
Semi-empirical Calculation of Oscillator Strengths and Lifetimes for the P V Spectrum

Cálculos Semi-Empíricos de Intensidades de Osciladores e Tempos de Vida para Espectro P V

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Resumo

As intensidades de osciladores (gf) e os tempos de vida calculados de forma semi-empírica, e apresentados neste trabalho para todas as linhas espectrais e níveis de energia conhecidos do P V foram realizados em uma aproximação de multiconfiguração usando a opção Hartree-Fock relativística. Nestes cálculos, os parâmetros eletrostáticos foram otimizados por um procedimento de mínimos quadrados para melhorar o ajuste aos níveis de energia experimentais. Este método, produz valores de (gf) que estão bem próximos daqueles que são esperados nas observações de intensidades usados para a interpretação de espectrogramas de plasmas estelares..

Palavras-chave Transições Atômicas, Níveis de Energia, Intensidade de Osciladores, Tempos de Vida.

Abstract

The semi-empirical oscillator strengths (gf) and the lifetimes presented in this work for all known P V spectral lines and energy levels were carried out in a multiconfiguration Hartree-Fock relativistic (HFR) approach. In this calculation, the electrostatic parameters were optimized by a least-squares procedure, in order to improve the adjustment to experimental energy levels. This method, produces values gf -values that are closer to those that are expected in intensity observations used for the interpretation of stellar plasmas spectrograms.

Keywords atomic transitions, energy levels, oscillator strengths, lifetimes.

1 Introdução

Hydrogenic ions belonging to the Na I-like isoelectronic sequence have been of considerable interest as these are simplest ions with two complete core plus a one-electron valence shell. For the ions in these sequence the 3s level is significantly lower than the 3p because of greater penetration past the shielding of the 1s electron. Both levels penetrate enough to be significantly lower than the $n = 3$ hydrogen energy which they would have if the shielding were perfect. Phosphorus four times ionized, P V, belongs to this sequence with ground state configuration $1s^2 2s^2 3s$ and the level $^2S_{1/2}$ having ionization limit estimated in $524462.9 \pm 1.0 \text{ cm}^{-1}$ ($65.02564 \pm 0.00021 \text{ eV}$)[1]. In the past, Peter Geuter[2,3] using a prism spectrograph was the first to obtain wavelengths in the air region. These spectrum was analyzed for the first time by Bowen and Millikan[4] in 1925 producing spectrogram of three to eight orders from spectra em

hot spark using phosphorus compounds in the electrodes of magnesium and silicon establishing classification of 12 energy levels based on 18 identification atomic transitions. Later, in 1937, Robinson[5] with data obtained from spectrograms taken on the two meter vacuum spectrograph using a Geissler tube discharge in phosphorus vapor as light source in which red phosphorus was packed firmly into holes drilled into in the tips of beryllium electrodes doing the intensity of the P V spectrum to be much increased by filling both electrodes instead of filling only one. In this way, Robinson added to the analysis 13 levels extending the observations toward shorter wavelengths. Magnusson and Zetterberg[6] has studied the spectrum in the wavelength region 200 – 9800 Å by using a sliding spark in vacuum obtaining 126 lines which were measured and classified, 88 being new. Kaufman and Martin[1], and Kelly[7] made a survey of all the wavelengths published for the P I - P XV spectra.

The purpose of this work is to present a review of all known electric dipole transitions of P V, their oscillator strengths (gf) and the lifetimes for all known experimental energy levels.

Methodology of analysis

A brief theoretical review[8] of the subject is presented to emphasize the importance of electrostatic parameters emerging from the solution of the Hamiltonian being manipulated later on obtaining the eigenvalues of our energy matrix.

In a multi-electron atom the Hamiltonian provide the theoretical predictions for the energy level values and are obtained by solving

$$H = \frac{-\hbar^2}{2m} \nabla_i^2 - \frac{Ze^2}{r_i} + \sum_{i < j} \frac{e^2}{r_{ij}} + \frac{1}{2m^2 c^2} \frac{1}{r} \frac{dV}{dr} \vec{\ell} \cdot \vec{s} = H_1 + (H_2^C + H_2^{NC}) + H_3 \quad (1)$$

with the first two terms (H_1) containing the kinetic and potential energies non-relativistic, H_2 can be separated into two parts, one of which (H_2^C) is centrally symmetric. This part is then held together with H_1 and leads to the central field approximation. H_3 is the energy containing the non-central part of H_2 and other terms of relativistic nature, being that in this work it is considered only the spin-orbit interaction. Other smaller relativistic terms (relativistic corrections to the electronics mass, energy Breit, Darwin term, energy spin-spin, energy spin-other-orbit) are neglected. Solutions can only be found with approximation methods as perturbation theory, variational method, method of self-consistent field, relativistic Thomas-Fermi model (HXR), relativistic model Hartree-Fock (HFR).

In order to compare the energies of the terms involved, the Hamiltonian can be written

$$H = \left(\frac{-\hbar^2}{2m} \nabla_i^2 - \frac{Ze^2}{r_i} + \sum_{i < j} \frac{e^2}{r_{ij}} \right)_C + \left[\left(\sum_{i < j} \frac{e^2}{r_{ij}} \right)_{NC} + \frac{1}{2m^2 c^2} \frac{1}{r} \frac{dV}{dr} \vec{\ell} \cdot \vec{s} \right] = H_C + H_{NC} + H_{SO} \quad (2)$$

If $H_{SO} \ll H_{NC}$ leads to Russell-Saunders coupling scheme, or LS , which is excellent agreement for lighter elements, $Z < 50$. If the opposite is the case, then angular momentum must be coupled according to the jj -coupling scheme, which should be used for heavier atoms ($Z > 50$). The non-central portion of the energy of electrostatic interaction between the electrons (interelectronic repulsion) provides corrections to the total energy required and are determined directly by the matrix elements of the Coulomb potential energy operator. This array element may be computed in terms of the integrals I and K ,

$$\Delta E_{SL} = I \pm K = \sum_k (f_k F^k \pm g_k G^k) \quad (3)$$

The integrals I representing the positive energy of mutual electrostatic repulsion for a spatial distribution of electrons, and the integrals K representing the decrease in this energy that results when one includes the positional correlation of electrons with spins parallel (arises due the Pauli

Exclusion Principle). The coefficients f_k and g_k are expressed in terms of matrix elements of the spherical functions, coming from the separation of variables for the wavefunction,

$$\Psi_{nlm} = R_{nl}(r)Y_{lm}(\theta, \phi) \quad (4)$$

The radial integrals F^k and G^k (often called Slater integrals), are essentially positive and their calculations are possible only if some of the approximation methods, are used.

Thus, the theoretical predictions for the energy level values are obtained by diagonalizing the energy matrices being that in these computations all strong configuration interactions should be included and HFR method is used to give better accuracy in many cases, as discussed in refs.[9,10].

The codes numeric Cowan[11] provides all information required to make the calculations that characterizes the ion under study.

The initial interpretation of the experimental values to the energy levels were determined by an iterative process using computer programs whose purpose is to verify the classification of the atomic transitions corresponding and optimizing these values in the output providing the experimental uncertainties. Now, for each parity and using the codes Cowan, the basic purpose is to adjust the values of the various theoretical electrostatic parameters to their energy levels, now replaced by their corresponding experimental values. Any of these parameters can be held fixed at specified values, or groups of parameters can be forced to vary in such a way that the ratios of the values within a group remain fixed relative to each other. The unknown configurations may be included in the calculations to take into account the configurations interaction effects. The fitting process is carried out by an automatic iterative procedure until the parameter values no longer change from one iteration cycle to the next or in which the standard deviation is less than one percent of the energy range covered by the energy levels. The accuracy is related to the calculation of the expected final values.

Once done these parameters are now used again to calculate the energy matrix so as to produce computed atomic energy levels in the best possible (least-squares-wise) agreement with experimentally known values.

