Canadian Journal of Physics

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Journal:	<i>Canadian Journal of Physics</i>
Manuscript ID	cjp-2018-0437.R2
Manuscript Type:	Article
Date Submitted by the Author:	06-Nov-2018
Complete List of Authors:	Konan, Gülay; Sakarya Universitesi
Keyword:	Energy levels, Transition parameters, AUTOSTRUCTURE, Mg-like ions, Electric dipole transitions
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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The calculation of energy levels and electric dipole (E1) transition parameters for magnesium like bismuth

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Abstract

Energy levels and electric dipole (E1) transition parameters such as wavelengths, transition probabilities (rates), weighted oscillator strengths and line strengths for the levels of $3/l'$ ($l, l'=0,1,2$) in magnesium like bismuth (Bi LXXII, Bi^{71+} , $Z=83$) are calculated using the AUTOSTRUCTURE code, which uses non-relativistic or kappa-averaged relativistic wave functions and the full Breit interaction in Pauli approximation. The results are compared with the available literature values and a good agreement is achieved. There is no available experimental data for Bi^{71+} . Therefore, these theoretical calculations can provide useful data for experimentalists in the identification process upon measurements.

Keywords: Energy levels; Transition parameters; AUTOSTRUCTURE; Mg like ions; Electric dipole transitions

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1. Introduction

Mg like ions which have two electrons outside a core of closed electronic shells play a significant role in astrophysics, plasma, and thermonuclear fusion research [1-3]. Accurate atomic data such as transition probabilities and oscillator strengths are required of analysis and modeling of plasmas. In addition, these theoretical data are used in interpretation of laboratory beam-foil experiments [3]. Furthermore, since the correlation effects between valence and core electrons are still a theoretical problem, the magnesium isoelectronic sequence is one of the simplest systems for studying the different correlation effects as especially core-valence or core-core correlations.

Although there are a lot of papers about magnesium like ions, only a few element of the sixth row of the periodic table have been studied. These sixth row elements have high Z and highly charged ions (HCIs) of high Z elements are important for many fields such as atomic physics, plasma physics, laser physics, astrophysics and radiation biology [4]. From a theoretical viewpoint, the investigations of HCIs provide an excellent possibility for testing relativistic and quantum electrodynamics effects (QED). Also accurate radiative data of HCIs are required for astrophysical studies. For example the spectral data of bismuth ions have aroused a great deal of attention for astrophysical applications [5]. Radiative parameters of magnesium like Bismuth ion (Bi^{71+}) are still extremely scarce both on theoretical and experimental sides in the literature. There are only two papers for Bi^{71+} . Theoretical relativistic energy levels of Bi^{71+} were calculated using the relativistic Multi-Reference Møller–Plesset (MR-MP) many-body perturbation theory for the energies of all excited states within the $3s3p$, $3p^2$, $3s3d$, $3p3d$ and $3d^2$ configurations by Santana [6]. Hu et al. reported theoretical multiconfiguration Dirac–Hartree–Fock (MCDHF) calculations of transition probabilities for the $n=3$ to $n=3$ transitions as well as energy levels for the lowest 35 levels of magnesium like Bi ion [7]. We have presented new theoretical values by using AUTOSTRUCTURE. So, accurate dataset presented here can provide the accuracy of theoretical values and useful data for the experimental studies in future work. Therefore the data of Bi^{71+} can use for astrophysical applications.

The purpose of the present work is to determine the energy levels, wavelengths, transition probabilities, weighted oscillator strengths and line strengths of electric dipole (E1) transitions

in Mg like Bi. The calculations have performed using AUTOSTRUCTURE code in the Breit–Pauli distorted wave approach [8]. Correlation contributions, Quantum electrodynamics (QED, self-energy and vacuum polarization) effects and relativistic corrections arising from the Breit interaction (magnetic interaction between the electrons and retardation effects of the electron electron interaction) have been included. We have here taken into account the configurations $3snl$ ($n=3-6$, $l=0-4$), $3pnl$ ($n=3-6$, $l=0-4$), $3dnl$ ($n=3-6$, $l=0-4$) for valence - valence correlation, $2p^53s^23p$, $2p^53s3p^2$, $2p^53p^3$, $2p^53s^23d$, $2p^53s^24s$, $2p^53s3p3d$, $2p^53p^23d$, $2p^53d^3$, $2p^53s3d^2$, $2p^53s3p4s$, $2p^53p3d^2$, $2p^53p3d4s$ for core - valence correlation and $2p^43s^23p^2$, $2p^43s3p^3$, $2p^43s^23d^2$, $2p^43s^23p3d$, $2s2p^53s^23p3d$ for core - core correlations.

2. Calculation method

AUTOSTRUCTURE code [8, 9] is used to calculate the atomic and ionic energy levels, radiative and autoionization rates and photoionization cross sections using the Breit–Pauli distorted wave method. It was developed from SUPERSTRUCTURE [10]. The wavefunctions are determined by diagonalization of the Breit–Pauli Hamiltonian using orbitals calculated in Thomas-Fermi or Slater-Type-Orbital potential model. In this code, the configuration set is chosen optionally and additional configuration to improve accuracy of the structure (a configuration interaction expansion, CI expansion). In the calculations, LS, IC (intermediate coupling) or ICR (relativistic intermediate coupling) coupling should be chosen. The hamiltonian is diagonalized to obtain eigenvalues and eigenvectors with which to construct the rates.

Both of quantum electrodynamics contributions and Breit relativistic effects are added as a perturbation correction. QED consist of self-energy and vacuum polarization contributions to level energies. Relativistic correction operators which can be grouped as the one-body operators, namely mass–velocity, Darwin and nuclear spin–orbit, and two-body operators which can be subdivided namely (two-body) fine-structure operators, namely spin–orbit, spin–other orbit and spin–spin, and the (two-body) non-fine-structure operators, namely contact spin–spin, Darwin and orbit–orbit. The finite-nucleus effect is taken into account by assuming an extended Fermi distribution for the nucleus. Orbitals are fixed, but the mixing coefficients are obtained by diagonalizing the modified hamiltonian. CI method was used to account for the correlation effects.

The details of the method can be found in Refs. [8,9,11] and we only summarize this here briefly. For a system with N electrons, a set of configurations

$$c = \prod_{nl} (nl)^{q_{nl}}, \quad \sum_i q_i = N \quad (1)$$

defines a trial solution $\Psi(\gamma)$ to a suitable hamiltonian H in the multiconfigurational sum form

$$\Psi(\gamma|\mathbf{x}_1, \dots, \mathbf{x}_N) = \sum_k a_k \Phi_k(c_k(\gamma)|\mathbf{x}_1, \dots, \mathbf{x}_N) \quad (2)$$

where γ denotes configuration and coupling scheme. In intermediate coupling (IC) wave functions can be written as

$$\Psi = \Psi(\Gamma SLJM_J|\mathbf{x}_1, \dots, \mathbf{x}_N) \quad (3)$$

which are eigenvectors to the Breit-Pauli matrix $\langle k|H_{BP}|k' \rangle$ with eigenvalues E_k .

