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Oscillator Strengths and Lifetimes for the P XIII Spectrum

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Abstract

The P XIII spectrum has been analyzed by several authors using different light sources. The semi-empirical oscillator strengths (*gf*) and the lifetimes presented in this work for all known P XIII spectral lines and energy levels were carried out in a multi-configuration Hartree-Fock relativistic (HFR) approach. In this calculation, the electrostatic parameters were optimized by a least-squares procedure in order to improve the adjustment of theoretical to experimental energy levels. The method produces *gf*-values that are in agreement with intensity observations and lifetime values closer to the experimental ones.

Keywords

P XIII Spectrum, Atomic Transitions, Energy Levels, Oscillator Strengths, Lifetimes

1. Introduction

The ground state configuration of twelve times ionized phosphorus, P XIII is $1s^22s$ with the term $^2S_{1/2}$ being this spectrum a member of the Li-like isoelectronic sequence with a complete core plus a single-electron valence shell. The ionization limit for this ion is estimated as being 4,934,000 ± 600 (611.74± 0.07 eV). This spectrum was originally analyzed in 1948 by H. A. Robinson to find the energy levels. These studies have being used in the compilation of Atomic Energy Levels published by C. E. Moore [1], although a wavelength list has never been published. R. L. Kelly in Ref. [2] has included some of these lines as given by Moore in his first compilation. Later in 1970, Fawcett [3], using a theta-pinch as light source, identified wavelengths of transitions occurring in the interval 22 - 41 Å and 278 - 594 Å. Fawcett *et al*. [4] using laser-produced plasma experiments confirmed the identity of many of their previous obtained lines classification. Goldsmith *et al*. [5] added, revised and extended the analyses performed by Robinson and Fawcett, classifying 13 lines in the range 23 - 39 Å with the transitions 2s-np, 2p-3s, and 2p-nd. Kasyanov *et al*. [6] and Dere [7] realized measurements of the transition $1s^22p\,^2P_{3/2}$ to the ground level $1s^22s\ ^2S_{1/2}$. Deschepper *et al.* [8] using a Doppler-tuned X-ray absorption technique realized measurements to the transition $1s^22s\ ^2S_{1/2}$-$1s2s2p\ ^4P_{1/2}$ and $^4P_{3/2}$. Edlén [9], using series formulae, has given results for the $1s^2nl$ systems that are in agreement with the expected experimental errors. Wavelengths observed by Fawcett and Ridgeley [10] and Goldsmith *et al.* [5] in the region 102 - 111 Å, were used in the spectral analysis to evaluate the 4p and 4f levels, being that the 4s levels were evaluated from isoelectronic sequence values for 2p - 4s separations. Aglitskii *et al.* [11] and Boiko *et al.* [12], using laser-produced plasma, have contributed to the spectral features that have been observed in transitions of doublet term of the configurations $1s2s^2$, $1s2p^2$, 1s2s2p, 1s2s3p, 1s2s4p, 1s2p3p, 1s2p4p, where the levels were derived from energy separations calculated by Vainshtein and Safronova [13] [14]. The wavelength tables given by these publications [15] [16], are lines arranged by spectra, being some lines of P XIII spectra which are not in other references. Martin *et al.* [17] compiles all the energy levels of all the phosphorus ions, revising the earlier version of Moore of all the published data so far, as well as the unpublished data of Robinson. Hayes and Fawcett [18] give a new original contribution by using the same spectrum obtained in theta-pinch experiment earlier. Kelly [19] reviews all P XIII line identifications in his compilation. Recently, Wang *et al.* [20]-[22] has published data of oscillator strengths for $1s^22s$ to $1s^2np$, and $1s^22p$ to $1s^2nd$ transitions of the Lithium isoelectronic sequence.