Specifically, for the oscillator strengths this procedure improves the values of the wavenumbers σ [8] in

$$gf = \frac{8\pi^2 m c a_0^2 \sigma}{3h} S, \quad (5)$$

(S being electric dipole line strength), and also in the quantities $y_{\beta J}^\gamma$ and $y_{\beta' J'}^{\gamma'}$ that measure the total strength of the spectral line, given by

$$\mathbf{S}_{\gamma\gamma'}^{1/2} = \sum_{\beta} \sum_{\beta'} y_{\beta J}^\gamma \langle \beta J \| \mathbf{P}^1 \| \beta' J' \rangle y_{\beta' J'}^{\gamma'} \quad (6)$$

with $\mathbf{P}^1$ being the tensor operator (first order) dipole moment for the atom.

For the lifetimes, the probability per unit time of an atom in a specific state γJ to make a spontaneous transition to any state with lower energy is given by

$$P(\gamma J) = \sum A(\gamma J, \gamma' J') \quad (7)$$

where $A(\gamma J, \gamma' J')$ is the Einstein spontaneous emission transition probability rate, and is related to the natural lifetime $\tau(\gamma J)$ of a state by,

$$\tau(\gamma J) = \left(\sum A(\gamma J, \gamma' J') \right)^{-1} \quad (8)$$

These equations have to be applied to an isolated atom. Matter or radiation interaction will tend to reduce their values.

The method described produces gf values that are expected to be in agreement with line intensity observations and lifetimes values that are close to the experimental ones.

Wavelength values in vacuum were converted to air by the relation[12], $\lambda_{vac} = n\lambda_{air}$ where the index of refraction of standard air (dry air containing 0.03 CO_2 by volume at normal pressure and $T = 15^{\circ}C$) is given by

$$n = 1 + 8342.13 \times 10^{-8} + \frac{2406030}{130 \times 10^8 - \sigma^2} + \frac{15997}{38.9 \times 10^8 - \sigma^2} \quad (9)$$

Results and discussion

Values for the wavelengths as obtained in this process are shown in the Tables 1. to 2. and are compared with those resulting of experiments from Magnusson and Zetterberg[6] verifying are in good agreement. We decided to let appear the wavelengths are not yet classified. Also in these tables are shown the results for the oscillator strengths. The Table 3. show the excitation energies of the 65 high-lying levels relative to the ground level and the lifetimes values as found here. Comparisons are made with use of experimental available data and are shown in the Table 4. and 5..

The semi-empirical values as provided it have been of particular importance since an extensive data source is not currently available.

Conclusion

We have presented oscillator strengths and lifetimes for all known electric dipole transitions in P V, being that the present work is part of an ongoing program, whose goal is to obtain gf , and lifetimes for ions of elements of theoretical and astrophysical importance. Phosphorus occupies the fifteenth place with respect to cosmic distribution[13].

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Table 1. Oscillator strengths and spectral lines for the P V spectrum in the vacuum.

gf -value	Intensity and shape ^a	λ_{vac} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.0043			205.3843	3s – 9p	$2S_{1/2} - 2P_{3/2}$	0.00 – 486892.20	
0.0021			205.3928	3s – 9p	$2S_{1/2} - 2P_{1/2}$	0.00 – 486872.10	
0.0063	2d	209.964	209.9676	3s – 8p	$2S_{1/2} - 2P_{3/2}$	0.00 – 476263.90	6
0.0032	2d	209.964	209.9806	3s – 8p	$2S_{1/2} - 2P_{1/2}$	0.00 – 476234.40	6
0.0050	2d	217.214	217.2089	3s – 7p	$2S_{1/2} - 2P_{3/2}$	0.00 – 460386.30	6
0.0101	2d	217.214	217.2300	3s – 7p	$2S_{1/2} - 2P_{1/2}$	0.00 – 460341.60	6
0.0175	3	229.820	229.8204	3s – 6p	$2S_{1/2} - 2P_{3/2}$	0.00 – 435122.44	6
0.0088	3	229.859	229.8592	3s – 6p	$2S_{1/2} - 2P_{1/2}$	0.00 – 435048.96	6
0.0023			252.4511	3p – 9s	$2P_{1/2} - 2S_{1/2}$	88651.87 – 484768.20	6
0.0047	1	252.959	252.9590	3p – 9s	$2P_{3/2} - 2S_{1/2}$	89447.25 – 484768.20	6
0.0129			255.1618	3p – 8d	$2P_{1/2} - 2D_*$	88651.87 – 480560.10	
0.0351	5	255.587	255.5898	3s – 5p	$2S_{1/2} - 2P_{3/2}$	0.00 – 391251.91	6
0.0175	4	255.674	255.6773	3s – 5p	$2S_{1/2} - 2P_{1/2}$	0.00 – 391118.07	6
0.0231		255.681	255.6807	3p – 8d	$2P_{3/2} - 2D_*$	89447.25 – 480560.10	6
0.0037			260.0716	3p – 8s	$2P_{1/2} - 2S_{1/2}$	88651.87 – 473161.30	
0.0073	2	260.619	260.6107	3p – 8s	$2P_{3/2} - 2S_{1/2}$	89447.25 – 473161.30	6
0.0196	3	264.358	264.3515	3p – 7d	$2P_{1/2} - 2D_*$	89447.25 – 466936.10	6
0.0352	4	264.911	264.9233	3p – 7d	$2P_{3/2} - 2D_*$	89447.25 – 466936.10	6
0.0064	2	272.513	272.5162	3p – 7s	$2P_{1/2} - 2S_{1/2}$	88651.87 – 455602.53	6
0.0127	3	273.112	273.1082	3p – 7s	$2P_{3/2} - 2S_{1/2}$	89447.25 – 455602.53	6
0.0319	4	279.965	279.9655	3p – 6d	$2P_{1/2} - 2D_*$	88651.87 – 445838.80	6
0.0573	5	280.593	280.5903	3p – 6d	$2P_{3/2} - 2D_*$	89447.25 – 445838.80	6
0.0128	4	295.392	295.3917	3p – 6s	$2P_{1/2} - 2S_{1/2}$	88651.87 – 427185.41	6
0.0256	5	296.085	296.0873	3p – 6s	$2P_{3/2} - 2S_{1/2}$	89447.25 – 427185.41	6
0.0555	6	310.578	310.5748	3p – 5d	$2P_{1/2} - 2D_{3/2}$	88651.87 – 410635.53	6
0.0996	7	311.342	311.3408	3p – 5d	$2P_{3/2} - 2D_{5/2}$	89447.25 – 410638.67	6
0.0111	7	311.342	311.3439	3p – 5d	$2P_{3/2} - 2D_{3/2}$	89447.25 – 410635.53	6
0.0862	10	328.470	328.4663	3s – 4p	$2S_{1/2} - 2P_{3/2}$	0.00 – 304445.28	6
0.0431	9	328.775	328.7734	3s – 4p	$2S_{1/2} - 2P_{1/2}$	0.00 – 304160.87	6
0.0162	1d	332.02	332.0186	3d – 12f	$2D_{3/2} - 2F_*$	204198.99 – 505386.90	6
0.0232	1d	332.02	332.0264	3d – 12f	$2D_{5/2} - 2F_*$	204206.04 – 505386.90	6
0.0220	2	336.072	336.0672	3d – 11f	$2D_{3/2} - 2F_*$	204198.99 – 501758.50	6
0.0314	2	336.072	336.0752	3d – 11f	$2D_{5/2} - 2F_*$	204206.04 – 501758.50	6
0.0308	3	341.549	341.5440	3d – 10f	$2D_{3/2} - 2F_*$	204198.99 – 496987.00	6
0.0440	3	341.549	341.5523	3d – 10f	$2D_{5/2} - 2F_*$	204206.04 – 496987.00	6
0.0347	7	347.234	347.2302	3p – 5s	$2P_{1/2} - 2S_{1/2}$	88651.87 – 376645.25	6
0.0693	8	348.196	348.1918	3p – 5s	$2P_{3/2} - 2S_{1/2}$	89447.25 – 376645.25	6
0.0454	4	349.242	349.2369	3d – 9f	$2D_{3/2} - 2F_*$	204198.99 – 490537.60	6
0.0649	4	349.242	349.2455	3d – 9f	$2D_{5/2} - 2F_*$	204206.04 – 490537.60	6
0.0004	1	353.763	353.7404	3d – 9p	$2D_{3/2} - 2P_{3/2}$	204198.99 – 486892.20	6
0.0039	1	353.763	353.7492	3d – 9p	$2D_{5/2} - 2P_{3/2}$	204206.04 – 486892.20	6
0.0021	1	353.763	353.7655	3d – 9p	$2D_{3/2} - 2P_{1/2}$	204198.99 – 486872.10	6
0.0716	5	360.600	360.5937	3d – 8f	$2D_{3/2} - 2F_*$	204198.99 – 481519.40	6
0.1022	5	360.600	360.6029	3d – 8f	$2D_{5/2} - 2F_*$	204206.04 – 481519.40	6
0.0034	2	367.588	367.5593	3d – 8p	$2D_{3/2} - 2P_{3/2}$	204198.99 – 476263.90	6
0.0062	2	367.588	367.5689	3d – 8p	$2D_{5/2} - 2P_{3/2}$	204206.04 – 476263.90	6
0.0007	2	367.588	367.5992	3d – 8p	$2D_{3/2} - 2P_{1/2}$	204198.99 – 476234.40	6
0.1242	6	378.561	378.5520	3d – 7f	$2D_{3/2} - 2F_*$	204198.99 – 468363.51	6
0.1774	6	378.561	378.5621	3d – 7f	$2D_{5/2} - 2F_*$	204206.04 – 468363.51	6
0.0872	9	389.496	389.4934	3p – 4d	$2P_{1/2} - 2D_{3/2}$	88651.87 – 345395.62	6
0.0012			390.3394	3d – 7p	$2D_{3/2} - 2P_{3/2}$	204198.99 – 460386.30	
0.0110	4	390.371	390.3501	3d – 7p	$2D_{5/2} - 2P_{3/2}$	204206.04 – 460386.30	6
0.0061	4	390.371	390.4075	3d – 7p	$2D_{3/2} - 2P_{1/2}$	204198.99 – 460341.60	6
0.1565	10	390.699	390.6960	3p – 4d	$2P_{3/2} - 2D_{5/2}$	89447.25 – 345400.75	6
0.0174	10	390.699	390.7038	3p – 4d	$2P_{3/2} - 2D_{3/2}$	89447.25 – 345395.62	6
0.0180	7	410.029	410.0188	3d – 6f	$2D_{3/2} - 2F_*$	204198.99 – 448090.23	6
0.3590	7	410.029	410.0307	3d – 6f	$2D_{5/2} - 2F_*$	204206.04 – 448090.23	6
0.0026	5	433.056	433.0439	3d – 6p	$2D_{3/2} - 2P_{3/2}$	204198.99 – 435122.44	6
0.0233	5	433.056	433.0572	3d – 6p	$2D_{5/2} - 2P_{3/2}$	204206.04 – 435122.44	6
0.0130	4	433.173	433.1818	3d – 6p	$2D_{3/2} - 2P_{1/2}$	204198.99 – 435048.96	6
0.0065	0	467.448	467.4362	4s – 9p	$2S_{1/2} - 2P_{3/2}$	272959.27 – 486892.20	6
0.0032	0	467.448	467.4801	4s – 9p	$2S_{1/2} - 2P_{1/2}$	272959.27 – 486872.10	6

