Ex@tas Online Revista Científica do Departamento de Química e Exatas
volume 3 número 1 maio/2012 páginas 21-29
Universidade Estadual do Sudoeste da Bahia – Jequié-Bahia

Oscillator Strengths and Lifetimes for the PIXV Spectrum

A. J. Mania
[1] Universidade Estadual de Santa Cruz, DCET, 45662-000 - Ilhéus, BA, Brazil.
mania@uesc.br

E. Mania
Universidade de S. Paulo, IFSC, 24210-340 - S. Carlos, SP, Brazil.
edrian_mania@hotmail.com

Resumo

As intensidades de osciladores (gf) e os tempos de vida, pesadas e calculadas semi-empiricamente, apresentadas neste trabalho para todas as raias espectrais e níveis de energia do espectro P XIV foram realizadas em uma aproximação Hartree-Fock relativistico (HFR) multiconfiguracional. Nestes cálculos, os parâmetros eletrostáticos foram otimizados por um procedimento de mínimos quadrados para melhorar o ajustamento aos níveis de energia conhecidos. Este método produz valores de tempos de vida e intensidades de osciladores queestão em acordo com as observações das intensidades usadas para a interpretação de espectrogramas de plasmas estelares.

Abstract

The semi-empirical weighted oscillator strengths (gf) and the lifetimes presented in this work for all known P XIV 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 known energy levels. This method produces lifetime values and gf-values that are in agreement with intensity observations used for the interpretation of spectrograms of stellares plasmas.

Keywords: *atomic transition, energy level, oscillator strength, lifetime.*

Introduction

Ions belonging to the He I-like isoelectronic sequence have been of considerable interest because the relative simplicit of the energy level structure. High-precision numerical calculations of various atomic characteristics make these spectra a convenient aid in investigations of the physical processes ocurring in laboratory and astrophysical spectra of multiply charged ions. In these isoelectronic sequence the atomic structure calculations have importance in effects, which in the configuration interaction approach lead to very large basis sets for the wavefunctions. For these two electrons ions should be more easily and precisely calculable than other more complicated species. It is therefore an important testing ground for the development of theoretical methods which attempt to calculate atomic structure of many-electron systems.

Ex@tas Online Revista Científica do Departamento de Química e Exatas
volume 3 número 1 maio/2012 páginas 21-29
Universidade Estadual do Sudoeste da Bahia – Jequié-Bahia

The ground state configuration of phosphorus thirteen times ionized P XIV is $1s^2$ with the level $^1S_0$ having the ionization energy estimated in 22719920.0 ±350.0 cm^{-1} (2816.93 ± 0.04 eV)[1].
Ermolaev and Jones[2] had developed a set of calculations that in several low Z cases the estimates based in a systematic analysis of the radiative corrections prevailed by the quantum electrodynamics (QED) having have been applied to energy levels calculations which allow predictions of resonance lines in the states of the $1s^2$-*1snp* and *1sns*-*1s2p* configurations (*n=2,3*). The satellites resonances lines to this spectrum were identified for the first time with details by Aglitski *et al.*[3] working with laser-produced plasma experiments and in which 10 lines 4.5-5.8 Å wavelengths range has been described and identified with estimated uncertantities corresponding to about 3 parts in 10^4. With the spectra obtained with laser-produced plasma source, Boiko *et al.*[4,5] carried through detailed analysis of experimental intensities of satellites to the He-like ion (Z=12-16) resonance lines. These data are compared with calculations of radiative probabilities and autoionization rates of doubly-excited levels, with the help of the method used by Vainstein and Safronova *et al.*[6,7]. Martin[8] has applied the method to evaluate the constants in Rydberg-Ritz formulae for *1snl* series by fitting the lower few terms. Each formula in this method allows prediction of the energies of all singlet and triplet terms of a particular type of spectrum allowing extending these calculations to all series members. Livingston and Hinterlong[9,10] had determined the lines corresponding to wavenumbers 122977 ± 8 cm^{-1} and 135139 ± 4 cm^{-1}. Deslattes *et al.*[11] reported precise wavelengths measurements of the $1s^2\ ^1S_0$ - $1s2p\ ^3P_{1,2}, ^1P_1$ transitions in helium-like argon produced with collisions in the quasi-stationary recoil light source driven by the heaviest primary ions. Howie *et al.*[12] using photographic spectroscopy in a beam-foil source measured the $1s2s\ ^3S_1$ - $1s2p\ ^3P_{0,2}$ transitions wavelengths. Martin *et al.*[1] made a survey of all the work published for the P I through P XV spectra.