For transitions from (3) code computes Einstein coefficients and associated quantities for multipole transitions of low multipolarity (for electric dipole, E1, radiation). Generally, electric multipole transitions exist in both of LS coupling and intermediate coupling (or jj-coupling). In the long wavelength low intensity approximation the probability for spontaneous emission by E1 radiation,

$$A_{i' \rightarrow i} = 2.6774 \times 10^9 \frac{(E_i - E_{i'})^3}{g_i} \cdot S(i, i') \quad (4)$$

Here, g_i is statistical weighted of level, E_i and $E_{i'}$ are energies of levels and $S(i, i')$ is line strengths in form

$$S(i, i') = \left| \langle i' || R^{[k]} || i \rangle \right|^2 \quad (5)$$

where $R^{[k]}$ is a transition operator and describes each multipole, k is 1 for electric dipole radiation. In addition weighted absorption or emission oscillator strength (gf) value can be written in terms of line strengths

$$(gf)_{i,i'} = (gf)_{i',i} = \frac{|E_i - E_{i'}|}{3} \cdot S(i, i') \quad (6)$$

3. Results and Discussion

Mg like bismuth ion (Bi LXXII or Bi^{71+}) has two valence electrons outside a closed core. The electronic configuration for Bi^{71+} ion is $1s^2 2s^2 2p^6 3s^2$. We have calculated the energy levels and electric dipole transition parameters such as wavelengths, transition probabilities, weighted oscillator strengths and line strengths for this ion using AUTOSTRUCTURE code developed by Badnell [8]. Since Bi^{71+} is a highly charged ion, relativistic and quantum electrodynamics corrections contribute significantly in the determination of energy levels and transition parameters. Furthermore, the electron correlation effects due to the Coulomb interaction between the electrons are important in precision calculations of heavy atoms. So, computed energy levels and transition parameters contain Breit interaction (magnetic interaction between the electrons and retardation effects of the electron–electron interaction), QED (self-energy and vacuum polarization) contributions and all types of correlations. We have taken into account the configurations $3snl$ ($n=3-6$, $l=0-4$), $3pnl$ ($n=3-6$, $l=0-4$), $3dnl$ ($n=3-6$, $l=0-4$) for valence - valence correlation, $2p^5 3s^2 3p$, $2p^5 3s 3p^2$, $2p^5 3p^3$, $2p^5 3s^2 3d$, $2p^5 3s^2 4s$, $2p^5 3s 3p 3d$, $2p^5 3p^2 3d$, $2p^5 3d^3$, $2p^5 3s 3d^2$, $2p^5 3s 3p 4s$, $2p^5 3p 3d^2$, $2p^5 3p 3d 4s$ for core - valence correlation and $2p^4 3s^2 3p^2$, $2p^4 3s 3p^3$, $2p^4 3s^2 3d^2$, $2p^4 3s^2 3p 3d$, $2s 2p^5 3s^2 3p 3d$ for core - core correlations.

3.1. Energy Levels

We have obtained 2005 energy levels using the configurations mentioned above. In Table 1, there are just given the energies of $3l3l'$ ($l, l'=0, 1, 2$) levels which have comparing values in the literature. To assess the accuracy and reliability of our present results, our AUTOSTRUCTURE energies have been compared with the other theoretical results of the relativistic Multi-Reference Møller–Plesset (MR-MP) theory based on the relativistic Dirac–Coulomb–Breit Hamiltonian [6] and the multiconfiguration Dirac–Hartree–Fock (MCDHF)

which the Breit interaction and leading quantum electrodynamic effects are included as perturbations [7]. There is no experimental data in the literature for energy levels of this ion. We have given $(|E_{\text{our}} - E_{\text{other}}|/E_{\text{other}}) \times 100$, the differences in per cent in the last column of Table 1. It has been found that the present AUTOSTRUCTURE energies agree with the results of MR-MP [6] to better than 0.72% for $3/3l'$ levels, but with the exception being longer by 1.07% – 1.59% for first three levels. Also, the differences in per cent between our AUTOSTRUCTURE results and the MCDHF [7] is better than 0.73% for $3/3l'$ levels, but with the exception being longer by 1.26% – 1.71% for first three levels. The levels 3P_0 and 3P_1 of $3s3p$ are 137.7067×10^4 and $153.6785 \times 10^4 \text{ cm}^{-1}$, with the compared values 136.2482×10^4 and $151.2798 \times 10^4 \text{ cm}^{-1}$ for MR-MP [6] and 135.9724×10^4 and $151.0518 \times 10^4 \text{ cm}^{-1}$ for MCDHF [7] respectively. The comparison of our energy results between this work and other works have been showed in Fig. 1. Linear correlation coefficient R^2 is 1 for MR-MP [6], and MCDHF [7]. It could be said that the present energy levels are in very good agreement with the theoretical values. On the other hand, all computed energy levels in this work have been given as supplementary (Table S1).

3.2. Electric Dipole (E1) Transitions

We have obtained 524 955 transitions from this calculation for E1 transitions among 2005 levels of Bi^{71+} . Wavelengths (λ), transition probabilities (A_r), weighted oscillator strengths (gf) and line strengths (S) for the only $3/3l'$ ($l, l'=0,1,2$) levels have been listed in Table 2. In this table we have given only the radiative parameters which have compared values. MCDHF values [7] for E1 transitions are one and only data in the available literature. In the table, the numbers in brackets represent the power of 10. All computed transition parameters for E1 transitions in this work have been given as supplementary (Table S2). These data which include transitions between upper levels (for $n > 3$ levels) have been presented for the first time.