Table 1. Continued.

<i>gf</i> -value	Intensity and shape ^a	λ_{vac} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.0480	11	475.598	475.5819	3d – 5f	² D _{3/2} – ² F _*	204198.99 – 414467.73	6
0.9608	11	475.598	475.5978	3d – 5f	² D _{5/2} – ² F _*	204206.04 – 414467.73	6
0.0100	2	491.872	491.8727	4s – 8p	² S _{1/2} – ² P _{3/2}	272959.27 – 476263.90	6
0.0050	1	491.944	491.9441	4s – 8p	² S _{1/2} – ² P _{1/2}	272959.27 – 476234.40	6
0.0167	2	533.541	533.5410	4s – 7p	² S _{1/2} – ² P _{3/2}	272959.27 – 460386.30	6
0.0084	1	533.672	533.6682	4s – 7p	² S _{1/2} – ² P _{1/2}	272959.27 – 460341.60	6
0.0078			534.6081	3d – 5p	² D _{3/2} – ² P _{3/2}	204198.99 – 391251.91	
0.0711	6	534.627	534.6282	3d – 5p	² D _{5/2} – ² P _{3/2}	204206.04 – 391251.91	6
0.0395	5	534.986	534.9909	3d – 5p	² D _{3/2} – ² P _{1/2}	204198.99 – 391118.07	6
0.2125	13	542.572	542.5718	3p – 4s	² P _{1/2} – ² S _{1/2}	88651.87 – 272959.27	6
0.4231	14	544.923	544.9234	3p – 4s	² P _{3/2} – ² S _{1/2}	89447.25 – 272959.27	6
0.0063			553.6874	4p – 9s	² P _{1/2} – ² S _{1/2}	304160.87 – 484768.20	
0.0126			554.5607	4p – 9s	² P _{3/2} – ² S _{1/2}	304445.28 – 484768.20	
0.0125	0d	566.904	566.8959	4p – 8d	² P _{1/2} – ² D _*	304160.87 – 480560.10	6
0.0225	0d	567.810	567.8114	4p – 8d	² P _{3/2} – ² D _*	304445.28 – 480560.10	6
0.0108	0	591.714	591.7145	4p – 8s	² P _{1/2} – ² S _{1/2}	304160.87 – 473161.30	6
0.0216	1	592.712	592.7119	4p – 8s	² P _{3/2} – ² S _{1/2}	304445.28 – 473161.30	6
0.0188	0	614.352	614.3441	4p – 7d	² P _{1/2} – ² D _*	304160.87 – 466936.10	6
0.0038	1	615.421	615.4194	4p – 7d	² P _{3/2} – ² D _*	304445.28 – 466936.10	6
0.0317	2	616.668	616.6628	4s – 6p	² S _{1/2} – ² P _{3/2}	272959.27 – 435122.44	6
0.0159	2	616.952	616.9424	4s – 6p	² S _{1/2} – ² P _{1/2}	272959.27 – 435048.96	6
0.0313			625.0341	4d – 12f	² D _{3/2} – ² F _*	345395.62 – 505386.90	
0.0447			625.0541	4d – 12f	² D _{5/2} – ² F _*	345400.75 – 505386.90	
0.0429			639.5380	4d – 11f	² D _{3/2} – ² F _*	345395.62 – 501758.50	
0.0613			639.5590	4d – 11f	² D _{5/2} – ² F _*	345400.75 – 501758.50	
0.0615			659.6681	4d – 10f	² D _{3/2} – ² F _*	345395.62 – 496987.00	
0.0879			659.6904	4d – 10f	² D _{5/2} – ² F _*	345400.75 – 496987.00	
0.0216	0	660.316	660.3203	4p – 7s	² P _{1/2} – ² S _{1/2}	304160.87 – 455602.53	6
0.0432	1	661.566	661.5627	4p – 7s	² P _{3/2} – ² S _{1/2}	304445.28 – 455602.53	6
3.4893	12	673.899	673.8760	3d – 4f	² D _{3/2} – ² F _*	204198.99 – 352594.24	6
4.9845	12	673.899	673.9080	3d – 4f	² D _{5/2} – ² F _*	204206.04 – 352594.24	6
0.0935			688.9812	4d – 9f	² D _{3/2} – ² F _*	345395.62 – 490537.60	
0.1336			689.0052	4d – 9f	² D _{5/2} – ² F _*	345400.75 – 490537.60	
0.0287	2	705.833	705.8265	4p – 6d	² P _{1/2} – ² D _*	304160.87 – 445838.80	6
0.0016			706.7311	4d – 9p	² D _{3/2} – ² P _{3/2}	345395.62 – 486892.20	
0.0141			706.7563	4d – 9p	² D _{5/2} – ² P _{3/2}	345400.75 – 486892.20	
0.0078			706.8318	4d – 9p	² D _{3/2} – ² P _{1/2}	345395.62 – 486872.10	
0.0515	3	707.241	707.2466	4p – 6d	² P _{3/2} – ² D _*	304445.28 – 445838.80	6
0.1192	0	724.688	724.6882	4f – 9g	² F _* – ² G _*	352594.24 – 490584.70	6
0.0110	0	734.65	734.6268	4d – 8f	² D _{3/2} – ² F _*	345395.62 – 481519.40	6
0.1544	0	734.65	734.6535	4d – 8f	² D _{5/2} – ² F _*	345400.75 – 481519.40	6
0.0028	0	764.157	764.1273	4d – 8p	² D _{3/2} – ² P _{3/2}	345395.62 – 476263.90	6
0.0248	0	764.157	764.1574	4d – 8p	² D _{5/2} – ² P _{3/2}	345400.75 – 476263.90	6
0.0138			764.2994	4d – 8p	² D _{3/2} – ² P _{1/2}	345395.62 – 476234.40	
0.2161	0	775.254	775.2542	4f – 8g	² F _* – ² G _*	352594.24 – 481584.20	6
0.0042			781.4588	4f – 8d	² F _* – ² D _*	352594.24 – 480560.10	
0.0583	1	812.843	812.8460	4p – 6s	² P _{1/2} – ² S _{1/2}	304160.87 – 427185.41	6
0.0207	0	813.241	813.2204	4d – 7f	² D _{3/2} – ² F _*	345395.62 – 468363.51	6
0.4137	0	813.241	813.2544	4d – 7f	² D _{5/2} – ² F _*	345400.75 – 468363.51	6
0.1164	2	814.732	847.295	4p – 6s	² P _{3/2} – ² S _{1/2}	304445.28 – 427185.41	6
0.0704	2	845.370	845.3611	4s – 5p	² S _{1/2} – ² P _{3/2}	272959.27 – 391251.91	6
0.0351	1 bl PIII	846.299	846.3187	4s – 5p	² S _{1/2} – ² P _{1/2}	272959.27 – 391118.07	6
0.3631	1	863.095	863.0960	4f – 7g	² F _* – ² G _*	352594.24 – 468456.20	6
1.4451	12	865.446	865.4478	3p – 3d	² P _{1/2} – ² D _{3/2}	88651.87 – 204198.99	6
0.0058	2	869.683	869.6362	4d – 7p	² D _{3/2} – ² P _{3/2}	345395.62 – 460386.30	6
0.0519			869.6741	4d – 7p	² D _{5/2} – ² P _{3/2}	345400.75 – 460386.30	
0.0288	1	869.974	869.9743	4d – 7p	² D _{3/2} – ² P _{1/2}	345395.62 – 460341.60	6
2.5834	14	871.394	871.3929	3p – 3d	² P _{3/2} – ² D _{5/2}	89447.25 – 204206.04	6
0.2870		871.446	871.4465	3p – 3d	² P _{3/2} – ² D _{3/2}	89447.25 – 204198.99	6
0.0124	0	874.568	874.5702	4f – 7d	² F _* – ² D _*	352594.24 – 466936.10	6
0.0101			907.0550	5s – 9p	² S _{1/2} – ² P _{3/2}	376645.25 – 486892.20	
0.0051			907.2201	5s – 9p	² S _{1/2} – ² P _{1/2}	376645.25 – 486872.10	