2. Methodology

Computations of wavelengths made with the aid of a Hartree-Fock Relativistic (HFR) computer program package and a program of least-square procedure as given by Cowan [23] to adjust the values of the energetic parameters, comparing the data and calculating its consistency with the identification of known energy levels. The adjustable parameters are to be determined empirically to give the best possible fitting between the calculated eigenvalues and the observed energy levels. The fitting process is carried out by a self-consistent procedure until the parameter values no longer change from one iteration cycle to the next. The main purpose is to reach a fitting to the experimental energy levels, which minimizes the uncertainties as much as possible, using the least-squares method for each parity in which the standard deviation is less than one percent of the energy range covered by the energy levels. The optimized electrostatic parameters substitute their corresponding theoretical values and they are used again to calculate energy matrices, the determination of the oscillator strengths and lifetimes values. All strong configuration interactions are to be included and HFR method is used to given a better accuracy [24]. It should also be noticed, that at higher levels, the *j-j* notation is better and it should be used to estimate the percentages of compositions.

The oscillator strengths $f(\gamma,\gamma')$ is a physical quantity related to line intensity I and transition probability $W(\gamma,\gamma')$, by:

$$W(\gamma,\gamma') = \frac{2\omega^2 e^2}{mc^3}\left|f(\gamma,\gamma')\right|, \tag{1}$$

With $I \propto gW(\gamma,\gamma') \propto g\left|f(\gamma,\gamma')\right| = gf$, being m the electron mass, e their charge, γ the initial quantum state, $\omega = \left(E(\gamma)-E(\gamma')\right)/\hbar$, $E(\gamma)$ the initial state energy and $g = (2J + 1)$ is the number of degenerate quantum states with angular momentum J. Quantities with primes refer to the final state. In the equation above, the weighted oscillator strength, gf, is

$$gf = \frac{8\pi^2 mca_0^2\sigma}{3h}\mathbf{S}, \tag{2}$$

where $\sigma = \left|E(\gamma)-E(\gamma')\right|/hc$, h is Planck's constant; c is the light velocity; and a_0 is the Bohr radius. The electric dipole line strength is defined by:

$$\mathbf{S} = \left|\left\langle \gamma J \left\| \mathbf{P}^1 \right\| \gamma' J' \right\rangle\right|^2 \tag{3}$$

This quantity is a measure of the total strength of the spectral line, including all possible transitions between $m'm$ and J_z eigenstates. The tensor operator $\mathbf{P}^1$ (first order) in the reduced matrix element is the classical dipole moment for the atom in units of $-ea_0$. To obtain gf, we need to calculate $\mathbf{S}$ first, or its square root

$$\mathbf{S}_{\gamma\gamma'}^{1/2} = \sqrt{\mathbf{S}_{\gamma\gamma'}} = \left\langle \gamma J \left\| \mathbf{P}^1 \right\| \gamma' J' \right\rangle. \tag{4}$$

In a multiconfiguration calculation we have to expand the wavefunction $|\gamma J\rangle$ in terms of single configuration wavefunction, $|\beta J\rangle$, for both upper and lower levels:

$$|\gamma J\rangle = \sum_{\beta} y^{\gamma}_{\beta J} |\beta J\rangle \tag{5}$$

Therefore, we can have the multiconfigurational expression for $\mathbf{S}^{1/2}_{\gamma\gamma'}$

$$\mathbf{S}^{1/2}_{\gamma\gamma'} = \sum_{\beta} \sum_{\beta'} y^{\gamma}_{\beta J} \left\langle \beta J \left\| P^1 \right\| \beta' J' \right\rangle y^{\gamma'}_{\beta' J'} \tag{6}$$

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

$$P(\gamma J) = \sum A(\gamma J, \gamma' J') \tag{7}$$

where $A(\gamma J, \gamma' J')$ is the Einstein spontaneous emission transition probability rate for a transition from the γJ to the $\gamma' J'$ state. The sum is over all $\gamma' J'$ states with $E(\gamma' J') < E(\gamma J)$. The Einstein probability rate is related to gf through the following relation by:

$$gA = \frac{8\pi^2 e^2 \sigma^2}{mc} gf \tag{8}$$

Since the natural lifetime $\tau(\gamma J) = \left(\sum A(\gamma J, \gamma' J')\right)^{-1}$. The natural lifetime is applicable to an isolated atom. The interaction with matter or radiation will reduce the lifetime of a state. The values for gf and lifetime given in **Table 1** and **Table 2**, respectively, were calculated according to these equations. In order to obtain better values for oscillator strengths, we calculated the reduced matrix elements $\mathbf{P^1}$ by using optimized values of energy parameters which were adjusted from a least-squares calculation. In this adjustment, the code tries to fit experimental energy values by varying the electrostatic parameters. This procedure improves σ values used in Equation (2) and $y^{\gamma}_{\beta J}$ and $y^{\gamma'}_{\beta' J'}$ values used in Equation (6).

Wavelength values in vacuum were converted to air by the relation [25], $\lambda_{vac} = n\lambda_{air}$, where the index of refraction of standard air (dry air containing $0.03CO_2$ by volume at normal pressure and $T = 15^{\circ}\mathrm{C}$) is

$$n = 1.0 + 8342.13 \times 10^{-8} + \frac{2406030.0}{130.0 \times 10^8 - \sigma^2} + \frac{15997.0}{38.9 \times 10^8 - \sigma^2}.$$

3. Results and Discussion

In our fitting process, the standard deviation reached for each parity as 12 cm^{-1} and 5 cm^{-1}, for even and odd configurations, respectively, is satisfactory for the aims of this work. Values for gf and lifetime given in **Table 1** and **Table 2**, respectively, were calculated by the previously described method. **Table 1** shows the results of the comparison between wavelength values as calculated by the method and the observed. In **Table 2**, we present lifetimes, energy levels and an estimation of their percentage composition. For the even-parity configurations we have the following picture: $1s^2 5g$, $1s^2 6g$, $1s^2 6s$, $1s^2 7s$, $1s^2 8s$, $1s^2 7d$, $1s^2 8d$, $1s2s^2$, and the series 1s2pnp ($3 \leq n \leq 4$). For the odd-parity case we study the configuration $1s^2 6h$, and the series $1s^2$nf ($4 \leq n \leq 6$), $1s^2$np ($5 \leq n \leq 8$), 1s2snp ($2 \leq n \leq 4$). The interpretation of the configuration levels structure was made by least-squares fit of the observed levels and we propose the new values possible of the energy levels marked with asterisk (*) in the table. The oscillator strengths and lifetimes for the lithium-like ions are of astrophysical interest for photo-ionization modelling of elemental abundances in cosmic objects since an extensive data source is not currently available. Transitions in this ion have been of particular importance in extrapolation analysis especially for the dense spectra from *N*-like sequence in which the phosphorus is one element in isoelectronic sequence linking lighter elements where the analysis is more extensive. Is also an important testing ground for the development of theoretical methods which attempt to calculate atomic structure of many-electron systems.

4. Conclusion

We have presented oscillator strengths and lifetimes for all known transitions in P XIII. The gf-values are better agreement with line intensity observations and lifetime values that are closer to the experimental ones. We have been stimulated by the need to determine both important parameters in the study of plasma laboratory and solar