Methodology

Values to the energy levels has been made through of the program named STRANS (selection transitions) whose role is to verify the values of the classified transitions with their respective levels. The values of these levels are optimized by an interactive procedure using the program ELCALC, Radziemski and Kaufman[13], in which the individual wavelengths are weighted according to their uncertainties.
The theoretical predictions are obtained by diagonalizing the energy matrices with appropriate Hartree-Fock relativistic (HFR) values for the electrostatic parameters. In these computations all strong configuration interactions were included and HFR method is used to give better accuracy in many cases, as discussed in refs.[14,15]. For this purpose, the computer code developed by Cowan[16] was used.
In order to obtain the oscillator strengths and lifetimes values, the reduced matrix elements are calculated by using an optimization of the energy parameters which are adjusted from a least-squares procedure for each parity. In this adjustment, the code tries to fit experimental levels by varying the electrostatic parameters. The main purpose is to reach a fitting to the energy levels minimizing the uncertainties as much as possible. In practical terms, this procedure improves the values of the wavenumbers σ in the equation,

$$gf = \frac{8\pi^2 mca_0\sigma}{3h} S \qquad (1)$$

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

$$S^{1/2}_{\gamma\gamma'} = \sum_{\beta} \sum_{\beta'} y^{\gamma}_{\beta J} \left\langle \beta J \left\| \mathbf{P}^1 \right\| \beta' J' \right\rangle y^{\gamma'}_{\beta' J'} \qquad (2)$$

Ex@tas Online Revista Científica do Departamento de Química e Exatas
volume 3 número 1 maio/2012 páginas 21-29
Universidade Estadual do Sudoeste da Bahia – Jequié-Bahia

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

$$\mathbf{P}(\gamma J) = \sum A(\gamma J, \gamma' J') \tag{3}$$

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,

$$\tau(\gamma J) = \left(\sum A(\gamma J, \gamma' J')\right)^{-1} \tag{4}$$

Strong atomic transitions have A's of 10^8 to $10^9\ s^{-1}$, so lifetimes are 1 to 10 ns. These equations have to be applied to an isolated atom. Matter or radiation interaction will tend to reduce their values.

Fitting process with standard deviations less than one percent of the energy range is considered typical for interest of use in calculations. The propagated experimental uncertainties of the input data when of the optimization of the energy levels, cause does not influence in the process, being small comparated to uncertanties coming from the fit. The radial integrals E_{AV}, F^k, G^k and R^k are considered simply as adjustable parameters, whose values are to be determined empirically, so as to give the best possible fitting between the calculated eigenvalues and the experimental energy levels.

The values for the optimized electrostatic parameters substitute their corresponding theoretical values and are used again to calculate energy matrices. The method produces *gf* and lifetimes values that are in agreement with line intensity observations and lifetimes that are close to the experimental ones.

Values for *gf* given in Table 1., and lifetime given in Tables 2. and 3. respectively, were calculated according with Eqs. (1-4).

Results and discussion

The P XIV spectrum is characterized by the interactions of proximity of the configurations *1s5d - 1s5g, 1s6d - 1s6g, 2s3d - 2p3p, 1s5p - 1s5f, 1s6p - 1s6f, 2s3p - 2p3s* yelding a mixture of levels that can difficult a severe analysis. The *2p3p* configuration has been held fixed for being poor in known values of its experimental energy levels. In our fitting process, the standard deviations reached for each parity has remained below of 50 cm^{-1}, being satisfactory for the aims of this work. In the first colunn of Table 1. are shown the *gf* values, which have been calculated according to the previous section, whereas in Tables 2. and 3. are the lifetime and the percentage composition showing the degree of purity of each energy level for the even and odd configurations, respectively.

The proximities of the wavelength values given in Ref.[4] we allow to suggest those designated with asterisks (*) as attempt of identification for the transitions, being that are in accordance with our fitting process.

Comparisons are made with use of experimental available data. An extensive data source is not currently existent, being difficult a comparison of values for lifetimes for this ion.

Conclusion

Oscillator strengths and lifetimes for the heliumlike phosphorus are of astrophysical interest for photo-ionization modelling of elemental abundances in cosmic objects. Transitions in these ions has been of considerable interest for theoretical calculations of relativistic and quantum electrodynamics (QED) effects.

Phosphorus occupies important place with respect to cosmic distribution having its abundance estimated to be about one atom per 100 atoms of silicon, the standard. In stellar sources the amounts of this element normally

are determined through the high resolution spectrum that allow to identify the lines presents in each stage of ionization. With these data it is possible to determine the local physical conditions in the fotosfera stellar to obtain the chemical abundance.
The present work is part of an ongoing program, whose goal is to obtain oscillator strength, *gf*, and lifetimes for elements of astrophysical importance.

References

[1] W. C. Martin, R. Zalubas and A. Musgrove. Energy Levels of Phosphorus, P I through P XV. J. Phys. Chem. Ref. Data, 14 (1985) 798-800.

[2] A. M. Ermolaev and M. Jones. Ionization Potentials, Radiative Corrections and Singlet-Triplet Corrections in the Ground, n1,3S and n1,3P States of Two-Electron Ions. J. Phys. B:Atom. Molec. Phys. 7 (1974) 199-207.

[3] E. V. Aglitskii, V. A. Boiko, S. M. Zakharov, S. A. Pikuz and A. Ya. Faenov. Observation in Laser Plasmas and Identification of Dielectron Satellites of Spectral Lines of Hydrogen- and Helium-like Ions of Elements in the Na-V Range. Sov. J. Quant. Electron. 4 (1974) 500-22.

