s2 4p 5s 3P+25% 4s2 4p 4d 3P
	181348.4	181626.0	−277.6	62% 4s2 4p 4d 3P+28% 4s2 4p 5s 3P + 8% 4s 4p3 3P
1	111083.1	111441.0	−357.9	84% 4s 4p3 3D+11% 4s2 4p 4d 3D
	127446.3	127262.0	184.3	85% 4s 4p3 3P+11% 4s2 4p 4d 3P
	161317.5	161135.0	182.5	75% 4s 4p3 3S+18% 4s 4p3 1P
	167357.7	167667.0	−309.3	58% 4s 4p3 1P+21% 4s 4p3 3S + 18% 4s2 4p 4d 1P
	177366.1	177483.0	−116.9	46% 4s2 4p 4d 3D+34% 4s2 4p 4d 3P + 6% 4s 4p3 3D+4% 4s2 4p 5s 3P
	179953.7	179758.0	195.7	57% 4s2 4p 5s 3P+17% 4s2 4p 4d 3D + 13% 4s2 4p 5s 1P+7% 4s2 4p 4d 3P
	181849.6	182040.0	−190.4	43% 4s2 4p 4d 3P+21% 4s2 4p 4d 3D + 17% 4s2 4p 5s 3P+6% 4s2 4p 5s 1P
	187105.8	187210.0	−104.2	68% 4s2 4p 5s 1P+19% 4s2 4p 5s 3P + 6% 4s2 4p 4d 1P
	200216.6	199651.0	565.6	67% 4s2 4p 4d 1P+15% 4s 4p3 1P + 10% 4s2 4p 5s 1P
2	82805.1	82614.0	191.1	99% 4s 4p3 5S
	111199.1	111465.0	−265.9	83% 4s 4p3 3D + 11% 4s2 4p 4d 3D
	127606.5	127290.0	316.5	79% 4s 4p3 3P + 11% 4s2 4p 4d 3P
	138486.2	138212.0	274.2	47% 4s2 4p 4d 1D + 46% 4s 4p3 1D
	157632.3	157571.0	61.3	96% 4s2 4p 4d 3F
	176057.4	176200.0	−142.6	55% 4s2 4p 4d 3P+21% 4s2 4p 4d 3D + 7% 4s 4p3 3P+5% 4s 4p3 1D
	181275.3	181360.07	−84.7	58% 4s2 4p 4d 3D+10% 4s2 4p 4d 1D + 9% 4s2 4p 4d 3P+9% 4s 4p3 1D
	182510.0	182726.0	−216.0	34% 4s2 4p 4d 1D+32% 4s 4p3 1D + 17% 4s2 4p 4d 3P+5% 4s2 4p 4d 3D
	185962.8	185907.0	55.8	92% 4s2 4p 5s 3P+4% 4s2 4p 4d 3P
3	112043.1	112272.0	−228.9	87% 4s 4p3 3D+11% 4s2 4p 4d 3D
	159519.4	159492.0	27.4	96% 4s2 4p 4d 3F
	181312.3	181093.0	219.3	84% 4s2 4p 4d 3D+10% 4s 4p3 3D
	192259.5	192283.07	−23.5	94% 4s2 4p 4d 1F
4	162534.6	162580.07	−45.4	97% 4s2 4p 4d 3F

(e) Kr V:

J	E(obs) (cm^{-1}) [20–22]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	38.0	−38.0	97% 3P
0	39203.9	39149.0	54.9	97% 1S
1	3742.9	3699.0	43.9	100% 3P
2	7595.3	7507.0	88.3	92% 3P + 8% 1D
2	19722.9	19872.0	−149.1	92% 1D + 8% 3P
				Excited configurations
0	147925.3	148378.0	−452.7	91% 4s 4p3 3P+7% 4s2 4p 4d 3P
	216420.0	217206.0	−786.0	89% 4s2 4p 4d 3P+7% 4s 4p3 3P
	238526.0	238914.0	−388.0	97% 4s2 4p 5s 3P
1	129658.2	129991.0	−332.8	90% 4s 4p3 3D+8% 4s2 4p 4d 3D
	148286.8	148291.0	−4.2	91% 4s 4p3 3P+8% 4s2 4p 4d 3P
	185063.5	184795.0	268.5	97% 4s 4p3 3S
	194041.1	194487.0	−445.9	85% 4s 4p3 1P+13% 4s2 4p 4d 1P
	213932.0	214023.0	−91.0	50% 4s2 4p 4d 3P+36% 4s2 4p 4d 3D + 5% 4s 4p3 3P
	218764.8	218710.0	54.8	51% 4s2 4p 4d 3D+38% 4s2 4p 4d 3P + 4% 4s 4p3 3D
	237720.5	236723.0	997.5	61% 4s2 4p 4d 1P+15% 4s2 4p 5s 1P + 10% 4s2 4p 5s 3P+8% 4s 4p3 1P
	240926.0	240737.0	189.0	76% 4s2 4p 5s 3P+15% 4s2 4p 4d 1P
	250993.0	251219.0	−226.0	79% 4s2 4p 5s 1P+11% 4s2 4p 5s 3P + 7% 4s2 4p 4d 1P
2	129779.3	130096.0	−316.7	91% 4s 4p3 3D+8% 4s2 4p 4d 3D
	148668.4	148107.0	561.4	90% 4s 4p3 3P+8% 4s2 4p 4d 3P
	163387.2	164848.0	−1460.8	60% 4s 4p3 1D+37% 4s2 4p 4d 1D
	190279.0	190439.0	−160.0	96% 4s2 4p 4d 3F
	213360.0	211254.0	2106.0	52% 4s2 4p 4d 3P+16% 4s2 4p 4d 1D + 12% 4s2 4p 4d 3D+11% 4s 4p3 1D
	216874.0	216242.0	632.0	45% 4s2 4p 4d 1D+24% 4s 4p3 1D + 18% 4s2 4p 4d 3P+6% 4s2 4p 4d 3D
	219823.3	219706.0	117.3	71% 4s2 4p 4d 3D+18% 4s2 4p 4d 3P + 6% 4s 4p3 3D
	246798.0	246657.0	141.0	98% 4s2 4p 5s 3P
3	131016.4	130258.0	758.4	91% 4s 4p3 3D+8% 4s2 4p 4d 3D
	192949.0	193279.0	−330.0	96% 4s2 4p 4d 3F
	219381.6	219703.0	−321.4	87% 4s2 4p 4d 3D+7% 4s 4p3 3D
	234120.9	234644.0	−523.1	94% 4s2 4p 4d 1F

(f) Rb VI:

J	E(obs) (cm^{-1}) [7, 23]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	49.0	−49.0	96% 3P + 4% 1S
0	45201.0	45151.0	50.0	96% 1S + 4% 3P
1	5140.0	5085.0	55.0	100% 3P
2	9899.0	9815.0	84.0	89% 3P + 11% 1D
2	23746.0	23887.0	−141.0	89% 1D + 11% 3P
				Excited configurations
0	168930.0	168954.0	−24.0	91% 4s 4p3 3P+8% 4s2 4p 4d 3P
	303480.0	303473.0	7.0	98% 4s2 4p 5s 3P
1	148531.0	148737.0	−206.0	85% 4s 4p3 3D+9% 4s2 4p 4d 3D
	169477.0	169412.0	65.0	86% 4s 4p3 3P+7% 4s2 4p 4d 3P
	208835.0	208766.0	69.0	76% 4s 4p3 3S+19% 4s 4p3 1P
	220609.0	220994.0	−385.0	67% 4s 4p3 1P+20% 4s 4p3 3S
				+ 10% 4s2 4p 4d 1P
	304640.0	304647.0	−7.0	80% 4s2 4p 5s 3P+17% 4s2 4p 5s 1P
	317070.0	317068.0	2.0	80% 4s2 4p 5s 1P+17% 4s2 4p 5s 3P
2	148667.0	148752.0	−85.0	84% 4s 4p3 3D+8% 4s2 4p 4d 3D
				+ 6% 4s 4p3 3P
	170125.0	169910.0	215.0	78% 4s 4p3 3P+8% 4s2 4p 4d 3P
				+ 6% 4s 4p3 3D
	188065.0	187576.0	489.0	56% 4s 4p3 1D+36% 4s2 4p 4d 1D
				+ 5% 4s 4p3 3P
	313630.0	313631.0	−1.0	98% 4s2 4p 5s 3P
3	150434.0	150428.0	6.0	90% 4s 4p3 3D+8% 4s2 4p 4d 3D