The transition probabilities, weighted oscillator strengths and line strengths comparisons for the only $3/3l'$ ($l, l'=0,1,2$) levels of the E1 transitions for Bi^{71+} have been displayed in Fig. 2, 3 and 4 respectively. In these graphics, linear correlation coefficients are 0.9994 for transition probabilities, 0.9991 for weighted oscillator strengths and 0.9987 for line strengths. There is generally a good agreement between present AUTOSTRUCTURE calculations and MCDHF results [7] for most transitions. Only the transition parameters for $3p3d \ ^3F_2 - 3s3d \ ^1D_2, 3d^2 \ ^3F_2 -$

$3p3d\ ^1P_1$, $3d^2\ ^1D_2 - 3p3d\ ^1F_3$ and $3d^2\ ^1S_0 - 3p3d\ ^3P_1$ transitions are somewhat poor. For these transitions there is 10 times difference between our transition probabilities and comparison results. For example, transition probability for $3p3d\ ^3F_2 - 3s3d\ ^1D_2$ transition is 1.49(04) with the compared value 1.06(03). The same comment could be made for line strengths and gf -values. We think that these cases occur due to some restrictions in two methods, and can be improved when configurations including more core-core correlations are considered, but program procedure doesn't run because of arising a huge number of levels. Similar studies which considered electron correlations for various materials have been reported recently [12-13]. As can be seen from the Table 2 the line strengths of some transitions are zero. The values less than 10^{-6} have been obtained as zero in computing. The wavelengths comparison of the E1 transitions has been displayed in Fig. 5. Linear correlation coefficient is 0.9967. So, the present AUTOSTRUCTURE wavelengths have had in an excellent agreement with other work [7] except $3p3d\ ^3F_2 - 3s3d\ ^1D_2$ transition. For this transition, present wavelength is 791.96 Å with the previous work 619.42 Å.

Conclusion

In this paper, it has been reported a complete and accurate data set of energies, wavelengths, transition probabilities, weighted oscillator strengths and line strengths for E1 transitions of Mg like Bi (Bi^{71+} , $Z=83$) ion using the AUTOSTRUCTURE code. The present study has performed as a part of extensive study about Mg like ions [14-16]. Our calculations have been compared with only theoretical data because there is lack of experimental data in available literature and good agreements have been obtained from the comparisons. Furthermore, energy levels and transition parameters for $n>3$ levels have been presented for the first time. Hopefully, this paper will facilitate experimental studies in connection with the diagnostic of astrophysical and laboratory plasma.

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Table 1. Energy levels, E ($\times 10000\text{ cm}^{-1}$), and differences (%) in energies of $3/3l'$ ($l, l'=0,1,2$) levels for Bi^{71+} .

Levels		This work	Other works		Differences (%)
		AS	MR-MP ^a	MCDHF ^b	(%)
$3s^2$	1S_0	0	0	0	$0^a, 0^b$
$3s3p$	3P_0	137.7067	136.2482	135.9724	$1.07^a, 1.26^b$
$3s3p$	3P_1	153.6785	151.2798	151.0518	$1.59^a, 1.71^b$
$3p^2$	3P_0	327.5378	323.4389	323.0539	$1.27^a, 1.37^b$
$3s3p$	3P_2	654.4829	652.5704	653.1811	$0.29^a, 0.20^b$
$3s3p$	1P_1	689.2590	686.9689	687.6810	$0.33^a, 0.23^b$
$3p^2$	1D_2	827.5020	823.5883	823.7553	$0.48^a, 0.45^b$
$3p^2$	3P_1	830.5458	826.3510	826.7580	$0.51^a, 0.46^b$
$3s3d$	3D_1	852.8638	852.1604	852.0752	$0.08^a, 0.09^b$
$3s3d$	3D_2	868.4171	866.3730	866.5807	$0.24^a, 0.21^b$
$3s3d$	3D_3	972.1702	966.2693	966.2864	$0.61^a, 0.61^b$
$3s3d$	1D_2	988.3277	981.8102	981.9711	$0.66^a, 0.64^b$
$3p3d$	3F_2	1000.9546	998.4387	998.1154	$0.25^a, 0.28^b$
$3p3d$	3D_1	1033.4831	1031.3457	1031.1400	$0.21^a, 0.23^b$
$3p3d$	3P_2	1137.6015	1130.5369	1130.3378	$0.62^a, 0.64^b$
$3p3d$	1F_3	1142.0116	1133.8101	1133.6669	$0.72^a, 0.73^b$
$3p^2$	3P_2	1353.5166	1348.8486	1350.1747	$0.35^a, 0.25^b$
$3p^2$	1S_0	1371.3265	1367.0642	1368.4650	$0.31^a, 0.21^b$
$3p3d$	3D_2	1529.7437	1527.5476	1528.1206	$0.14^a, 0.11^b$
$3p3d$	3P_0	1538.2031	1536.8599	1537.4538	$0.09^a, 0.05^b$
$3p3d$	3P_1	1538.9552	1537.1903	1537.7894	$0.11^a, 0.08^b$
$3p3d$	3F_3	1539.9005	1536.7105	1537.3716	$0.21^a, 0.16^b$
$3p3d$	3F_4	1638.7454	1630.9823	1631.6560	$0.48^a, 0.43^b$
$3p3d$	1D_2	1648.5113	1641.6320	1642.3100	$0.42^a, 0.38^b$
$3p3d$	3D_3	1666.0250	1658.2045	1658.9799	$0.47^a, 0.42^b$
$3p3d$	1P_1	1676.9983	1670.1022	1670.9618	$0.41^a, 0.36^b$
$3d^2$	3F_2	1717.3697	1717.5517	1717.4420	$0.01^a, 0.00^b$
$3d^2$	3P_0	1741.2279	1742.7705	1742.8035	$0.09^a, 0.09^b$
$3d^2$	3F_3	1832.8688	1827.6959	1827.6572	$0.28^a, 0.28^b$
$3d^2$	3P_2	1842.8814	1838.7425	1838.7520	$0.23^a, 0.22^b$
$3d^2$	3P_1	1847.5452	1844.1264	1844.1282	$0.19^a, 0.18^b$
$3d^2$	1G_4	1847.9658	1840.9999	1841.0769	$0.38^a, 0.37^b$
$3d^2$	3F_4	1956.7853	1945.9139	1946.0191	$0.56^a, 0.55^b$
$3d^2$	1D_2	1965.0982	1955.8618	1956.0034	$0.47^a, 0.46^b$
$3d^2$	1S_0	1990.5054	1981.8555	1982.2333	$0.44^a, 0.42^b$

^a Ref. [6], ^bRef. [7].

Table 2. Transition probabilities, A_r (s^{-1}), line strengths, S , weighted oscillator strengths, gf , and wavelengths, λ ($\text{\AA}$), for $3/3l'$ ($l, l'=0, 1, 2$) transitions in Bi^{71+} . Numbers in brackets represent powers of 10. It has been omitted to give the core $1s^2 2s^2 2p^6$ in the table.