[4] V. A. Boiko, A. Ya. Faenov, S. A. Pikuz and U. I. Safronova. The Analysis of Satellites to the H-like Ion Resonance Lines Observed in the X-ray Region. Mon. Not. R. Astr. Soc. 181 (1977) 107-120.

[5] V. A. Boiko, A. Ya. Faenov and S. A. Pikuz. X-Ray Spectroscopy of Multiply-Charged Ions from Laser Plasmas. J. Quant. Spectrosc. Radiat. Transfer 19 (1978) 11-50.

[6] L. A.Vainstein and U. I. Safronova. Wavelengths and Transition Probabilities of Satellites to Resonance Lines of H-and He-Like Ions. Atom. Data Nucl. Data Tabl. 21 (1978) 49-68.

[7] U. I. Safronova. Relativistic and Radiative Efeccts in He-like Ions. Phys. Scr. 23 (1981) 241-248.

[8] W. C. Martin. Phys. Series Formulae for the He I-like Spectra Na X through Ar XVII (Z=11-18). Phys. Scr. 24 (1981) 725-31.

[9] A. E. Livingston and S. J. Hinterlong. Fine Structure Energies and Lifetimes of n=2 States in Helium-like Phosphorus. Nucl. Instr. Meth. Phys. 202 (1982) 103-05.

[10] S. J. Hinterlong. Fine-Structure Wavelength Measurements in Two-Electron Phosphorus and Calcium. Diss. Abstr. Int. B 44 (1983) 1865-67.

[11] R. D. Deslattes, H. F. Beyer and F. Folkmann. Precision X-ray Wavelength Measurements in Helium-Like Argon Recoil Ions. J. Phys. B: At. Mol. Phys. 17 (1984) 689-94.

[12] D. J. H. Howie, J. D. Silver and E. G. Myers. Measurement of 1s2s 3S1-1s2p 3P2,0 Wavelengths in Heliumlike Phosphorus. Phys. Rev. A 52 (1995) 1761-64.

[13] L. J. Radziemski, V. Kaufman. Energy Levels and Analysis of Neutral Atomic Chlorine (ClI). J. Opt. Soc. Amer. 59 (1969) 424-43.

[14] S. O. Kastner, A. K. Bhatia and L. Cohen. Prediction and Identification of Some Transitions Associated with 2*pk* and 2*pk*-13*l* Configurations in Six-, Seven- and Eight-electron Ions. Phys. Scr. 15 (1977) 259-67.

[15] A. G. Trigueiros and C. Jupén. Analysis of the 2*p*43*s*, 2*p*43*p* and 2*p*43*d* Configurations of Seven Times Ionized Sulphur (S-VIII). Phys. Scr. 31 (1985) 359-63.

[16] R. D. Cowan. The Theory of Atomic Structure and Spectra. Berkeley, CA: University of California Press, 1981.

Table 1. Weighted oscillator strengths and spectral lines for the P XIV spectrum.