(g) Sr VII:

J	E(obs) (cm^{-1}) [7,24]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	38.0	−38.0	95% 3P + 5% 1S
0	51814.0	51785.0	29.0	95% 1S + 5% 3P
1	6845.0	6795.0	50.0	100% 3P
2	12545.0	12503.0	42.0	85% 3P + 15% 1D
2	28490.0	28572.0	−82.0	85% 1D + 15% 3P
				Excited configurations
0	190425.0	190446.0	−21.0	92% 4s 4p3 3P+6% 4s2 4p 4d 3P
	373400.0	373402.0	−2.0	98% 4s2 4p 5s 3P
1	167806.0	167996.0	−190.0	85% 4s 4p3 3D+7% 4s2 4p 4d 3D
				+ 5% 4s 4p3 3P
	191215.0	191152.0	63.0	86% 4s 4p3 3P+6% 4s2 4p 4d 3P
				+ 5% 4s 4p3 3D
	232870.0	232779.0	91.0	74% 4s 4p3 3S+21% 4s 4p3 1P
	247754.0	248009.0	−255.0	67% 4s 4p3 1P+22% 4s 4p3 3S
				+ 8% 4s2 4p 4d 1P
	374670.0	374668.0	2.0	78%4s2 4p5s 3P+20% 4s2 4p 5s 1P
	389730.0	389749.0	−19.0	78%4s2 4p5s 1P+20% 4s2 4p 5s 3P
2	167977.0	168030.0	−53.0	83% 4s 4p3 3D+8% 4s 4p3 3P
				+ 7% 4s2 4p 4d 3D
	192193.0	192011.0	182.0	76% 4s 4p3 3P+8% 4s 4p3 3D
				+6%4s2 4p 4d 3P+5% 4s 4p3 1D
	213095.0	212881.0	214.0	61% 4s 4p3 1D+31% 4s2 4p 4d 1D
				+ 6% 4s 4p3 3P
	386270.0	386251.0	19.0	98% 4s2 4p 5s 3P
3	170427.0	170407.0	20.0	91% 4s 4p3 3D+8% 4s2 4p 4d 3D

(h) Y VIII:

J	E(obs) (cm^{-1}) [2, 8]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	58.0	−58.0	94% 3P + 6% 1S
0	58784.0	58746.0	38.0	94% 1S + 6% 3P
1	8905.0	8834.0	71.0	100% 3P
2	15565.0	15502.0	63.0	81% 3P + 19% 1D
2	33675.0	33789.0	−114.0	81% 1D + 19% 3P
				Excited configurations
0	212747.0	212156.0	591.0	94% 4s 4p3 3P + 5% 4s2 4p 4d 3P
	326664.0	326983.0	−319.0	93% 4s2 4p 4d 3P + 5% 4s 4p3 3P
	448866.0	448857.0	9.0	98% 4s2 4p 5s 3P
1	187562.0	187575.0	−13.0	84% 4s 4p3 3D + 7% 4s 4p3 3P + 6% 4s2 4p 4d 3D
	213645.0	213271.0	374.0	85% 4s 4p3 3P + 7% 4s 4p3 3D + 5% 4s2 4p 4d 3P
	257331.0	256436.0	895.0	72% 4s 4p3 3S + 23% 4s 4p3 1P
	275381.0	275734.0	−353.0	68% 4s 4p3 1P + 24% 4s 4p3 3S + 5% 4s2 4p 4d 1P
	318831.0	318341.0	490.0	46% 4s2 4p 4d 3D + 42% 4s2 4p 4d 3P
	329757.0	329706.0	51.0	49% 4s2 4p 4d 3P + 42% 4s2 4p 4d 3D
	361506.0	361284.0	222.0	87% 4s2 4p 4d 1P + 5% 4s 4p3 1P
	450244.0	450253.0	−9.0	77% 4s2 4p 5s 3P + 21% 4s2 4p 5s 1P
	468525.0	468523.0	2.0	77% 4s2 4p 5s 1P + 21% 4s2 4p 5s 3P
2	143986.8	143763.0	223.8	97% 4s 4p3 5S
	185958.0	187650.0	−1692.0	82% 4s 4p3 3D + 10% 4s 4p3 3P + 5% 4s2 4p 4d 3D
	215490.0	214735.0	755.0	74% 4s 4p3 3P + 11% 4s 4p3 3D + 6% 4s 4p3 1D + 5% 4s2 4p 4d 3P
	239458.0	240601.0	−1143.0	69% 4s 4p3 1D + 22% 4s2 4p 4d 1D + 7% 4s 4p3 3P
	286031.0	286385.0	−354.0	94% 4s2 4p 4d 3F
	310998.0	311120.0	−122.0	40% 4s2 4p 4d 3P + 33% 4s2 4p 4d 1D + 10% 4s 4p3 1D + 10% 4s2 4p 4d 3D
	323632.0	323189.0	443.0	39% 4s2 4p 4d 1D + 27% 4s2 4p 4d 3P + 16% 4s2 4p 4d 3D + 10% 4s 4p3 1D
	331841.0	331862.0	−21.0	64% 4s2 4p 4d 3D + 25% 4s2 4p 4d 3P + 4% 4s 4p3 3D
	464833.0	464835.0	−2.0	98% 4s2 4p 5s 3P
3	191117.0	191092.0	25.0	93% 4s 4p3 3D + 6% 4s2 4p 4d 3D
	293046.0	292816.0	230.0	95% 4s2 4p 4d 3F
	331320.0	331257.0	63.0	87% 4s2 4p 4d 3D + 5% 4s 4p3 3D
	355506.0	355852.0	−346.0	94% 4s2 4p 4d 1F

(i) Zr IX:

J	E(obs) (cm^{-1}) [2, 8]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	59.0	−59.0	93% 3P + 8% 1S
0	66604.0	66570.0	34.0	93% 1S + 8% 3P
1	11362.0	11280.0	82.0	100% 3P
2	18977.0	18933.0	44.0	77% 3P + 23% 1D
2	39776.0	39878.0	−102.0	77% 1D + 23% 3P
				Excited configurations
0	231675.0	230836.0	839.0	95% 4s 4p3 3P + 4% 4s2 4p 4d 3P
	362928.0	362722.0	206.0	94% 4s2 4p 4d 3P + 4% 4s 4p3 3P
	529476.0	529476.0	0.0	98% 4s2 4p 5s 3P
1	202697.0	203488.0	−791.0	81% 4s 4p3 3D + 10% 4s 4p3 3P + 5% 4s2 4p 4d 3D
	233862.0	232869.0	993.0	82% 4s 4p3 3P + 10% 4s 4p3 3D
	282370.0	281500.0	870.0	63% 4s 4p3 3S + 31% 4s 4p3 1P
	304110.0	305649.0	−1539.0	60% 4s 4p3 1P + 32% 4s 4p3 3S + 4% 4s2 4p 4d 1P
	354697.0	356560.0	−1863.0	51%4s2 4p 4d 3P+39% 4s2 4p 4d 3D
	367082.0	366127.0	955.0	50%4s2 4p 4d 3D+42% 4s2 4p 4d 3P
	402026.0	399845.0	2181.0	89%4s2 4p 4d 1P+ 5% 4s 4p3 1P
	531136.0	531137.0	−1.0	77%4s2 4p 5s 3P+21% 4s2 4p 5s 1P
	553008.0	553008.0	0.0	77%s2 4p 5s 1P+21% 4s2 4p 5s 3P
2	156942.0	155983.0	959.0	95% 4s 4p3 5S
	202589.0	203760.0	−1171.0	79% 4s 4p3 3D+13% 4s 4p3 3P + 4% 4s2 4p 4d 3D
	236359.0	235628.0	731.0	69% 4s 4p3 3P+14% 4s 4p3 3D + 7% 4s 4p3 1D
	267109.0	266100.0	1009.0	69% 4s 4p3 1D+21% 4s2 4p 4d 1D + 8% 4s 4p3 3P
	317808.0	318032.0	−224.0	95% 4s2 4p 4d 3F
	346881.0	346263.0	618.0	55% 4s2 4p 4d 1D+22% 4s2 4p 4d 3P + 15% 4s 4p3 1D
	359881.0	358345.0	1536.0	49%4s2 4p 4d 3P+20% 4s2 4p 4d 1D +19% 4s2 4p 4d 3D+5% 4s 4p3 1D
	369552.0	368587.0	965.0	69%4s2 4p 4d 3D+22% 4s2 4p 4d 3P + 4% 4s 4p3 3D
3	206808.0	209018.0	−2210.0	94% 4s 4p3 3D+5% 4s2 4p 4d 3D
	325260.0	324072.0	1188.0	97% 4s2 4p 4d 3F
	368826.0	368758.0	68.0	90% 4s2 4p 4d 3D+5% 4s 4p3 3D
	395762.0	397989.0	−2227.0	95% 4s2 4p 4d 1F
4	329533.2	332617.0	−3083.8	98% 4s2 4p 4d 3F

(j) Nb X:

J	E(obs) (cm^{-1}) [2, 8]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	56.0	−56.0	91% 3P + 9% 1S
0	75254.0	75223.0	31.0	91% 1S + 9% 3P
1	14257.0	14170.0	87.0	100% 3P
2	22832.0	22805.0	27.0	73% 3P + 27% 1D
2	46777.0	46866.0	−89.0	73% 1D + 27% 3P
				Excited configurations
0	259239.0	257589.0	1650.0	95% 4s 4p3 3P+4% 4s2 4p 4d 3P
	399356.0	399774.0	−418.0	94% 4s2 4p 4d 3P+4% 4s 4p3 3P
	615624.0	615707.0	−83.0	98% 4s2 4p 5s 3P
1	228799.0	229751.0	−952.0	78% 4s 4p3 3D+13% 4s 4p3 3P + 5% 4s2 4p 4d 3D
	261171.0	260264.0	907.0	80% 4s 4p3 3P+12% 4s 4p3 3D
	308103.0	307314.0	789.0	57% 4s 4p3 3S+37% 4s 4p3 1P
	333987.0	333827.0	160.0	54% 4s 4p3 1P+38% 4s 4p3 3S
	389595.0	391412.0	−1817.0	45%4s2 4p4d 3P+44% 4s2 4p 4d 3D + 4% 4s2 4p 4d 1P
	403977.0	403260.0	717.0	47% 4s2 4p 4d 3P+45% 4s2 4p 4d 3D
	442400.0	439715.0	2685.0	89% 4s2 4p 4d 1P+4% 4s 4p3 1P
	617450.0	617365.0	85.0	75% 4s2 4p 5s 3P+23% 4s2 4p 5s 1P
	643233.0	643260.0	−27.0	75% 4s2 4p 5s 1P+23% 4s2 4p 5s 3P
2	188164.0	186994.0	1170.0	93% 4s 4p3 5S+6% 4s 4p3 3P
	229438.0	230499.0	−1061.0	76% 4s 4p3 3D+15% 4s 4p3 3P + 4% 4s2 4p 4d 3D
	263552.0	263621.0	−69.0	63% 4s 4p3 3P+17% 4s 4p3 3D + 10% 4s 4p3 1D
	291758.0	293274.0	−1516.0	67% 4s 4p3 1D+19% 4s2 4p 4d 1D + 11% 4s 4p3 3P
	349488.0	349583.0	−95.0	95% 4s2 4p 4d 3F
	381752.0	380017.0	1735.0	54% 4s2 4p 4d 1D+24% 4s2 4p 4d 3P + 14%4s4p3 1D+4% 4s2 4p 4d 3D
	395510.0	394345.0	1165.0	45% 4s2 4p 4d 3P+22% 4s2 4p 4d 3D + 21%4s2 4p 4d 1D+5% 4s 4p3 1D
	407150.0	406080.0	1070.0	66% 4s2 4p 4d 3D+25% 4s2 4p 4d 3P + 4% 4s 4p3 3D
	639196.0	639171.0	25.0	98% 4s2 4p 5s 3P
3	235011.0	236969.0	−1958.0	94% 4s 4p3 3D+5% 4s2 4p 4d 3D
	357395.0	357138.0	257.0	96% 4s2 4p 4d 3F
	406271.0	406012.0	259.0	89% 4s2 4p 4d 3D+5% 4s 4p3 3D
	435257.0	437628.0	−2371.0	95% 4s2 4p 4d 1F
4	365569.8	367868.0	−2298.2	98% 4s2 4p 4d 3F