				A_r		S		gf		λ	
Upper level		Lower level		This work	Other work ^a	This work	Other work ^a	This work	Other work ^a	This work	Other work ^a
3s3p	3P_1	$3s^2$	1S_0	2.75(10)	2.89(10)	1.12(02)	1.24(02)	5.23(02)	5.70(02)	65.07	66.20
3p ²	3P_0	3s3p	3P_1	1.77(11)	1.80(11)	1.67(02)	1.74(02)	8.80(02)	9.10(02)	57.52	58.14
3s3p	1P_1	$3s^2$	1S_0	7.36(12)	7.45(12)	3.33(02)	3.39(02)	6.97(01)	7.09(01)	14.51	14.54
3s3p	1P_1	$3p^2$	3P_0	3.17(09)	3.28(09)	9.90(05)	1.00(04)	1.09(03)	1.11(03)	27.65	27.43
3p ²	1D_2	3s3p	3P_1	1.02(12)	1.27(12)	8.23(03)	1.03(02)	1.69(01)	2.11(01)	14.84	14.87
3p ²	1D_2	3s3p	3P_2	4.52(10)	4.56(10)	2.15(02)	2.27(02)	1.13(01)	1.17(01)	57.80	58.63
3p ²	1D_2	3s3p	1P_1	1.07(10)	1.20(10)	9.99(03)	1.18(02)	4.20(02)	4.86(02)	72.34	73.49
3p ²	3P_1	3s3p	3P_0	3.47(12)	3.49(12)	1.55(02)	1.57(02)	3.25(01)	3.28(01)	14.43	14.48
3p ²	3P_1	3s3p	3P_1	1.88(12)	1.92(12)	8.98(03)	9.22(03)	1.85(01)	1.89(01)	14.77	14.80
3p ²	3P_1	3s3p	3P_2	6.78(10)	6.91(10)	1.84(02)	1.96(02)	9.84(02)	1.03(01)	56.80	57.61
3p ²	3P_1	3s3p	1P_1	6.07(09)	6.38(09)	3.19(03)	3.51(03)	1.37(02)	1.48(02)	70.78	71.90
3s3d	3D_1	3s3p	3P_0	3.03(12)	3.01(12)	1.23(02)	1.21(02)	2.66(01)	2.64(01)	13.98	13.96
3s3d	3D_1	3s3p	3P_1	1.37(12)	1.32(12)	5.92(03)	5.67(03)	1.26(01)	1.21(01)	14.30	14.26
3s3d	3D_1	3s3p	3P_2	2.35(09)	2.17(09)	4.45(04)	4.08(04)	2.68(03)	2.46(03)	50.41	50.28
3s3d	3D_1	3s3p	1P_1	6.30(09)	6.45(09)	2.13(03)	2.15(03)	1.06(02)	1.07(02)	61.12	60.83
3s3d	3D_2	3s3p	3P_1	8.31(12)	8.07(12)	5.62(02)	5.44(02)	1.22(00)	1.18(00)	13.99	13.98
3s3d	3D_2	3s3p	3P_2	0.48(08)	1.94(08)	1.20(05)	4.93(05)	7.92(05)	3.19(04)	46.74	46.86
3s3d	3D_2	3s3p	1P_1	7.28(09)	6.94(09)	3.13(03)	2.99(03)	1.70(02)	1.62(02)	55.82	55.90
3s3d	3D_3	3s3p	3P_2	4.49(11)	4.21(11)	4.84(02)	4.74(02)	4.67(01)	4.51(01)	31.48	31.94
3s3d	1D_2	3s3p	3P_1	3.30(11)	3.26(11)	1.40(03)	1.40(03)	3.55(02)	3.54(02)	11.98	12.03
3s3d	1D_2	3s3p	3P_2	1.05(11)	9.76(10)	6.93(03)	6.77(03)	7.03(02)	6.76(02)	29.95	30.41
3s3d	1D_2	3s3p	1P_1	3.81(11)	3.53(11)	3.52(02)	3.42(02)	3.19(01)	3.05(01)	33.44	33.98
3p3d	3F_2	$3p^2$	1D_2	3.47(10)	3.45(10)	1.64(02)	1.61(02)	8.64(02)	8.52(02)	57.65	57.35
3p3d	3F_2	$3p^2$	3P_1	1.31(09)	1.46(09)	6.51(04)	7.17(04)	3.37(03)	3.73(03)	58.68	58.36
3p3d	3F_2	3s3d	3D_1	2.52(10)	2.67(10)	1.91(02)	2.12(02)	8.61(02)	9.40(02)	67.53	68.47
3p3d	3F_2	3s3d	3D_2	7.41(09)	8.82(09)	7.86(03)	9.56(03)	3.16(02)	3.82(02)	75.45	76.03
3p3d	3F_2	3s3d	3D_3	1.34(04)	3.40(04)	1.00(06)	2.60(06)	1.21(06)	2.51(06)	347.41	314.18
3p3d	3F_2	3s3d	1D_2	1.49(04)	1.06(03)	1.80(05)	6.19(07)	6.99(06)	3.03(07)	791.96	619.42
3p3d	3D_1	$3s^2$	1S_0	2.43(08)	1.93(08)	0.00(00)	2.60(07)	1.02(05)	8.15(06)	9.68	9.70
3p3d	3D_1	$3p^2$	3P_0	5.71(12)	5.61(12)	2.40(02)	2.34(02)	5.15(01)	5.03(01)	14.17	14.12
3p3d	3D_1	$3p^2$	1D_2	8.98(09)	8.03(09)	1.52(03)	1.33(03)	9.52(03)	8.40(03)	48.55	48.22
3p3d	3D_1	$3p^2$	3P_1	1.84(10)	1.90(10)	3.26(03)	3.30(03)	2.01(02)	2.05(02)	49.28	48.93
3p3d	3D_1	3s3d	3D_1	1.57(10)	1.59(10)	3.94(03)	4.11(03)	2.16(02)	2.24(02)	55.37	55.85
3p3d	3D_1	3s3d	3D_2	5.80(10)	5.86(10)	1.91(02)	1.95(02)	9.57(02)	9.72(02)	60.58	60.77
3p3d	3D_1	3s3d	1D_2	2.85(07)	2.44(07)	4.59(04)	3.05(04)	6.29(04)	4.55(04)	221.46	203.38
3p3d	3P_2	$3p^2$	1D_2	5.11(10)	4.99(10)	4.23(03)	4.28(03)	3.98(02)	3.98(02)	32.25	32.62
3p3d	3P_2	$3p^2$	3P_1	3.78(11)	3.56(11)	3.23(02)	3.14(02)	3.01(01)	2.90(01)	32.57	32.94
3p3d	3P_2	3s3d	3D_1	3.39(07)	7.02(07)	4.00(06)	8.04(06)	3.14(05)	6.80(05)	35.12	35.94

Table 2 (continued)