gf-value	Wavelengths (Å)*		Levels (cm^{-1})		Config.		Terms		Ref.
	Observed	This Work	Even	Odd					
0.0164	813.4 ±0.2 / .32 ±0.06	813.180	17136753.5	17259727.5	1s2s	1s2p	$^3S_1$	$^3P_0$	10 / 12
0.0902	739.9 ±0.1 / .920 ±0.025	739.987	17136753.5	17271891.0	1s2s	1s2p	$^3S_1$	$^3P_2$	10 / 12
0.0027	5.7919 ±0.0015 / 7924	5.7926	0.0	17263447.6	$1s^2$	1s2p	$^1S_0$	$^3P_1$	3 / 4
0.7990	5.7591 ±0.0015 / 7596	5.7597	0.0	17362067.8	$1s^2$	1s2p	$^1S_0$	$^1P_1$	3 / 4
129.850	5.4485 ±0.0015 / 4493	5.4498	35711232.8	17362067.8	$2p^2$	1s2p	$^1D_2$	$^1P_1$	3 / 4
0.2003	5.4397	5.4397	35656890.1	17271891.0	$2p^2$	1s2p	$^3P_1$	$^3P_1$	4
0.9836	5.4397	5.4392	35656890.1	17271891.0	$2p^2$	1s2p	$^3P_2$	$^3P_2$	4
0.1346	5.4371	5.4377	17136753.5	35526735.5	1s2s	2s2p	$^3S_1$	$^3P_0$	4
0.3382	5.4368	*5.4367	35656890.1	17263447.6	$2p^2$	1s2p	$^3P_2$	$^3P_1$	4
0.4031	5.4361	5.4361	17136753.5	35532142.4	1s2s	2s2p	$^3S_1$	$^3P_1$	4
0.6736	5.4328	5.4326	17136753.5	35544035.5	1s2s	2s2p	$^3S_1$	$^3P_2$	4
0.0094	5.4230	*5.4234	20329138.6	38767591.1	1s3d	2s3p	$^3D_3$	$^3P_2$	4
0.0073	5.4230	*5.4234	20327996.6	38752992.2	1s3d	2s3p	$^3D_1$	$^3P_0$	4
0.0013	5.4230	*5.4232	20328260.0	38767591.1	1s3d	2s3p	$^3D_2$	$^3P_2$	4
0.0001	5.4230	*5.4231	20327996.6	38767591.1	1s3d	2s3p	$^3D_1$	$^3P_2$	4
0.0217	5.4230	5.4232	35711232.8	17271891.0	$2p^2$	1s2p	$^1D_2$	$^3P_2$	4
0.0460	5.4206	*5.4208	20306836.3	38754455.3	1s3s	2s3p	$^1S_0$	$^1P_1$	4
0.4083	5.4206	5.4207	17269402.3	35717244.5	1s2s	2s2p	$^1S_0$	$^1P_1$	4
0.0003	5.4202	5.4207	35711232.8	17263447.6	$2p^2$	1s2p	$^1D_2$	$^3P_1$	4
0.0616	5.4005	*5.4005	20328260.0	38844805.6	1s3d	2p3d	$^3D_3$	$^3F_2$	4
0.2034	5.4005	*5.4005	20328260.0	38844805.6	1s3d	2p3d	$^3D_2$	$^3F_2$	4
0.4159	5.4005	5.4005	20327996.6	38844805.6	1s3d	2p3d	$^3D_1$	$^3F_2$	4
0.1222	5.3987	5.3987	20330071.8	38860310.5	1s3d	2p3d	$^3F_3$	$^1D_2$	4
0.2097	5.3984	5.3984	20329138.6	38853224.5	1s3d	2p3d	$^3D_3$	$^3F_3$	4
0.6230	5.3981	5.3981	20328260.0	38853224.5	1s3d	2p3d	$^3D_2$	$^3F_3$	4
0.0705	5.3980	5.3970	20230937.9	38752992.2	1s3s	2p3s	$^3S_1$	$^3P_0$	4
0.0797	5.3972	5.3971	38857689.7	20329212.0	2s3d	1s3p	$^3D_2$	$^1P_1$	4
0.2361	5.3964	5.3963	20230937.9	38758494.9	1s3s	2p3s	$^3S_1$	$^3P_1$	4
0.5652	5.3960	5.3960	20330071.8	38860310.5	1s3d	2p3d	$^1D_2$	$^1D_2$	4
0.2194	5.3956	5.3956	35895718.3	17362067.8	$2p^2$	1s2p	$^1S_0$	$^1P_1$	4
12.281	5.3954	5.3954	20329138.6	38863445.6	1s3d	2p3d	$^3D_3$	$^3F_4$	4
0.2009	5.3954	*5.3951	38864494.8	38863445.6	2s3d	1s3p	$^1D_2$	$^1P_1$	4