(k) Mo XI:

J	E(obs) (cm^{-1}) [2,8,25]	E(LSF)	Diff.	LS-composition
				Ground configuration $4s^2 4p^2$
0	0.0	0.3	−0.3	90% 3P + 10% 1S
0	84827.0	84797.0	30.0	90% 1S + 10% 3P
1	17634.0	17535.0	99.0	100% 3P
2	27144.0	27140.0	4.0	70% 3P + 30% 1D
2	54744.0	54824.0	−80.0	70% 1D + 30% 3P
				Excited configurations
0	283971.0	283982.0	−11.0	95% 4s 4p3 3P + 4% 4s2 4p 4d 3P
	435602.0	437284.0	−1682.0	94% 4s2 4p 4d 3P + 4% 4s 4p3 3P
	707202.0	707225.0	−23.0	98% 4s2 4p 5s 3P
1	250372.0	250949.0	−577.0	81% 4s 4p3 3D + 10% 4s 4p3 3P
				+ 5% 4s2 4p 4d 3D
	286470.0	286168.0	302.0	82% 4s 4p3 3P + 10% 4s 4p3 3D
	334629.0	334213.0	416.0	69% 4s 4p3 3S + 25% 4s 4p3 1P
	365151.0	364918.0	233.0	66% 4s 4p3 1P + 26% 4s 4p3 3S
				+ 4% 4s2 4p 4d 1P
	424418.0	425106.0	−688.0	47% 4s2 4p 4d 3D + 41% 4s2 4p 4d 3P
				+ 5% 4s2 4p 4d 1P
	441704.0	441068.0	636.0	52% 4s2 4p 4d 3P + 41% 4s2 4p 4d 3D
	482674.0	479832.0	2842.0	87% 4s2 4p 4d 1P + 4% 4s2 4p 4d 3D
	709077.0	709053.0	24.0	74% 4s2 4p 5s 3P + 24% 4s2 4p 5s 1P
	739589.0	739597.0	−8.0	74% 4s2 4p 5s 1P + 24% 4s2 4p 5s 3P
2	251396.0	251512.0	−116.0	79% 4s 4p3 3D + 14% 4s 4p3 3P
				+ 4% 4s2 4p 4d 3D
	289416.0	289094.0	322.0	66% 4s 4p3 3P + 14% 4s 4p3 3D
				+ 10% 4s 4p3 1D
	320056.0	321598.0	−1542.0	68% 4s 4p3 1D + 18% 4s2 4p 4d 1D
				+ 11% 4s 4p3 3P
	380857.0	380888.0	−31.0	94% 4s2 4p 4d 3F
	415627.0	414016.0	1611.0	45% 4s2 4p 4d 1D + 32% 4s2 4p 4d 3P
				+ 11% 4s 4p3 1D + 7% 4s2 4p 4d 3D
	430171.0	431098.0	−927.0	35% 4s2 4p 4d 3P + 30% 4s2 4p 4d 1D
				+ 21% 4s2 4p 4d 3D + 6% 4s 4p3 1D
	445358.0	444485.0	873.0	64% 4s2 4p 4d 3D + 27% 4s2 4p 4d 3P
	735196.0	735189.0	7.0	98% 4s2 4p 5s 3P
3	258396.0	257917.0	479.0	94% 4s 4p3 3D + 5% 4s2 4p 4d 3D
	390034.0	390735.0	−701.0	95% 4s2 4p 4d 3F
	475316.0	476909.0	−1593.0	94% 4s2 4p 4d 1F