				A_r		S		gf		λ	
Upper level		Lower level		This work	Other work ^a	This work	Other work ^a	This work	Other work ^a	This work	Other work ^a
3p3d	3P_2	3s3d	3D_2	1.28(10)	1.08(10)	1.62(03)	1.46(03)	1.32(02)	1.17(02)	37.15	37.91
3p3d	3P_2	3s3d	3D_3	5.71(10)	5.75(10)	3.11(02)	3.21(02)	1.56(01)	1.60(01)	60.45	60.96
3p3d	3P_2	3s3d	1D_2	9.25(09)	9.88(09)	6.87(03)	7.46(03)	3.11(02)	3.36(02)	66.99	67.40
3p3d	1F_3	$3p^2$	1D_2	2.80(11)	2.67(11)	3.11(02)	3.10(02)	2.97(01)	2.92(01)	31.80	32.27
3p3d	1F_3	3s3d	3D_2	2.10(10)	1.50(10)	3.54(03)	2.72(03)	2.94(02)	2.21(02)	36.55	37.44
3p3d	1F_3	3s3d	3D_3	3.49(10)	3.53(10)	2.46(02)	2.60(02)	1.27(01)	1.32(01)	58.88	59.74
3p3d	1F_3	3s3d	1D_2	4.10(10)	4.29(10)	3.90(02)	4.25(02)	1.82(01)	1.96(01)	65.07	65.92
$3p^2$	3P_2	3s3p	3P_1	1.21(09)	1.59(09)	2.00(06)	2.28(06)	6.31(05)	8.30(05)	8.33	8.34
$3p^2$	3P_2	3s3p	3P_2	5.36(12)	5.44(12)	3.87(02)	3.96(02)	8.22(01)	8.39(01)	14.31	14.35
$3p^2$	3P_2	3s3p	1P_1	5.26(12)	5.31(12)	4.43(02)	4.51(02)	8.94(01)	9.07(01)	15.05	15.09
$3p^2$	3P_2	3p3d	3F_2	3.27(08)	3.36(08)	1.80(05)	1.90(05)	1.97(04)	2.03(04)	28.36	28.40
$3p^2$	3P_2	3p3d	3D_1	2.04(09)	2.24(09)	1.54(04)	1.70(04)	1.50(03)	1.65(03)	31.25	31.34
$3p^2$	3P_2	3p3d	3P_2	1.25(08)	1.51(08)	3.10(05)	3.50(05)	2.01(04)	2.33(04)	46.31	45.49
$3p^2$	3P_2	3p3d	1F_3	5.60(07)	5.97(07)	1.50(05)	1.45(05)	9.38(05)	9.54(05)	47.28	46.19
$3p^2$	1S_0	3s3p	3P_1	2.15(10)	2.15(10)	6.00(06)	5.89(06)	2.17(04)	2.18(04)	8.21	8.21
$3p^2$	1S_0	3s3p	1P_1	1.04(13)	1.05(13)	1.62(02)	1.65(02)	3.36(01)	3.41(01)	14.66	14.69
$3p^2$	1S_0	3p3d	3D_1	1.16(08)	1.65(08)	1.00(06)	2.13(06)	1.53(05)	2.18(05)	29.60	29.65
3p3d	3D_2	$3p^2$	1D_2	4.26(12)	4.15(12)	3.03(02)	2.93(02)	6.47(01)	6.26(01)	14.24	14.20
3p3d	3D_2	$3p^2$	3P_1	1.97(12)	1.91(12)	1.42(02)	1.37(02)	3.02(01)	2.91(01)	14.30	14.26
3p3d	3D_2	3s3d	3D_1	2.62(12)	2.69(12)	2.09(02)	2.15(02)	4.29(01)	4.42(01)	14.77	14.79
3p3d	3D_2	3s3d	3D_2	5.51(11)	6.75(11)	4.70(03)	5.75(03)	9.44(02)	1.16(01)	15.12	15.12
3p3d	3D_2	3s3d	3D_3	3.02(09)	3.53(09)	4.30(05)	4.92(05)	7.28(04)	8.39(04)	17.93	17.80
3p3d	3D_2	3s3d	1D_2	0.35(09)	1.06(09)	5.00(06)	1.61(05)	8.96(05)	2.67(04)	18.47	18.31
3p3d	3D_2	$3p^2$	3P_2	8.50(09)	8.61(09)	3.83(03)	3.77(03)	2.05(02)	2.04(02)	56.75	56.20
3p3d	3P_0	$3p^2$	3P_1	3.98(12)	3.87(12)	5.55(03)	5.32(03)	1.19(01)	1.15(01)	14.13	14.07
3p3d	3P_0	3s3d	3D_1	5.68(12)	5.79(12)	8.70(03)	8.88(03)	1.81(01)	1.85(01)	14.59	14.59
3p3d	3P_1	$3s^2$	1S_0	3.95(08)	2.95(08)	0.00(00)	1.20(07)	7.50(06)	5.61(06)	6.50	6.50
3p3d	3P_1	$3p^2$	3P_0	1.56(09)	1.60(09)	1.00(06)	1.32(06)	4.78(05)	4.88(05)	8.25	8.23
3p3d	3P_1	$3p^2$	1D_2	7.32(10)	9.11(10)	3.01(04)	3.70(04)	6.50(03)	8.03(03)	14.06	14.00
3p3d	3P_1	$3p^2$	3P_1	3.67(12)	3.66(12)	1.53(02)	1.51(02)	3.29(01)	3.26(01)	14.12	14.06
3p3d	3P_1	3s3d	3D_1	4.28(12)	4.30(12)	1.96(02)	1.98(02)	4.09(01)	4.12(01)	14.58	14.58
3p3d	3P_1	3s3d	3D_2	1.52(12)	1.49(12)	7.44(03)	7.29(03)	1.52(01)	1.49(01)	14.91	14.90
3p3d	3P_1	3s3d	1D_2	1.25(10)	1.23(10)	1.11(04)	1.06(04)	1.85(03)	1.79(03)	18.16	17.99
3p3d	3P_1	$3p^2$	3P_2	1.46(10)	1.52(10)	3.38(03)	3.41(03)	1.90(02)	1.94(02)	53.93	53.30
3p3d	3P_1	$3p^2$	1S_0	5.07(09)	5.25(09)	1.59(03)	1.60(03)	8.11(03)	8.24(03)	59.66	59.06
3p3d	3F_3	$3p^2$	1D_2	5.72(11)	6.69(11)	5.46(03)	6.36(03)	1.18(01)	1.38(01)	14.04	14.01
3p3d	3F_3	3s3d	3D_2	8.13(12)	8.07(12)	9.27(02)	9.24(02)	1.89(00)	1.88(00)	14.89	14.91
3p3d	3F_3	3s3d	3D_3	3.81(10)	3.71(10)	7.20(04)	6.89(04)	1.24(02)	1.19(02)	17.61	17.51
3p3d	3F_3	3s3d	1D_2	9.93(10)	1.01(11)	2.05(03)	2.05(03)	3.43(02)	3.45(02)	18.13	18.01
3p3d	3F_3	$3p^2$	3P_2	2.48(09)	2.60(09)	1.32(03)	1.37(03)	7.50(03)	7.78(03)	53.65	53.42