0.2418	5.3946	5.3947	20230937.9	38767591.1	1s3s	2s3p	$^3S_1$	$^3P_2$	4
0.1695	5.3937	5.3930	20230937.9	38773650.2	1s3s	2s3p	$^3S_1$	$^3P_1$	4
0.1041	5.3896	5.3897	38857099.7	20303133.1	2s3d	1s3p	$^3D_1$	$^3P_1$	4
0.0683	5.3895	5.3895	38857099.7	20303133.1	2s3d	1s3p	$^3D_2$	$^3P_1$	4
0.0345	5.3895	*5.3894	38857099.7	20302036.3	2s3d	1s3p	$^3D_1$	$^3P_0$	4
0.0683	5.3893	5.3895	38857689.7	20303133.1	2s3d	1s3p	$^3D_2$	$^3P_1$	4
0.2783	5.3893	*5.3894	20329138.6	38884012.0	1s3d	2p3d	$^3D_3$	$^3D_2$	4
0.2638	5.3893	*5.3892	20328260.0	38884012.0	1s3d	2p3d	$^3D_2$	$^3D_2$	4
0.1382	5.3893	*5.3891	20327996.6	38884012.0	1s3d	2p3d	$^3D_1$	$^3D_2$	4
0.7444	5.3888	*5.3886	20329138.6	38886630.0	1s3d	2p3d	$^3D_3$	$^3D_3$	4
0.0004	5.3888	*5.3883	38864494.8	20305664.3	2s3d	1s3p	$^1D_2$	$^3P_2$	4
0.4703	5.3888	5.3883	38864500.0	38886630.0	2s3d	1s3p	$^3D_3$	$^3P_2$	4
0.1117	5.3875	*5.3875	38864494.8	20303133.1	2s3d	1s3p	$^1D_2$	$^3P_1$	4
0.1872	5.3867	*5.3866	20328260.0	38882593.5	1s3d	2p3d	$^3D_2$	$^3D_1$	4
0.2199	5.3867	*5.3865	20327996.6	38882593.5	1s3d	2p3d	$^3D_1$	$^3D_1$	4
0.0029	5.3867	*5.3862	20329138.6	38884012.0	1s3d	2p3d	$^1D_2$	$^3D_2$	4
0.0029	5.3867	*5.3859	20329138.6	38884012.0	1s3d	2p3d	$^3D_3$	$^3D_2$	4
0.0021	5.3813	*5.3815	20327996.6	38910472.0	1s3d	2p3s	$^3D_1$	$^1P_1$	4
0.0010	5.3813	*5.3814	20327996.6	38910472.0	1s3d	2p3s	$^3D_2$	$^1P_1$	4
0.0593	5.3813	*5.3812	20330071.8	38902690.0	1s3d	2p3d	$^1D_2$	$^3P_2$	4
0.3395	5.3813	*5.3809	20329138.6	38886630.0	1s3d	2p3d	$^3D_3$	$^3P_2$	4
0.0460	5.3813**	5.4208	20306836.3	38754455.3	1s3s	2s3p	$^1S_0$	$^1P_1$	4
0.1313	5.3797	*5.3797	20327996.6	38901915.0	1s3d	2p3d	$^3D_1$	$^3P_0$	4
0.2009	5.3797**	5.3951	38864494.8	20329212.0	2s3d	1s3p	$^1D_2$	$^1P_1$	4
0.8253	5.3731	5.3731	20330071.8	38941431.5	1s3d	2p3d	$^1D_2$	$^1F_3$	4
0.1188	5.3725	5.3725	20328260.0	38941431.5	1s3d	2p3d	$^3D_2$	$^1F_3$	4
0.3874	5.3699	5.3698	20330071.8	38952700.0	1s3d	2p3d	$^1D_2$	$^1P_1$	4
0.0158	5.3693	5.3693	20328260.0	38952700.0	1s3d	2p3d	$^3D_2$	$^1P_1$	4
0.0007	4.9249	4.9253	0.0	20303133.1	$1s^2$	1s3p	$^1S_0$	$^3P_1$	4
0.1592	4.9195 / 9180 ±0.0015	4.9190	0.0	20329212.0	$1s^2$	1s3p	$^1S_0$	$^1P_1$	3 / 5
0.0599	4.6795 ±0.0015	4.6795	0.0	21369758.9	$1s^2$	1s4p	$^1S_0$	$^1P_1$	3,5
0.0295	4.5755 ±0.0015	4.5755	0.0	21855396.6	$1s^2$	1s5p	$^1S_0$	$^1P_1$	3,5
0.0169	4.520 ±0.002	4.5201	0.0	22123253.5	$1s^2$	1s6p	$^1S_0$	$^1P_1$	3,5
0.0107	4.485 ±0.002	4.4852	0.0	22295398.1	$1s^2$	1s7p	$^1S_0$	$^1P_1$	3,5