Table 1. Continued.

<i>gf</i> -value	Intensity and shape ^a	λ_{vac} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.0309	0b	939.20	939.1906	4p – 5d	² P _{1/2} – ² D _{3/2}	304160.87 – 410635.53	6
0.0554	1	941.692	941.6782	4p – 5d	² P _{3/2} – ² D _{5/2}	304445.28 – 410638.67	6
0.0062	1	941.692	941.7060	4p – 5d	² P _{3/2} – ² D _{3/2}	304445.28 – 410635.53	6
0.6763	4	973.793	973.7609	4d – 6f	² D _{3/2} – ² F _*	345395.62 – 448090.23	6
0.9661	4	973.793	973.8096	4d – 6f	² D _{5/2} – ² F _*	345400.75 – 448090.23	6
0.0759			997.5432	3d – 4p	² D _{3/2} – ² P _{3/2}	204198.99 – 304445.28	
0.6831	9	997.617	997.6133	3d – 4p	² D _{5/2} – ² P _{3/2}	204206.04 – 304445.28	6
0.3785	7	1000.381	1000.381	3d – 4p	² D _{3/2} – ² P _{1/2}	204198.99 – 304160.87	6
0.0166			1003.828	5s – 8p	² S _{1/2} – ² P _{3/2}	376645.25 – 476263.90	
0.0083			1004.125	5s – 8p	² S _{1/2} – ² P _{1/2}	376645.25 – 476234.40	
1.4453	3	1045.631	10456309	4f – 6g	² F _* – ² G _*	352594.24 – 448230.28	6
0.0477			1055.394	5d – 12f	² D _{3/2} – ² F _*	410635.53 – 505386.90	
0.0681			1055.429	5d – 12f	² D _{5/2} – ² F _*	410638.67 – 505386.90	
0.0153			1067.804	5p – 9s	² P _{1/2} – ² S _{1/2}	391118.07 – 484768.20	
0.0306			1069.332	5p – 9s	² P _{3/2} – ² S _{1/2}	391251.91 – 484768.20	
0.0352			1072.449	4f – 6d	² F _* – ² D _*	352594.24 – 445838.80	
0.0672			1097.418	5d – 11f	² D _{3/2} – ² F _*	410635.53 – 501758.50	
0.0048			1097.456	5d – 11f	² D _{5/2} – ² F _*	410638.67 – 501758.50	
0.0005			1102.534	5g – 12f	² G _* – ² F _*	414686.79 – 505386.90	
0.0172	4	1114.550	1114.494	4d – 6p	² D _{3/2} – ² P _{3/2}	345395.62 – 435122.44	6
0.1547	4	1114.550	1114.558	4d – 6p	² D _{5/2} – ² P _{3/2}	345400.75 – 435122.44	6
0.0859	2	1115.413	1115.407	4d – 6p	² D _{3/2} – ² P _{1/2}	345395.62 – 435048.96	6
0.9792	17	1117.978	1117.977	3s – 3p	² S _{1/2} – ² P _{3/2}	0.00 – 89447.25	6
0.0122			1118.043	5p – 8d	² P _{1/2} – ² D _*	391118.07 – 480560.10	
0.0220			1119.718	5p – 8d	² P _{3/2} – ² D _*	391251.91 – 480560.10	
0.4852	15	1128.007	1128.008	3s – 3p	² S _{1/2} – ² P _{1/2}	0.00 – 88651.87	6
0.0008			1148.479	5g – 11f	² G _* – ² F _*	414686.79 – 501758.50	
0.0999			1158.058	5d – 10f	² D _{3/2} – ² F _*	410635.53 – 496987.00	
0.1427			1158.100	5d – 10f	² D _{5/2} – ² F _*	410638.67 – 496987.00	
0.0306			1194.157	5s – 7p	² S _{1/2} – ² P _{3/2}	376645.25 – 460386.30	
0.0153			1194.795	5s – 7p	² S _{1/2} – ² P _{1/2}	376645.25 – 460341.60	
0.0013			1215.064	5g – 10f	² G _* – ² F _*	414686.79 – 496987.00	
0.0305			1218.870	5p – 8s	² P _{1/2} – ² S _{1/2}	391118.07 – 473161.30	
0.0608			1220.861	5p – 8s	² P _{3/2} – ² S _{1/2}	391251.91 – 473161.30	
0.0115			1251.532	5d – 9f	² D _{3/2} – ² F _*	410635.53 – 490537.60	
0.2290			1251.581	5d – 9f	² D _{5/2} – ² F _*	410638.67 – 490537.60	
0.0044			1311.361	5d – 9p	² D _{3/2} – ² P _{3/2}	410635.53 – 486892.20	
0.0395			1311.415	5d – 9p	² D _{5/2} – ² P _{3/2}	410638.67 – 486892.20	
0.0219			1311.706	5d – 9p	² D _{3/2} – ² P _{1/2}	410635.53 – 486872.10	
0.3317			1313.767	5f – 9g	² F _* – ² G _*	414467.73 – 490584.70	
0.0018			1318.377	5g – 9f	² G _* – ² F _*	414686.79 – 490537.60	
0.0166			1318.947	5p – 7d	² P _{1/2} – ² D _*	391118.07 – 466936.10	
0.0033			1321.280	5p – 7d	² P _{3/2} – ² D _*	391251.91 – 466936.10	
0.3645	7	1379.615	1379.608	4p – 5s	² P _{1/2} – ² S _{1/2}	304160.87 – 376645.25	6
0.7261	9	1385.048	1385.042	4p – 5s	² P _{3/2} – ² S _{1/2}	304445.28 – 376645.25	6
0.2889	1d	1410.795	1410.758	5d – 8f	² D _{3/2} – ² F _*	410635.53 – 481519.40	6
0.4127	1d	1410.795	1410.821	5d – 8f	² D _{5/2} – ² F _*	410638.67 – 481519.40	6
2.5113	11	1447.827	1447.762	4d – 5f	² D _{3/2} – ² F _*	345395.62 – 414467.73	6
3.5872	11	1447.827	1447.870	4d – 5f	² D _{5/2} – ² F _*	345400.75 – 414467.73	6
0.6686			1489.947	5f – 8g	² F _* – ² G _*	414467.73 – 481584.20	
0.0051			1496.276	5g – 8f	² G _* – ² F _*	414686.79 – 481519.40	
0.0320			1513.034	5f – 8d	² F _* – ² D _*	414467.73 – 480560.10	
0.0091			1523.731	5d – 8p	² D _{3/2} – ² P _{3/2}	410635.53 – 476263.90	
0.0820			1523.804	5d – 8p	² D _{5/2} – ² P _{3/2}	410638.67 – 476263.90	
0.0455			1524.417	5d – 8p	² D _{3/2} – ² P _{1/2}	410635.53 – 476234.40	
0.0821		1550.768	1550.761	5p – 7s	² P _{1/2} – ² S _{1/2}	391118.07 – 455602.53	6
0.1639		1554.001	1553.986	5p – 7s	² P _{3/2} – ² S _{1/2}	391251.91 – 455602.53	6
10.2163		1610.499	1610.499	4f – 5g	² F _* – ² G _*	352594.24 – 414686.79	6
0.0167			1674.851	6s – 9p	² S _{1/2} – ² P _{3/2}	427185.41 – 486892.20	
0.0084			1675.415	6s – 9p	² S _{1/2} – ² P _{1/2}	427185.41 – 486872.10	
0.0995			1679.315	6d – 12f	² D _* – ² F _*	445838.80 – 505386.90	
0.0642		1710.065	1710.068	5s – 6p	² S _{1/2} – ² P _{3/2}	376645.25 – 435122.44	6
0.0321		1712.212	1712.220	5s – 6p	² S _{1/2} – ² P _{1/2}	376645.25 – 435048.96	6