Table 2 (continued)

Upper level		Lower level		A _r		S		gf		λ	
				This work	Other work ^a	This work	Other work ^a	This work	Other work ^a	This work	Other work ^a
3p3d	³ F ₄	3s3d	³ D ₃	4.86(12)	4.97(12)	7.29(02)	7.50(02)	1.48(00)	1.52(00)	15.00	15.03
3p3d	¹ D ₂	3p ²	¹ D ₂	4.59(09)	5.17(09)	2.00(05)	2.33(05)	5.10(04)	5.78(04)	12.18	12.22
3p3d	¹ D ₂	3p ²	³ P ₁	4.22(09)	4.75(09)	1.90(05)	2.16(05)	4.73(04)	5.35(04)	12.23	12.26
3p3d	¹ D ₂	3s3d	³ D ₁	1.25(10)	1.37(10)	6.10(05)	6.87(05)	1.48(03)	1.65(03)	12.57	12.65
3p3d	¹ D ₂	3s3d	³ D ₂	1.40(11)	1.43(11)	7.26(04)	7.54(04)	1.72(02)	1.78(02)	12.82	12.89
3p3d	¹ D ₂	3s3d	³ D ₃	1.23(12)	1.24(12)	9.78(03)	9.89(03)	2.01(01)	2.03(01)	14.79	14.79
3p3d	¹ D ₂	3s3d	¹ D ₂	3.96(12)	4.02(12)	3.40(02)	3.45(02)	6.82(01)	6.92(01)	15.15	15.14
3p3d	¹ D ₂	3p ²	³ P ₂	2.36(11)	2.23(11)	2.27(02)	2.21(02)	2.04(01)	1.96(01)	33.90	34.23
3p3d	³ D ₃	3p ²	¹ D ₂	1.30(09)	1.95(09)	8.00(06)	1.16(05)	1.93(04)	2.93(04)	11.93	11.97
3p3d	³ D ₃	3s3d	³ D ₂	1.01(07)	3.77(07)	0.00(00)	2.62(07)	1.66(06)	6.30(06)	12.54	12.62
3p3d	³ D ₃	3s3d	³ D ₃	2.93(12)	2.98(12)	3.03(02)	3.10(02)	6.38(01)	6.51(01)	14.41	14.44
3p3d	³ D ₃	3s3d	¹ D ₂	2.04(12)	2.10(12)	2.26(02)	2.34(02)	4.65(01)	4.81(01)	14.76	14.77
3p3d	³ D ₃	3p ²	³ P ₂	7.57(11)	7.14(11)	8.57(02)	8.37(02)	8.14(01)	7.85(01)	32.00	32.38
3p3d	¹ P ₁	3s ²	¹ S ₀	2.12(10)	1.86(10)	7.00(06)	5.92(06)	3.40(04)	3.00(04)	5.96	5.98
3p3d	¹ P ₁	3p ²	³ P ₀	4.65(09)	3.72(09)	3.00(06)	2.25(06)	1.15(04)	9.20(05)	7.41	7.42
3p3d	¹ P ₁	3p ²	¹ D ₂	5.20(10)	5.61(10)	1.26(04)	1.37(04)	3.24(03)	3.51(03)	11.77	11.80
3p3d	¹ P ₁	3p ²	³ P ₁	5.70(09)	5.43(09)	1.40(05)	1.34(05)	3.58(04)	3.43(04)	11.81	11.85
3p3d	¹ P ₁	3s3d	³ D ₁	6.05(09)	6.16(09)	1.60(05)	1.66(05)	4.01(04)	4.13(04)	12.13	12.21
3p3d	¹ P ₁	3s3d	³ D ₂	9.95(10)	1.02(11)	2.79(04)	2.89(04)	6.85(03)	7.06(03)	12.37	12.43
3p3d	¹ P ₁	3s3d	¹ D ₂	5.42(12)	5.48(12)	2.46(02)	2.48(02)	5.14(01)	5.19(01)	14.52	14.51
3p3d	¹ P ₁	3p ²	³ P ₂	6.54(10)	5.94(10)	2.86(03)	2.66(03)	2.81(02)	2.59(02)	30.91	31.17
3p3d	¹ P ₁	3p ²	¹ S ₀	4.14(11)	3.86(11)	2.15(02)	2.07(02)	1.99(01)	1.90(01)	32.71	33.06
3d ²	³ F ₂	3s3p	³ P ₁	2.13(08)	1.58(08)	0.00(00)	1.01(07)	6.52(06)	4.83(06)	6.40	6.38
3d ²	³ F ₂	3s3p	³ P ₂	7.88(08)	8.07(08)	2.00(06)	1.65(06)	5.23(05)	5.34(05)	9.41	9.40
3d ²	³ F ₂	3s3p	¹ P ₁	4.10(09)	4.27(09)	9.00(06)	9.66(06)	2.90(04)	3.02(04)	9.73	9.71
3d ²	³ F ₂	3p3d	³ F ₂	4.40(12)	4.32(12)	2.95(02)	2.86(02)	6.42(01)	6.26(01)	13.96	13.90
3d ²	³ F ₂	3p3d	³ D ₁	3.89(12)	3.84(12)	3.00(02)	2.93(02)	6.23(01)	6.12(01)	14.62	14.57
3d ²	³ F ₂	3p3d	³ P ₂	2.57(09)	3.37(09)	3.20(05)	4.11(05)	5.72(04)	7.34(04)	17.25	17.03
3d ²	³ F ₂	3p3d	¹ F ₃	4.92(08)	8.93(08)	6.00(06)	1.11(05)	1.11(04)	1.96(04)	17.38	17.13
3d ²	³ F ₂	3p3d	³ D ₂	1.09(10)	1.09(10)	4.07(03)	3.96(03)	2.32(02)	2.28(02)	53.30	52.82
3d ²	³ F ₂	3p3d	³ P ₁	9.63(09)	1.02(10)	4.19(03)	4.36(03)	2.27(02)	2.38(02)	56.05	55.66
3d ²	³ F ₂	3p3d	³ F ₃	7.97(09)	7.57(09)	3.52(03)	3.20(03)	1.90(02)	1.75(02)	56.35	55.53
3d ²	³ F ₂	3p3d	¹ D ₂	5.56(06)	8.39(06)	4.20(05)	4.88(05)	8.79(05)	1.11(04)	145.23	133.10
3d ²	³ F ₂	3p3d	³ D ₃	7.11(06)	5.82(06)	1.30(04)	7.19(05)	2.02(04)	1.28(04)	194.76	171.05
3d ²	³ F ₂	3p3d	¹ P ₁	1.52(04)	1.33(05)	1.00(06)	3.26(06)	7.00(07)	4.60(06)	247.70	215.15
3d ²	³ P ₀	3s3p	³ P ₁	2.12(08)	0.66(07)	0.00(00)	8.14(10)	1.26(06)	3.93(08)	6.30	6.28
3d ²	³ P ₀	3s3p	¹ P ₁	1.33(06)	0.64(06)	0.00(00)	2.72(08)	1.81(08)	8.71(07)	9.51	9.48
3d ²	³ P ₀	3p3d	³ D ₁	8.90(12)	8.68(12)	1.24(02)	1.19(02)	2.66(01)	2.57(01)	14.13	14.05
3d ²	³ P ₀	3p3d	³ P ₁	4.31(10)	4.34(10)	2.57(03)	2.49(03)	1.58(02)	1.55(02)	49.44	48.78
3d ²	³ P ₀	3p3d	¹ P ₁	7.15(05)	3.05(06)	1.00(06)	4.06(06)	2.60(06)	8.85(06)	155.69	139.19