*Analysis lead us suggest as candidates lines for the transitions.
** Wavelengths appear in the fitting process as a different value.

Table 2. Lifetimes for the P XIV spectrum – even levels*

Lifetimes (sec)	Energy Levels (cm^{-1})	Percentage	Composition
	0.0	100%	$1s^2$ (^1S) $^1S_0$
	17136753.5	100%	1s2s (^2S) $^3S_1$
5.088×10^{-3}	17269402.3	100%	1s2s (^2S) $^1S_0$
3.470×10^{-12}	20230937.9	100%	1s3s (^2S) $^3S_1$
3.376×10^{-12}	20306836.3	100%	1s3s (^2S) $^1S_0$
3.955×10^{-13}	20327996.6	100%	1s3d (^2S) $^3D_1$
3.974×10^{-13}	20328260.0	89%	1s3d (^2S) $^3D_2$ + 11% 1s3d (^2S) $^1D_2$
3.990×10^{-13}	20329138.6	100%	1s3d (^2S) $^3D_3$
4.111×10^{-13}	20330071.8	89%	1s3d (^2S) $^1D_2$ + 11% 1s3d (^2S) $^3D_2$
4.959×10^{-12}	21351671.5	100%	1s4s (^2S) $^3S_1$
4.717×10^{-12}	21365822.2	100%	1s4s (^2S) $^1S_0$
9.183×10^{-13}	21374919.4	100%	1s4d (^2S) $^3D_1$
9.209×10^{-13}	21374995.6	97%	1s4d (^2S) $^3D_2$
9.251×10^{-13}	21375159.7	100%	1s4d (^2S) $^3D_3$
9.562×10^{-13}	21375711.0	97%	1s4d (^2S) $^1D_2$
7.888×10^{-12}	21847708.0	100%	1s5s (^2S) $^3S_1$
7.006×10^{-12}	21854795.0	100%	1s5s (^2S) $^1S_0$
2.653×10^{-12}	21858780.0	100%	1s5d (^2S) $^3D_1$
2.660×10^{-12}	21858780.0	100%	1s5d (^2S) $^3D_2$
2.670×10^{-12}	21858780.0	100%	1s5d (^2S) $^3D_3$
1.824×10^{-12}	21859210.0	100%	1s5d (^2S) $^1D_2$
6.119×10^{-12}	21859465.0	100%	1s5g (^2S) $^3G_3$
6.119×10^{-12}	21859465.0	58%	1s5g (^2S) $^3G_4$ + 42% 1s5g (^2S) $^1G_4$
6.119×10^{-12}	21859465.0	100%	1s5g (^2S) $^3G_5$
6.119×10^{-12}	21859465.0	58%	1s5g (^2S) $^1G_4$ + 42% 1s5g (^2S) $^3G_4$
1.230×10^{-11}	22115904.9	100%	1s6s (^2S) $^3S_1$
1.005×10^{-11}	22119941.2	100%	1s6s (^2S) $^1S_0$
3.022×10^{-12}	22121978.7	100%	1s6d (^2S) $^3D_1$
3.029×10^{-12}	22122010.2	88%	1s6d (^2S) $^3D_2$ + 12% 1s6d (^2S) $^1D_2$
3.039×10^{-12}	22122120.9	100%	1s6d (^2S) $^3D_3$
3.077×10^{-12}	22122226.9	88%	1s6d (^2S) $^1D_2$ + 12% 1s6d (^2S) $^3D_2$
1.894×10^{-11}	22122371.0	100%	1s6g (^2S) $^3G_3$
1.894×10^{-11}	22122371.0	58%	1s6g (^2S) $^3G_4$ + 42% 1s6g (^2S) $^1G_4$
1.894×10^{-11}	22122371.0	58%	1s6g (^2S) $^1G_4$ + 42% 1s6g (^2S) $^3G_4$
1.050×10^{-11}	22122371.0	100%	1s6g (^2S) $^3G_5$
1.871×10^{-11}	22277113.0	100%	1s7s (^2S) $^3S_1$
1.376×10^{-11}	22279620.2	100%	1s7s (^2S) $^1S_0$
2.864×10^{-11}	22381504.0	100%	1s8s (^2S) $^3S_1$
1.746×10^{-11}	22383161.5	100%	1s8s (^2S) $^1S_0$
4.187×10^{-11}	22452950.0	100%	1s9s (^2S) $^3S_1$
1.940×10^{-11}	22454096.8	100%	1s9s (^2S) $^1S_0$
6.809×10^{-11}	22503986.0	100%	1s10s (^2S) $^3S_1$
1.592×10^{-11}	22504806.6	100%	1s10s (^2S) $^1S_0$
9.045×10^{-14}	35498968.7	82%	$2s^2$ (^1S) $^1S_0$ + 18% $2p^2$ (^1S) $^1S_0$
1.664×10^{-14}	35640827.7	99%	$2p^2$ (^3P) $^3P_0$
1.656×10^{-14}	35646908.4	100%	$2p^2$ (^3P) $^3P_1$
1.655×10^{-14}	35656890.1	98%	$2p^2$ (^3P) $^3P_2$
1.685×10^{-14}	35711232.8	98%	$2p^2$ (^1D) $^1D_2$
1.988×10^{-14}	35895718.3	82%	$2p^2$ (^1S) $^1S_0$ + 17% $2s^2$ (^1S) $^1S_0$
3.130×10^{-14}	*38810012.1	66%	2p3p (^2P) $^3D_1$ + 21% 2s3d (^2S) $^3D_1$ + 12% 2p3p (^2P) $^1P_1$
3.562×10^{-14}	*38816305.6	67%	2p3p (^2P) $^3D_2$ + 32% 2s3d (^2S) $^3D_2$
4.231×10^{-14}	*38822988.5	55%	2p3p (^2P) $^3D_3$ + 45% 2s3d (^2S) $^3D_3$
2.662×10^{-14}	*38826316.6	80%	2p3p (^2P) $^1P_1$ + 7% 2p3p (^2P) $^3D_1$ + 6% 2s3d (^2S) $^3D_1$
2.591×10^{-14}	*38851253.6	87%	2p3p (^2P) $^3S_1$ + 6% 2p3p (^2P) $^1P_1$ + 5% 2p3p (^2P) $^3P_1$
2.425×10^{-14}	*38862761.3	98%	2p3p (^2P) $^3P_0$
2.446×10^{-14}	*38869205.8	92%	2p3p (^2P) $^3P_1$ + 5% 2p3p (^2P) $^3S_1$
2.558×10^{-14}	*38875585.3	93%	2p3p (^2P) $^3P_2$
3.914×10^{-14}	*38921865.3	57%	2p3p (^2P) $^1D_2$ + 42% 2s3d (^2S) $^1D_2$
2.329×10^{-14}	*38935974.4	98%	2p3p (^2P) $^1S_0$
6.680×10^{-14}	38857099.7	69%	2s3d (^2S) $^3D_1$ + 26% 2p3p (^2P) $^3D_1$
6.266×10^{-14}	38857689.7	38%	2s3d (^2S) $^3D_2$ + 23% 2s3d (^2S) $^1D_2$ + 21% 2p3p (^2P) $^1D_2$
5.422×10^{-14}	38864494.8	31%	2s3d (^2S) $^1D_2$ + 29% 2s3d (^2S) $^3D_2$ + 20% 2p3p (^2P) $^1D_2$
5.214×10^{-14}	38864500.0	55%	2s3d (^2S) $^3D_3$ + 45% 2p3p (^2P) $^3D_3$

* Predicted data for energy levels.