Table 1. Continued.

<i>gf</i> -value	Intensity and shape ^a	λ_{vac} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.2185	4	1722.856	1722.818	4 <i>f</i> – 5 <i>d</i>	² <i>F</i> _* – ² <i>D</i> _{5/2}	352594.24 – 410638.67	6
0.1529	4	1722.856	1722.911	4 <i>f</i> – 5 <i>d</i>	² <i>F</i> _* – ² <i>D</i> _{3/2}	352594.24 – 410635.53	6
0.0453	2d	1732.315	1732.262	5 <i>d</i> – 7 <i>f</i>	² <i>D</i> _{3/2} – ² <i>F</i> _*	410635.53 – 468363.51	6
0.9056	2d	1732.315	1732.356	5 <i>d</i> – 7 <i>f</i>	² <i>D</i> _{5/2} – ² <i>F</i> _*	410638.67 – 468363.51	6
0.0025			1749.579	6 <i>g</i> – 12 <i>f</i>	² <i>G</i> _* – ² <i>F</i> _*	448230.28 – 505386.90	
0.1429			1788.279	6 <i>d</i> – 11 <i>f</i>	² <i>D</i> _* – ² <i>F</i> _*	445838.80 – 501758.50	
0.0113			1827.461	5 <i>p</i> – 6 <i>d</i>	² <i>P</i> _{1/2} – ² <i>D</i> _*	391118.07 – 445838.80	6
0.0203	0	1831.935	1831.942	5 <i>p</i> – 6 <i>d</i>	² <i>P</i> _{3/2} – ² <i>D</i> _*	391251.91 – 445838.80	6
1.7753	1b	1852.241	1852.247	5 <i>f</i> – 7 <i>g</i>	² <i>F</i> _* – ² <i>G</i> _*	414467.73 – 468456.20	6
1.9902	3bl	1859.330	1859.333	5 <i>g</i> – 7 <i>h</i>	² <i>G</i> _* – ² <i>H</i> _*	414686.79 – 468469.52	6
0.0150			1863.005	5 <i>g</i> – 7 <i>f</i>	² <i>G</i> _* – ² <i>F</i> _*	414686.79 – 468363.51	
0.0041			1868.173	6 <i>g</i> – 11 <i>f</i>	² <i>G</i> _* – ² <i>F</i> _*	448230.28 – 501758.50	
0.0890			1905.910	5 <i>f</i> – 7 <i>d</i>	² <i>F</i> _* – ² <i>D</i> _*	414467.73 – 466936.10	
0.2302			1955.104	6 <i>d</i> – 10 <i>f</i>	² <i>D</i> _* – ² <i>F</i> _*	445838.80 – 496987.00	

Table 2. Oscillator strengths and spectral lines for the P V spectrum in the air.