Table 2 (continued)

				A _r		S		gf		λ	
Upper level		Lower level		This work	Other work ^a	This work	Other work ^a	This work	Other work ^a	This work	Other work ^a
3d ²	³ F ₃	3s3p	³ P ₂	1.00(09)	9.90(08)	2.00(06)	2.11(06)	7.59(05)	7.53(05)	8.49	8.51
3d ²	³ F ₃	3p3d	³ F ₂	5.44(08)	3.88(08)	3.00(06)	2.35(06)	8.25(05)	5.91(05)	12.02	12.05
3d ²	³ F ₃	3p3d	³ P ₂	1.73(12)	1.71(12)	1.78(02)	1.75(02)	3.76(01)	3.70(01)	14.38	14.34
3d ²	³ F ₃	3p3d	¹ F ₃	2.38(12)	2.34(12)	2.49(02)	2.42(02)	5.22(01)	5.09(01)	14.47	14.41
3d ²	³ F ₃	3p3d	³ D ₂	3.19(11)	3.01(11)	3.96(02)	3.86(02)	3.64(01)	3.52(01)	32.99	33.38
3d ²	³ F ₃	3p3d	³ F ₃	5.56(10)	5.21(10)	7.64(03)	7.36(03)	6.80(02)	6.49(02)	34.13	34.45
3d ²	³ F ₃	3p3d	³ F ₄	5.55(09)	5.59(09)	2.62(03)	2.57(03)	1.55(02)	1.53(02)	51.51	51.02
3d ²	³ F ₃	3p3d	¹ D ₂	8.12(09)	8.45(09)	4.48(03)	4.58(03)	2.51(02)	2.58(02)	54.24	53.95
3d ²	³ F ₃	3p3d	³ D ₃	3.87(09)	4.06(09)	2.88(03)	2.92(03)	1.46(02)	1.50(02)	59.94	59.28
3d ²	³ P ₂	3s3p	³ P ₁	9.11(09)	8.19(09)	5.00(06)	4.20(06)	2.39(04)	2.15(04)	5.92	5.93
3d ²	³ P ₂	3s3p	³ P ₂	1.43(07)	2.48(07)	0.00(00)	3.67(08)	7.61(07)	1.32(06)	8.41	8.43
3d ²	³ P ₂	3s3p	¹ P ₁	3.83(06)	4.44(07)	0.00(00)	7.19(08)	2.16(07)	2.51(06)	8.67	8.69
3d ²	³ P ₂	3p3d	³ F ₂	1.17(10)	1.31(10)	4.80(05)	5.44(05)	1.23(03)	1.39(03)	11.88	11.90
3d ²	³ P ₂	3p3d	³ D ₁	7.40(09)	8.83(09)	3.40(05)	4.14(05)	8.47(04)	1.02(03)	12.35	12.38
3d ²	³ P ₂	3p3d	³ P ₂	3.34(12)	3.28(12)	2.35(02)	2.28(02)	5.03(01)	4.91(01)	14.18	14.12
3d ²	³ P ₂	3p3d	¹ F ₃	1.00(12)	9.80(11)	7.20(03)	6.90(03)	1.53(01)	1.48(01)	14.27	14.18
3d ²	³ P ₂	3p3d	³ D ₂	1.63(11)	1.53(11)	1.31(02)	1.26(02)	1.25(01)	1.19(01)	31.93	32.19
3d ²	³ P ₂	3p3d	³ P ₁	2.46(11)	2.30(11)	2.17(02)	2.09(02)	2.00(01)	1.91(01)	32.90	33.23
3d ²	³ P ₂	3p3d	³ F ₃	2.12(10)	1.90(10)	1.88(03)	1.71(03)	1.73(02)	1.57(02)	33.01	33.18
3d ²	³ P ₂	3p3d	¹ D ₂	7.39(08)	6.03(08)	2.48(04)	1.96(04)	1.47(03)	1.17(03)	51.45	50.91
3d ²	³ P ₂	3p3d	³ D ₃	5.91(09)	6.01(09)	2.63(03)	2.55(03)	1.42(02)	1.39(02)	56.54	55.63
3d ²	³ P ₂	3p3d	¹ P ₁	6.39(09)	6.86(09)	3.46(03)	3.58(03)	1.74(02)	1.83(02)	60.28	59.60
3d ²	³ P ₁	3s3p	³ P ₀	4.80(09)	4.45(09)	1.00(06)	1.32(06)	7.38(05)	6.86(05)	5.85	5.85
3d ²	³ P ₁	3s3p	³ P ₁	2.46(09)	2.26(09)	1.00(06)	6.89(07)	3.86(05)	3.54(05)	5.90	5.91
3d ²	³ P ₁	3s3p	³ P ₂	8.63(08)	9.90(08)	1.00(06)	8.68(07)	2.73(05)	3.14(05)	8.38	8.40
3d ²	³ P ₁	3s3p	¹ P ₁	1.22(08)	8.28(07)	0.00(00)	7.93(08)	4.07(06)	2.79(06)	8.63	8.65
3d ²	³ P ₁	3p3d	³ F ₂	3.24(07)	5.83(07)	0.00(00)	1.43(07)	2.04(06)	3.66(06)	11.81	11.82
3d ²	³ P ₁	3p3d	³ D ₁	4.35(08)	3.61(08)	1.00(06)	9.94(07)	2.95(05)	2.45(05)	12.28	12.30
3d ²	³ P ₁	3p3d	³ P ₂	4.44(12)	4.36(12)	1.84(02)	1.77(02)	3.96(01)	3.85(01)	14.09	14.01
3d ²	³ P ₁	3p3d	³ D ₂	3.35(10)	3.08(10)	1.55(03)	1.45(03)	1.49(02)	1.39(02)	31.47	31.64
3d ²	³ P ₁	3p3d	³ P ₀	2.23(11)	2.08(11)	1.11(02)	1.07(02)	1.05(01)	9.93(02)	32.33	32.61
3d ²	³ P ₁	3p3d	³ P ₁	2.08(11)	1.93(11)	1.05(02)	9.95(03)	9.80(02)	9.26(02)	32.41	32.64
3d ²	³ P ₁	3p3d	¹ D ₂	1.26(10)	1.29(10)	2.36(03)	2.33(03)	1.43(02)	1.43(02)	50.24	49.55
3d ²	³ P ₁	3p3d	¹ P ₁	2.57(09)	2.68(09)	7.66(04)	7.63(04)	3.97(03)	4.02(03)	58.63	57.75
3d ²	¹ G ₄	3p3d	¹ F ₃	3.62(12)	3.61(12)	4.58(02)	4.53(02)	9.81(01)	9.73(01)	14.17	14.14
3d ²	¹ G ₄	3p3d	³ F ₃	4.48(11)	4.21(11)	6.80(02)	6.68(02)	6.36(01)	6.16(01)	32.46	32.93
3d ²	¹ G ₄	3p3d	³ F ₄	2.16(10)	2.08(10)	1.05(02)	1.00(02)	6.65(02)	6.39(02)	47.80	47.75
3d ²	¹ G ₄	3p3d	³ D ₃	4.38(09)	4.76(09)	3.23(03)	3.50(03)	1.79(02)	1.94(02)	54.96	54.92
3d ²	³ F ₄	3p3d	¹ F ₃	1.70(10)	1.46(10)	1.40(04)	1.21(04)	3.46(03)	2.98(03)	12.27	12.31
3d ²	³ F ₄	3p3d	³ F ₃	2.57(09)	2.68(09)	1.58(04)	1.75(04)	2.00(03)	2.17(03)	23.99	24.47