Table 3. Lifetimes for the P XIV spectrum – odd levels*

Lifetimes (sec)	Energy Levels (cm^{-1})	Percentage	Composition
6.047×10^{-9}	17259727.5	100%	1s2p (^{2}S) ^{3}P$_0$
5.575×10^{-12}	17263447.6	100%	1s2p (^{2}S) ^{3}P$_1$
4.557×10^{-9}	17271891.0	100%	1s2p (^{2}S) ^{3}P$_2$
1.867×10^{-14}	17362067.8	100%	1s2p (^{2}S) ^{1}P$_1$
1.145×10^{-14}	20302036.3	100%	1s3p (^{2}S) ^{3}P$_0$
1.067×10^{-12}	20303133.1	100%	1s3p (^{2}S) ^{3}P$_1$
1.141×10^{-12}	20305664.3	100%	1s3p (^{2}S) ^{3}P$_2$
6.459×10^{-14}	20329212.0	100%	1s3p (^{2}S) ^{1}P$_1$
1.922×10^{-12}	21358234.1	100%	1s4p (^{2}S) ^{3}P$_0$
1.830×10^{-12}	21358696.6	100%	1s4p (^{2}S) ^{3}P$_1$
1.919×10^{-12}	21359763.1	100%	1s4p (^{2}S) ^{3}P$_2$
1.519×10^{-13}	21369758.9	100%	1s4p (^{2}S) ^{1}P$_1$
1.894×10^{-12}	21375302.5	100%	1s4f (^{2}S) ^{3}F$_2$
1.897×10^{-12}	21375302.5	100%	1s4f (^{2}S) ^{3}F$_3$
1.900×10^{-12}	21375302.5	100%	1s4f (^{2}S) ^{3}F$_4$
1.900×10^{-12}	21375301.7	100%	1s4f (^{2}S) ^{1}F$_3$
3.332×10^{-12}	21849560.8	100%	1s5p (^{2}S) ^{3}P$_0$
3.185×10^{-12}	21849797.6	100%	1s5p (^{2}S) ^{3}P$_1$
3.328×10^{-12}	21850344.7	100%	1s5p (^{2}S) ^{3}P$_2$
2.911×10^{-13}	21855396.6	100%	1s5p (^{2}S) ^{1}P$_1$
3.660×10^{-12}	21859341.0	100%	1s5f (^{2}S) ^{3}F$_2$
5.719×10^{-12}	21859341.0	100%	1s5f (^{2}S) ^{3}F$_3$
5.726×10^{-12}	21859341.0	100%	1s5f (^{2}S) ^{3}F$_4$
3.670×10^{-12}	21859342.0	100%	1s5f (^{2}S) ^{1}F$_3$
5.380×10^{-12}	22119904.0	100%	1s6p (^{2}S) ^{3}P$_0$
5.151×10^{-12}	22120040.5	100%	1s6p (^{2}S) ^{3}P$_1$
5.375×10^{-12}	22120355.9	100%	1s6p (^{2}S) ^{3}P$_2$
4.899×10^{-13}	22123252.5	100%	1s6p (^{2}S) ^{1}P$_1$
7.569×10^{-12}	22122303.0	100%	1s6f (^{2}S) ^{3}F$_2$
3.584×10^{-11}	22122303.0	100%	1s6f((^{2}S) ^{3}F$_3$
1.296×10^{-11}	22122303.0	100%	1s6f (^{2}S) ^{3}F$_4$
6.256×10^{-12}	22122304.0	100%	1s6f (^{2}S) ^{1}F$_3$
1.582×10^{-11}	22122413.1	100%	1s6h (^{2}S) ^{3}H$_4$
1.582×10^{-11}	22122413.1	100%	1s6h (^{2}S) ^{3}H$_5$
1.582×10^{-11}	22122413.1	100%	1s6h (^{2}S) ^{3}H$_6$
1.582×10^{-11}	22122414.1	100%	1s6h (^{2}S) ^{1}H$_5$
7.996×10^{-12}	22293304.2	100%	1s7p (^{2}S) ^{3}P$_0$
7.662×10^{-12}	22293390.1	100%	1s7p (^{2}S) ^{3}P$_1$
7.990×10^{-12}	22293589.2	100%	1s7p (^{2}S) ^{3}P$_2$
7.544×10^{-13}	22295398.1	100%	1s7p (^{2}S) ^{1}P$_1$
1.252×10^{-11}	22382498.2	100%	1s8p (^{2}S) ^{3}P$_0$
1.194×10^{-11}	22382555.8	100%	1s8p (^{2}S) ^{3}P$_1$
1.252×10^{-11}	22382689.2	100%	1s8p (^{2}S) ^{3}P$_2$
1.063×10^{-12}	22383901.9	100%	1s8p (^{2}S) ^{1}P$_1$
1.841×10^{-11}	22453433.1	100%	1s9p (^{2}S) ^{3}P$_0$
1.744×10^{-11}	22453473.5	100%	1s9p (^{2}S) ^{3}P$_1$
1.840×10^{-11}	22453567.1	100%	1s9p (^{2}S) ^{3}P$_2$
1.388×10^{-12}	22454416.5	100%	1s9p (^{2}S) ^{1}P$_1$
2.846×10^{-11}	22504143.0	100%	1s10p (^{2}S) ^{3}P$_0$
2.635×10^{-11}	22504172.3	100%	1s10p (^{2}S) ^{3}P$_1$
2.846×10^{-11}	22504240.1	100%	1s10p (^{2}S) ^{3}P$_2$
1.511×10^{-12}	22504858.2	100%	1s10p (^{2}S) ^{1}P$_1$
3.293×10^{-14}	35526735.5	100%	2s2p (^{2}S) ^{3}P$_0$
3.290×10^{-14}	35532142.4	100%	2s2p (^{2}S) ^{3}P$_1$
3.284×10^{-14}	35544035.5	100%	2s2p (^{2}S) ^{3}P$_2$
3.228×10^{-14}	35717244.5	100%	2s2p (^{2}S) ^{1}P$_1$
4.759×10^{-14}	38766593.7	89%	2p3s (^{2}P) ^{3}P$_0$ + 6% 2p3d (^{2}P) ^{3}P$_0$ + 5% 2s3p (^{2}S) ^{3}P$_0$
4.316×10^{-14}	38758494.9	85%	2p3s (^{2}P) ^{3}P$_1$ + 6% 2p3d (^{2}P) ^{3}P$_1$ + 5% 2s3p (^{2}S) ^{3}P$_1$
3.982×10^{-14}	*38780609.9	92%	2p3s (^{2}P) ^{3}P$_2$ + 7% 2p3d (^{2}P) ^{3}P$_2$
3.585×10^{-14}	*38910472.0	56%	2p3s (^{2}P) ^{1}P$_1$ + 39% 2p3d (^{2}P) ^{1}P$_1$
7.777×10^{-14}	38754455.3	52%	2s3p (^{2}S) ^{1}P$_1$ + 32% 2s3p (^{2}S) ^{3}P$_1$ + 10% 2p3s (^{2}P) ^{1}P$_1$
4.930×10^{-14}	*38752992.2	87%	2s3p (^{2}S) ^{3}P$_0$ + 8% 2p3s (^{2}P) ^{3}P$_0$ + 6% 2p3d (^{2}P) ^{3}P$_0$
4.988×10^{-14}	38773650.2	54%	2s3p (^{2}S) ^{3}P$_1$ + 24% 2s3p (^{2}S) ^{1}P$_1$ + 11% 2p3s (^{2}P) ^{3}P$_1$
5.979×10^{-14}	38767591.1	87%	2s3p (^{2}S) ^{3}P$_2$ + 9% 2p3d (^{2}P) ^{3}P$_2$
3.163×10^{-14}	38844805.6	79%	2p3d (^{2}P) ^{3}F$_2$ + 21% 2p3d (^{2}P) ^{1}D$_2$
3.186×10^{-14}	38853224.5	97%	2p3d (^{2}P) ^{3}F$_3$