gf -value	Intensity and shape ^a	λ_{air} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.0269			2009.369	5d – 7p	$^2D_{3/2} - ^2P_{3/2}$	410635.53 – 460386.30	
0.2418			2009.496	5d – 7p	$^2D_{5/2} - ^2P_{3/2}$	410638.67 – 460386.30	
0.0393			2010.644	6p – 9s	$^2P_{1/2} - ^2S_{1/2}$	435048.96 – 484768.20	
0.1342			2011.177	5d – 7p	$^2D_{3/2} - ^2P_{1/2}$	410635.53 – 460341.60	
0.0785			2013.621	6p – 9s	$^2P_{3/2} - ^2S_{1/2}$	435122.44 – 484768.20	
0.0303			2036.898	6s – 8p	$^2S_{1/2} - ^2P_{3/2}$	427185.41 – 476263.90	
0.0152			2038.123	6s – 8p	$^2S_{1/2} - ^2P_{1/2}$	427185.41 – 476234.40	
0.0072			2050.342	6g – 10f	$^2G_* - ^2F_*$	448230.28 – 496987.00	
0.1541	4	2180.042	2180.043	4d – 5p	$^2D_{3/2} - ^2P_{3/2}$	345395.62 – 391251.91	6
1.3866	8	2180.286	2180.287	4d – 5p	$^2D_{5/2} - ^2P_{3/2}$	345400.75 – 391251.91	6
0.7682	7	2186.419	2186.425	4d – 5p	$^2D_{3/2} - ^2P_{1/2}$	345395.62 – 391118.07	6
0.0102			2196.571	6p – 8d	$^2P_{1/2} - ^2D_*$	435048.96 – 480560.10	
0.0183			2200.133	6p – 8d	$^2P_{3/2} - ^2D_*$	435122.44 – 480560.10	
0.4055			2236.517	6d – 9f	$^2D_* - ^2F_*$	445838.80 – 490537.60	
0.7582			2352.534	6f – 9g	$^2F_* - ^2G_*$	448090.23 – 490584.70	
0.0035			2361.439	6h – 9g	$^2H_* - ^2G_*$	448250.34 – 490584.70	
0.0152			2362.944	6g – 9f	$^2G_* - ^2F_*$	448230.28 – 490537.60	
2.1686	11	2424.403	2424.403	4p – 4d	$^2P_{1/2} - ^2D_{3/2}$	304160.87 – 345395.62	6
0.1124			2435.115	6d – 9p	$^2D_* - ^2P_{3/2}$	445838.80 – 486892.20	
0.0624			2436.311	6d – 9p	$^2D_* - ^2P_{1/2}$	445838.80 – 486872.10	
3.8770	12	2440.934	2440.936	4p – 4d	$^2P_{3/2} - ^2D_{5/2}$	304445.28 – 345400.75	6
0.4307	8	2441.239	2441.242	4p – 4d	$^2P_{3/2} - ^2D_{3/2}$	304445.28 – 345395.62	6
0.1476			2599.954	7d – 12f	$^2D_* - ^2F_*$	466936.10 – 505386.90	
0.1059			2623.042	6p – 8s	$^2P_{1/2} - ^2S_{1/2}$	435048.96 – 473161.30	
0.2114			2628.117	6p – 8s	$^2P_{3/2} - ^2S_{1/2}$	435122.44 – 473161.30	
2.0927			2669.098	5d – 6f	$^2D_{3/2} - ^2F_*$	410635.53 – 448090.23	
2.9893	4	2669.320	2669.322	5d – 6f	$^2D_{5/2} - ^2F_*$	410638.67 – 448090.23	6
0.0081			2706.972	7g – 12f	$^2G_* - ^2F_*$	468456.20 – 505386.90	
0.5172	3	2771.778	2771.773	5p – 6s	$^2P_{1/2} - ^2S_{1/2}$	391118.07 – 427185.41	6
1.0306	5	2782.095	2782.097	5p – 6s	$^2P_{3/2} - ^2S_{1/2}$	391251.91 – 427185.41	6
0.8620			2801.810	6d – 8f	$^2D_* - ^2F_*$	445838.80 – 481519.40	
0.2302			2870.871	7d – 11f	$^2D_* - ^2F_*$	466936.10 – 501758.50	
8.7768	10	2960.997	2960.997	5f – 6g	$^2F_* - ^2G_*$	414467.73 – 448230.28	6
16.4014	12	2978.554	2978.554	5g – 6h	$^2G_* - ^2H_*$	414686.79 – 448250.34	6
1.8719			2984.745	6f – 8g	$^2F_* - ^2G_*$	448090.23 – 481584.20	
0.0941	1	2992.833	2992.831	5g – 6f	$^2G_* - ^2F_*$	414686.79 – 448090.23	6
0.0114			2999.086	6h – 8g	$^2H_* - ^2G_*$	448250.34 – 481584.20	
0.0142			3001.928	7g – 11f	$^2G_* - ^2F_*$	468456.20 – 501758.50	
0.0434			3003.102	6g – 8f	$^2G_* - ^2F_*$	448230.28 – 481519.40	
0.0617			3011.094	6s – 7p	$^2S_{1/2} - ^2P_{3/2}$	427185.41 – 460386.30	
0.0308			3015.155	6s – 7p	$^2S_{1/2} - ^2P_{1/2}$	427185.41 – 460341.60	
0.1535			3078.898	6f – 8d	$^2F_* - ^2D_*$	448090.23 – 480560.10	
0.0035			3135.156	6p – 7d	$^2P_{1/2} - ^2D_*$	435048.96 – 466936.10	
0.0062			3142.396	6p – 7d	$^2P_{3/2} - ^2D_*$	435122.44 – 466936.10	
1.4376	15	3175.091	3175.095	4s – 4p	$^2S_{1/2} - ^2P_{3/2}$	272959.27 – 304445.28	6
0.5302	3	3186.731	3186.732	5f – 6d	$^2F_* - ^2D_*$	414467.73 – 445838.80	6
0.0305			3195.028	7s – 9p	$^2S_{1/2} - ^2P_{3/2}$	455602.53 – 486892.20	
0.0153			3197.085	7s – 9p	$^2S_{1/2} - ^2P_{1/2}$	455602.53 – 486872.10	
0.7094	13	3204.037	3204.038	4s – 4p	$^2S_{1/2} - ^2P_{1/2}$	272959.27 – 304160.87	6
0.3298			3285.811	6d – 8p	$^2D_* - ^2P_{3/2}$	445838.80 – 476263.90	
0.1830			3289.003	6d – 8p	$^2D_* - ^2P_{1/2}$	445838.80 – 476234.40	
0.4001			3326.738	7d – 10f	$^2D_* - ^2F_*$	466936.10 – 496987.00	
0.0295			3503.983	7g – 10f	$^2G_* - ^2F_*$	468456.20 – 496987.00	
0.2307			4026.774	8d – 12f	$^2D_* - ^2F_*$	480560.10 – 505386.90	
0.2344	4	4082.667	4082.662	5d – 6p	$^2D_{3/2} - ^2P_{3/2}$	410635.53 – 435122.44	6
2.1090	7	4083.184	4083.185	5d – 6p	$^2D_{5/2} - ^2P_{3/2}$	410638.67 – 435122.44	6
0.1297			4092.749	7p – 9s	$^2P_{1/2} - ^2S_{1/2}$	460341.60 – 484768.20	
1.1683	6	4094.950	4094.950	5d – 6p	$^2D_{3/2} - ^2P_{1/2}$	410635.53 – 435048.96	6
0.2589			4100.247	7p – 9s	$^2P_{3/2} - ^2S_{1/2}$	460386.30 – 484768.20	
0.0230			4200.022	8g – 12f	$^2G_* - ^2F_*$	481584.20 – 505386.90	
0.8364			4235.835	7d – 9f	$^2D_* - ^2F_*$	466936.10 – 490537.60	
2.7064	2h	4438.319	4438.323	6d – 7f	$^2D_* - ^2F_*$	445838.80 – 468363.51	6
1.9089			4498.952	7f – 9g	$^2F_* - ^2G_*$	468363.51 – 490584.70	
0.0344			4520.515	7h – 9g	$^2H_* - ^2G_*$	468469.52 – 490584.70	
0.0823			4527.434	7g – 9f	$^2G_* - ^2F_*$	468456.20 – 490537.60	

Table 2. Continued.