Table 2. Calculated transition probabilities and Oscillator strengths for Ge I atom.

Wavelength (Å)	j	i	loggf	$gA_{ki} * 10^{-08}$ (sec^{-1})
	$4s^2 4p5s$	$4s^2 4p^2$		
2895.05	3P0	3P1	−0.619	1.913
2834.935	3P1	3P0	−0.656	1.832
2875.077	3P1	3P1	−0.798	1.284
2941.666	3P1	3P2	−0.54	2.22
3700.114	3P1	1D2	−1.126	3.643
2772.965	3P2	3P1	−0.495	2.774
2834.856	3P2	3P2	−0.037	7.619
3532.694	3P2	1D2	−2.28	0.028
2673.39	1P1	3P0	−1.54	0.269
2709.059	1P1	3P1	−1.642	0.207
2768.1	1P1	3P2	−1.849	0.123
3429.625	1P1	1D2	−0.129	4.213
5492.53	1P1	1S0	−1.242	0.126
	$4s^2 4p4d$	$4s^2 4p^2$		
2227.493	3D2	3P1	6.562	6.562
2267.255	3D2	3P2	0.347	0.347
2692.657	3D2	1D2	0.065	0.065
2200.424	3D1	3P0	4.248	4.248
2224.532	3D1	3P1	2.137	2.137
2264.188	3D1	3P2	0.04	0.04
2688.331	3D1	1D2	0.046	0.046
3810.012	3D1	1S0	0.015	0.015
2211.451	1D2	3P1	1.859	1.859
2250.637	1D2	3P2	0.95	0.95
2669.25	1D2	1D2	0.976	0.976
2247.03	3D3	3P2	12.98	12.98
	$4s^2 4p4d$	$4s^2 4p^2$		
2664.177	3D3	1D2	0.192	0.192
2140.932	3F2	3P3	0.652	0.652
2177.638	3F2	3P2	0.339	0.339
2567.186	3F2	1P2	0.286	0.286
2167.018	3F3	3P2	1.5	1.5
2552.438	3F3	1D2	0.996	0.996
2104.543	3P2	3P1	0.25	0.25
2140.002	3P2	3P2	5.731	5.731
2515.041	3P2	1D2	0.249	0.249
2071.018	3P1	3P0	0.587	0.587
2092.36	3P1	3P1	1.663	1.663
2127.406	3P1	3P2	1.769	1.769
3438.046	3P1	1S0	0.027	0.027
2083.569	3P0	3P1	1.355	1.355
2069.035	1F3	3P2	0.051	0.051
2417.587	1F3	1D2	22.3	22.3
1993.616	1P1	3P0	0.059	0.059
2385.944	1P1	1D2	1.011	1.011
3229.873	1P1	1S0	2.225	2.225
	$4s4p^3$	$4s^2 4p^2$		
2724.193	5S2	3P1	−2.908	0.011
2783.903	5S2	3P2	−2.442	0.031

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

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

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