Table 3. Continued

Lifetimes (sec)	Energy Levels (cm^{-1})	Percentage Composition		
3.056×10^{-14}	38860310.5	77%	2p3d	$(^2P)\ ^1D_2$ + 20% 2p3d $(^2P)\ ^3F_2$
3.194×10^{-14}	38863445.6	100%	2p3d	$(^2P)\ ^3F_4$
2.788×10^{-14}	38882593.5	95%	2p3d	$(^2P)\ ^3D_1$
2.813×10^{-14}	*38884012.0	91%	2p3d	$(^2P)\ ^3D_2$ + 5% 2p3d $(^2P)\ ^3P_2$
2.779×10^{-14}	*38886630.0	97%	2p3d	$(^2P)\ ^3D_3$
3.017×10^{-14}	*38902690.0	79%	2p3d	$(^2P)\ ^3P_2$ + 10% 2s3p $(^2S)\ ^3P_2$ + 7% 2p3d $(^2P)\ ^3D_2$
3.012×10^{-14}	*38901958.0	84%	2p3d	$(^2P)\ ^3P_1$ + 9% 2s3p $(^2S)\ ^3P_1$
3.015×10^{-14}	*38901915.0	89%	2p3d	$(^2P)\ ^3P_0$ + 8% 2s3p $(^2S)\ ^3P_0$
2.690×10^{-14}	*38941431.5	99%	2p3d	$(^2P)\ ^1F_3$
2.899×10^{-14}	38952700.0	53%	2p3d	$(^2P)\ ^1P_1$ + 28% 2p3s $(^2P)\ ^1P_1$ + 18% 2s3p $(^2S)\ ^1P_1$

* Predicted data for energy levels.