<i>gf</i> -value	Intensity and shape ^a	λ_{air} (Å)		Configs.	Terms	Energy Levels (cm ⁻¹)	Ref.
		Obs.	Calc.				
0.3977			4716.029	8d – 11f	$^2D_* - ^2F_*$	480560.10 – 501758.50	
0.0608			4838.602	7s – 8p	$^2S_{1/2} - ^2P_{3/2}$	455602.53 – 476263.90	
0.0304			4845.528	7s – 8p	$^2S_{1/2} - ^2P_{1/2}$	455602.53 – 476234.40	
0.6712	1	4863.976	4863.976	6p – 7s	$^2P_{1/2} - ^2S_{1/2}$	435048.96 – 455602.53	6
1.3376			4881.428	6p – 7s	$^2P_{3/2} - ^2S_{1/2}$	435122.44 – 455602.53	6
8.0505			4908.786	6f – 7g	$^2F_* - ^2G_*$	448090.23 – 468456.20	
14.5344	3h	4939.54	4939.518	6g – 7h	$^2G_* - ^2H_*$	448230.28 – 468469.52	6
23.7811	4h	4943.130	4943.130	6h – 7i	$^2H_* - ^2I_*$	448250.34 – 468474.79	6
0.3088			4944.598	7p – 8d	$^2P_{1/2} - ^2D_*$	460341.60 – 480560.10	
0.0793			4947.678	6h – 7g	$^2H_* - ^2G_*$	448250.34 – 468456.20	
0.0472			4955.422	8g – 11f	$^2G_* - ^2F_*$	481584.20 – 501758.50	
0.0364			4955.540	7p – 8d	$^2P_{3/2} - ^2D_*$	460386.30 – 480560.10	
0.2518			4965.527	6g – 7f	$^2G_* - ^2F_*$	448230.28 – 468363.51	
0.4176			5009.600	7d – 9p	$^2D_* - ^2P_{3/2}$	466936.10 – 486892.20	
0.2317			5014.653	7d – 9p	$^2D_* - ^2P_{1/2}$	466936.10 – 486872.10	
2.8081	5	5122.195	5122.191	5p – 5d	$^2P_{1/2} - ^2D_{3/2}$	391118.07 – 410635.53	6
5.0209	6	5156.723	5156.717	5p – 5d	$^2P_{3/2} - ^2D_{5/2}$	391251.91 – 410638.67	6
0.5578	2	5157.559	5157.558	5p – 5d	$^2P_{3/2} - ^2D_{3/2}$	391251.91 – 410635.53	6
0.8886			5304.727	6f – 7d	$^2F_* - ^2D_*$	448090.23 – 466936.10	
0.8237			6085.911	8d – 10f	$^2D_* - ^2F_*$	480560.10 – 496987.00	
0.1294			6490.567	8g – 10f	$^2G_* - ^2F_*$	481584.20 – 496987.00	
0.0676			6753.932	9g – 12f	$^2G_* - ^2F_*$	490584.70 – 505386.90	
1.8697	3b	6844.302	6844.306	5s – 5p	$^2S_{1/2} - ^2P_{3/2}$	376645.25 – 391251.91	6
2.5662			6855.321	7d – 8f	$^2D_* - ^2F_*$	466936.10 – 481519.40	
2.8477			6872.167	6d – 7p	$^2D_* - ^2P_{3/2}$	445838.80 – 460386.30	
1.5722			6893.332	6d – 7p	$^2D_* - ^2P_{1/2}$	445838.80 – 460341.60	
0.9263	2b	6907.607	6907.592	5s – 5p	$^2S_{1/2} - ^2P_{1/2}$	376645.25 – 391118.07	6
0.0608			7280.876	8s – 9p	$^2S_{1/2} - ^2P_{3/2}$	473161.30 – 486892.20	
0.0304			7291.532	8s – 9p	$^2S_{1/2} - ^2P_{1/2}$	473161.30 – 486872.10	
7.6663			7561.865	7f – 8g	$^2F_* - ^2G_*$	468363.51 – 481584.20	
0.2163			7622.982	7h – 8g	$^2H_* - ^2G_*$	468469.52 – 481584.20	
0.4550			7653.038	7g – 8f	$^2G_* - ^2F_*$	468456.20 – 481519.40	
0.8257			7798.426	7p – 8s	$^2P_{1/2} - ^2S_{1/2}$	460341.60 – 473161.30	
1.6457			7825.665	7p – 8s	$^2P_{3/2} - ^2S_{1/2}$	460386.30 – 473161.30	
1.2742			8196.754	7f – 8d	$^2F_* - ^2D_*$	468363.51 – 480560.10	
0.1829			8947.032	9g – 11f	$^2G_* - ^2F_*$	490584.70 – 501758.50	
3.4122			9265.521	6p – 6d	$^2P_{1/2} - ^2D_*$	435048.96 – 445838.80	
6.1000			9328.941	6p – 6d	$^2P_{3/2} - ^2D_*$	435122.44 – 445838.80	
2.5016			10019.987	8d – 9f	$^2D_* - ^2F_*$	480560.10 – 490537.60	
3.5953			10717.798	7d – 8p	$^2D_* - ^2P_{3/2}$	466936.10 – 476263.90	
1.9910			10751.843	7d – 8p	$^2D_* - ^2P_{1/2}$	466936.10 – 476234.40	
7.4743			11028.121	8f – 9g	$^2F_* - ^2G_*$	481519.40 – 490584.70	
0.6921			11165.812	8g – 9f	$^2G_* - ^2F_*$	481584.20 – 490537.60	
0.9008			11714.966	8p – 9s	$^2P_{1/2} - ^2S_{1/2}$	476234.40 – 484768.20	
1.9547			11755.672	8p – 9s	$^2P_{3/2} - ^2S_{1/2}$	476263.90 – 484768.20	
2.2992			12595.726	6s – 6p	$^2S_{1/2} - ^2P_{3/2}$	427185.41 – 435122.44	
1.1390			12713.423	6s – 6p	$^2S_{1/2} - ^2P_{1/2}$	427185.41 – 435048.96	
0.5537			13887.757	4d – 4f	$^2D_{3/2} - ^2F_*$	345395.62 – 352594.24	
0.7904			13897.665	4d – 4f	$^2D_{5/2} - ^2F_*$	345400.75 – 352594.24	
3.9974			15160.190	7p – 7d	$^2P_{1/2} - ^2D_*$	460341.60 – 466936.10	
7.1466			15263.401	7p – 7d	$^2P_{3/2} - ^2D_*$	460386.30 – 466936.10	
0.9550			15615.115	9g – 10f	$^2G_* - ^2F_*$	490584.70 – 496987.00	
4.3483			15788.225	8d – 9p	$^2D_* - ^2P_{3/2}$	480560.10 – 486892.20	
2.4081			15838.538	8d – 9p	$^2D_* - ^2P_{1/2}$	480560.10 – 486872.10	
2.7242			20898.351	7s – 7p	$^2S_{1/2} - ^2P_{3/2}$	455602.53 – 460386.30	
1.3494			21095.484	7s – 7p	$^2S_{1/2} - ^2P_{1/2}$	455602.53 – 460341.60	
4.5718			23112.142	8p – 8d	$^2P_{1/2} - ^2D_*$	476234.40 – 480560.10	
8.1731			23270.677	8p – 8d	$^2P_{3/2} - ^2D_*$	476263.90 – 480560.10	
1.0345			26087.6	5d – 5f	$^2D_{3/2} - ^2F_*$	410635.53 – 414467.73	
1.4766			26109.0	5d – 5f	$^2D_{5/2} - ^2F_*$	410638.67 – 414467.73	
3.1465			32222.	8s – 8p	$^2S_{1/2} - ^2P_{3/2}$	473161.30 – 476263.90	
1.5583			32531.	8s – 8p	$^2S_{1/2} - ^2P_{1/2}$	473161.30 – 476234.40	
2.0858			44404.	6d – 6f	$^2D_* - ^2F_*$	445838.80 – 448090.23	
3.5644			47068.	9s – 9p	$^2S_{1/2} - ^2P_{3/2}$	484768.20 – 486892.20	
1.7653			47518.	9s – 9p	$^2S_{1/2} - ^2P_{1/2}$	484768.20 – 486872.10	

^a Abbreviations used according to Ref.[6] .