Table 2 (continued)

				A_r		S		gf		λ	
Upper level		Lower level		This work	Other work ^a	This work	Other work ^a	This work	Other work ^a	This work	Other work ^a
3d ²	³ F ₄	3p3d	³ F ₄	2.17(11)	2.04(11)	3.00(02)	2.92(02)	2.90(01)	2.79(01)	31.44	31.81
3d ²	³ F ₄	3p3d	³ D ₃	5.48(11)	5.18(11)	9.91(02)	9.73(02)	8.75(01)	8.48(01)	34.39	34.84
3d ²	¹ D ₂	3s3p	³ P ₁	1.93(09)	1.44(09)	1.00(06)	6.05(07)	4.40(05)	3.32(05)	5.52	5.54
3d ²	¹ D ₂	3s3p	³ P ₂	9.46(09)	1.01(10)	1.00(05)	1.13(05)	4.13(04)	4.45(04)	7.63	7.68
3d ²	¹ D ₂	3s3p	¹ P ₁	1.49(10)	1.34(10)	1.80(05)	1.62(05)	6.86(04)	6.25(04)	7.84	7.88
3d ²	¹ D ₂	3p3d	³ F ₂	1.62(09)	1.45(09)	4.00(06)	4.08(06)	1.31(04)	1.19(04)	10.37	10.44
3d ²	¹ D ₂	3p3d	³ D ₁	4.62(07)	3.12(07)	0.00(00)	9.74(08)	3.99(06)	2.74(06)	10.73	10.81
3d ²	¹ D ₂	3p3d	³ P ₂	1.04(08)	5.62(08)	0.00(00)	2.46(06)	1.14(05)	6.18(05)	12.08	12.11
3d ²	¹ D ₂	3p3d	¹ F ₃	2.53(07)	2.00(08)	0.00(00)	8.87(07)	2.80(06)	2.22(05)	12.15	12.16
3d ²	¹ D ₂	3p3d	³ D ₂	2.53(09)	2.35(09)	7.60(05)	7.42(05)	1.00(03)	9.64(04)	22.97	23.37
3d ²	¹ D ₂	3p3d	³ P ₁	3.54(09)	3.57(09)	1.13(04)	1.20(04)	1.46(03)	1.53(03)	23.47	23.91
3d ²	¹ D ₂	3p3d	³ F ₃	1.28(09)	1.50(09)	4.10(05)	5.04(05)	5.33(04)	6.40(04)	23.52	23.89
3d ²	¹ D ₂	3p3d	¹ D ₂	5.73(11)	5.37(11)	4.45(02)	4.29(02)	4.28(01)	4.09(01)	31.59	31.88
3d ²	¹ D ₂	3p3d	³ D ₃	1.15(11)	1.06(11)	1.06(02)	9.98(03)	9.67(02)	9.00(02)	33.44	33.67
3d ²	¹ D ₂	3p3d	¹ P ₁	2.00(11)	1.87(11)	2.07(02)	2.00(02)	1.81(01)	1.73(01)	34.71	35.08
3d ²	¹ S ₀	3s3p	³ P ₁	5.49(09)	3.40(09)	0.00(00)	2.73(07)	2.44(05)	1.52(05)	5.44	5.46
3d ²	¹ S ₀	3s3p	¹ P ₁	9.74(10)	8.79(10)	2.20(05)	2.00(05)	8.63(04)	7.86(04)	7.68	7.72
3d ²	¹ S ₀	3p3d	³ D ₁	7.04(10)	6.76(10)	4.00(05)	3.88(05)	1.15(03)	1.12(03)	10.45	10.51
3d ²	¹ S ₀	3p3d	³ P ₁	1.42(07)	1.92(06)	0.00(00)	1.08(08)	1.04(06)	1.45(07)	22.15	22.50
3d ²	¹ S ₀	3p3d	¹ P ₁	1.03(12)	9.49(11)	1.65(02)	1.55(02)	1.57(01)	1.47(01)	31.90	32.13

^a MCDHF code in Ref. [7]

Fig. 1. The comparison between present AUTOSTRUCTURE results and other MR-MP [6], MCDHF [7] results for energy levels

Fig.2. The transition probabilities comparison between this work and MCDHF results [7] for E1 transitions

Fig. 3. The weighted oscillator strengths comparison between this work and MCDHF results [7] for E1 transitions

Fig. 4. The comparison of line strengths between present AUTOSTRUCTURE work with MCDHF results [7].

Fig. 5. The wavelengths (Å) comparison between this work and MCDHF results [7] for E1 transitions