Table 3. Lifetimes for the P V spectrum

Lifetimes	Energy (cm^{-1})		Even Levels	Lifetimes	Energy (cm^{-1})		Odd Levels
	Observed	Adjusted			Observed	Adjusted	
	0.0	0.0	$3s\ (^2S)\ ^2S_{1/2}$	7.863×10^{-10}	88651.87	88651.87	$3p\ (^2P)\ ^2P_{1/2}$
2.599×10^{-10}	204199.0	204198.99	$3d\ (^1S)\ ^2D_{3/2}$	7.655×10^{-10}	89447.2	89447.25	$3p\ (^2P)\ ^2P_{3/2}$
2.644×10^{-10}	204206.0	204206.04	$3d\ (^1S)\ ^2D_{5/2}$	3.546×10^{-10}	304160.9	304160.87	$4p\ (^2P)\ ^2P_{1/2}$
1.397×10^{-10}	272959.3	272959.27	$4s\ (^1S)\ ^2S_{1/2}$	3.521×10^{-10}	304445.3	304445.28	$4p\ (^2P)\ ^2P_{3/2}$
5.308×10^{-10}	345395.6	345395.62	$4d\ (^1S)\ ^2D_{3/2}$	1.092×10^{-10}	352594.2	352594.24	$4f\ (^1S)\ ^2F_{5/2}$
5.369×10^{-10}	345400.7	345400.75	$4d\ (^1S)\ ^2D_{5/2}$	1.092×10^{-10}	352594.2	352594.24	$4f\ (^1S)\ ^2F_{7/2}$
2.097×10^{-10}	376645.2	376645.25	$5s\ (^1S)\ ^2S_{1/2}$	4.719×10^{-10}	391118.8	391118.07	$5p\ (^1S)\ ^2P_{1/2}$
6.586×10^{-10}	410635.5	410635.53	$5d\ (^1S)\ ^2D_{3/2}$	4.700×10^{-10}	391251.9	391251.91	$5p\ (^1S)\ ^2P_{3/2}$
6.634×10^{-10}	410638.7	410638.67	$5d\ (^1S)\ ^2D_{5/2}$	2.012×10^{-10}	414467.7	414467.73	$5f\ (^1S)\ ^2F_{5/2}$
3.806×10^{-10}	414686.8	414687.73	$5g\ (^1S)\ ^2G_{7/2}$	2.012×10^{-10}	414467.7	414467.73	$5f\ (^1S)\ ^2F_{7/2}$
5.150×10^{-10}	414686.8	414687.73	$5g\ (^1S)\ ^2G_{9/2}$	6.920×10^{-10}	435048.9	435048.96	$6p\ (^1S)\ ^2P_{1/2}$
3.319×10^{-10}	427185.4	427185.41	$6s\ (^1S)\ ^2S_{1/2}$	6.901×10^{-10}	435122.4	435122.44	$6p\ (^1S)\ ^2P_{3/2}$
6.349×10^{-9}	445838.8	445838.80	$6d\ (^1S)\ ^2D_{3/2}$	3.345×10^{-10}	448090.2	448090.23	$6f\ (^1S)\ ^2F_{5/2}$
7.206×10^{-10}	445838.8	445838.80	$6d\ (^1S)\ ^2D_{5/2}$	3.345×10^{-10}	448090.2	448090.23	$6f\ (^1S)\ ^2F_{7/2}$
6.456×10^{-10}	448230.3	448230.28	$6g\ (^1S)\ ^2G_{7/2}$	9.738×10^{-10}	448250.3	448250.28	$6h\ (^1S)\ ^2H_{9/2}$
1.499×10^{-9}	448230.3	448230.28	$6g\ (^1S)\ ^2G_{9/2}$	9.738×10^{-10}	448250.3	448250.28	$6h\ (^1S)\ ^2H_{11/2}$
5.076×10^{-10}	455602.5	455602.53	$7s\ (^1S)\ ^2S_{1/2}$	1.008×10^{-9}	460341.6	460341.60	$7p\ (^1S)\ ^2P_{1/2}$
7.262×10^{-9}	466936.1	466936.10	$7d\ (^1S)\ ^2D_{3/2}$	1.006×10^{-9}	460386.3	460386.30	$7p\ (^1S)\ ^2P_{3/2}$
9.978×10^{-9}	466936.1	466936.10	$7d\ (^1S)\ ^2D_{5/2}$	5.173×10^{-10}	468363.5	468363.51	$7f\ (^1S)\ ^2F_{5/2}$
1.009×10^{-9}	468456.2	468456.20	$7g\ (^1S)\ ^2G_{7/2}$	5.174×10^{-10}	468363.5	468363.51	$7f\ (^1S)\ ^2F_{7/2}$
1.754×10^{-9}	468456.2	468456.20	$7g\ (^1S)\ ^2G_{9/2}$	1.536×10^{-9}	468469.5	468469.53	$7h\ (^1S)\ ^2H_{9/2}$
2.158×10^{-9}	468474.8	468474.79	$7i\ (^1S)\ ^2I_{11/2}$	1.536×10^{-9}	468469.5	468469.53	$7h\ (^1S)\ ^2H_{11/2}$
2.158×10^{-9}	468474.8	468474.79	$7i\ (^1S)\ ^2I_{13/2}$	1.429×10^{-9}	476234.4	476234.40	$8p\ (^1S)\ ^2P_{1/2}$
7.447×10^{-10}	473161.3	473161.30	$8s\ (^1S)\ ^2S_{1/2}$	1.427×10^{-9}	476263.9	476263.90	$8p\ (^1S)\ ^2P_{3/2}$
2.533×10^{-9}	480560.1	480560.10	$8d\ (^1S)\ ^2D_{3/2}$	7.581×10^{-10}	481519.4	481519.40	$8f\ (^1S)\ ^2F_{5/2}$
2.546×10^{-9}	480560.1	480560.10	$8d\ (^1S)\ ^2D_{5/2}$	7.581×10^{-10}	481519.4	481519.40	$8f\ (^1S)\ ^2F_{7/2}$
1.719×10^{-9}	481584.2	481584.20	$8g\ (^1S)\ ^2G_{7/2}$	1.970×10^{-9}	486872.1	486872.10	$9p\ (^1S)\ ^2P_{1/2}$
4.170×10^{-9}	481584.2	481584.20	$8g\ (^1S)\ ^2G_{9/2}$	1.968×10^{-9}	486892.2	486892.20	$9p\ (^1S)\ ^2P_{3/2}$
1.052×10^{-9}	484768.2	484768.20	$9s\ (^1S)\ ^2S_{1/2}$	1.065×10^{-9}	490537.6	490537.60	$9f\ (^1S)\ ^2F_{5/2}$
9.526×10^{-9}	490584.7	490584.70	$9g\ (^1S)\ ^2G_{7/2}$	1.065×10^{-9}	490537.6	490537.60	$9f\ (^1S)\ ^2F_{7/2}$
3.078×10^{-9}	490584.7	490584.70	$9g\ (^1S)\ ^2G_{9/2}$	1.463×10^{-9}	496987.0	496987.00	$10f\ (^1S)\ ^2F_{5/2}$
				1.464×10^{-9}	496987.0	496987.00	$10f\ (^1S)\ ^2F_{7/2}$
				1.960×10^{-9}	501758.5	501758.50	$11f\ (^1S)\ ^2F_{5/2}$
				1.960×10^{-9}	501758.5	501758.50	$11f\ (^1S)\ ^2F_{7/2}$
				2.563×10^{-9}	505386.9	505386.90	$12f\ (^1S)\ ^2F_{5/2}$
				2.563×10^{-9}	505386.9	505386.90	$12f\ (^1S)\ ^2F_{7/2}$

Table 4. Comparisons lifetimes values.

Level		Lifetimes values (ns)	
Config.	Term	Measured ^a	Semi-empirical
3p	$^2P_{1/2,3/2}$	0.70 ± 0.06^a	(0.7655 , 0.7863)
3d	$^2D_{3/2,5/2}$	0.30 ± 0.06^a	(0.2599 , 0.2644)

^a According to Ref.[14].

Table 5. Comparisons oscillator strength values.

Wavelength (Å)		Transition	Measured ^a	Semi-empirical
Exp. ^a	This Work			
1121.	1117.977	$3s\ ^2S_{1/2} - ^2P_{3/2}$	0.80 ± 0.16	0.9792
1121.	1128.008	$3s\ ^2S_{1/2} - ^2P_{1/2}$	0.80 ± 0.16	0.4852
865.	865.4478	$3p\ ^2P_{1/2} - ^2D_{3/2}$	0.63 ± 0.13	1.4445
865.	871.3929	$3p\ ^2P_{3/2} - ^2D_{5/2}$	0.63 ± 0.13	2.5834
865.	871.4460	$3p\ ^2P_{3/2} - ^2D_{3/2}$	0.63 ± 0.13	0.2870

^a Ref.[14].