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

gf-value	Int.	Lambda (Å)		Levels (cm^{-1})	Configurations	Terms	Ref.
		Obs.	Calc.	Even-Odd			
0.0549		4.788	4.7878	0 - 20,886,130	$1s^2 2s$ - $1s(^1S)2s4p(^3P)$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.0275		4.788	4.7879	0 - 20,886,620	$1s^2 2s$ - $1s(^1S)2s4p(^3P)$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.0071		4.807	4.8033	21,027,320 - 208,204	$1s(^1S)2p4p(^1P)$ - $1s^2 2p$	$^2P_{1/2}$ - $^2P_{1/2}$	[11]
0.0247		4.807	4.8059	21,027,320 - 219,430	$1s(^1S)2p4p(^1P)$ - $1s^2 2p$	$^2P_{1/2}$ - $^2P_{3/2}$	[11]
0.0064		4.807	4.8053	21,018,640 - 208,204	$1s(^1S)2p4p(^3P)$ - $1s^2 2p$	$(^1P)\,^2D_{3/2}$ - $^2P_{1/2}$	[11]
0.0209		4.807	4.8077	21,019,240 - 219,430	$1s(^1S)2p4p(^3P)$ - $1s^2 2p$	$(^1P)\,^2D_{5/2}$ - $^2P_{3/2}$	[11]
0.1369		5.0126	5.0126	0 - 19,949,895	$1s^2(^1S)2s$ - $1s(^1S)2s3p(^3P)$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.0685		5.0126	5.0123	0 - 19,951,015	$1s^2(^1S)2s$ - $1s(^1S)2s3p(^3P)$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.0006		5.0199	5.0196	0 - 19,921,845	$1s^2 2s$ - $1s(^1S)2s3p(^1P)$	$(^3P)\,^2S_{1/2}$ - $^4P_{3/2}$	[11]
0.0001		5.0199	5.0199	0 - 19,920,720	$1s^2 2s$ - $1s(^1S)2s3p(^1P)$	$(^3P)\,^2S_{1/2}$ - $^4P_{1/2}$	[11]
0.0191		5.0395	5.0422	20,040,625 - 208,204	$1s(^1S)2p3p(^1P)$ - $1s^2 2p$	$(^1P)\,^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.0396		5.0395	5.0451	20,040,625 - 219,430	$1s(^1S)2p3p(^1P)$ - $1s^2 2p$	$(^1P)\,^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.1704		5.0395	5.0479	20,029,775 - 219,430	$1s(^1S)2p3p(^1P)$ - $1s^2 2p$	$(^1P)\,^2D_{5/2}$ - $^2P_{3/2}$	[11] [19]
0.0585		5.7836	5.7836	17,498,570 - 208,204	$1s2p^2$ - $1s^2 2p$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.1803		5.7874	5.7873	17,498,570 - 219,430	$1s2p^2$ - $1s^2 2p$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.0702		5.7923	5.7923	0 - 17,264,350	$1s^2 2s$ - $1s(^1S)2s2p(^1P)$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.0688		5.7933	5.7934	0 - 17,261,115	$1s^2 2s$ - $1s(^1S)2s2p(^1P)$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.9818		5.8169	5.8167	0 - 17,191,815	$1s^2 2s$ - $1s(^1S)2s2p(^3P)$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.4574		5.8169	5.8184	0 - 17,186,895	$1s^2 2s$ - $1s(^1S)2s2p(^3P)$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.0019		5.0395	5.0422	20,040,625 - 208,204	$1s(^1S)2p3p(^1P)$ - $1s^2 2p$	$(^1P)\,^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.5428		5.8230	5.8240	17,378,605 - 208,204	$1s2p^2$ - $1s^2 2p$	$^2P_{1/2}$ - $^2P_{1/2}$	[11]
1.3817		5.8230	5.8245	17,388,180 - 219,430	$1s2p^2$ - $1s^2 2p$	$^2P_{3/2}$ - $^2P_{3/2}$	[11]
0.0000		5.8316	*5.8321	37,400,400 - 20,886,620	$1s^2 4s$ - $1s2s4p$	$^2S_{1/2}$ - $^2P_{1/2}$	[11]
0.0000		5.8316	*5.8322	37,400,400 - 20,886,130	$1s^2 4s$ - $1s2s4p$	$^2S_{1/2}$ - $^2P_{3/2}$	[11]
0.0000		5.8316	*5.8322	20,920,465 - 37,742,400	$1s2p4p$ - $1s^2 4f$	$^4D_{5/2}$ - $^2F_{5/2}$	[11]
0.0000		5.8316	*5.8322	20,920,465 - 37,743,800	$1s2p4p$ - $1s^2 4f$	$^4D_{5/2}$ - $^2F_{7/2}$	[11]
0.5274		5.8316	5.8324	17,353,875 - 208,204	$1s2p^2$ - $1s^2 2p$	$^2D_{3/2}$ - $^2P_{1/2}$	[11]
0.0109		5.8361	5.8361	17,353,875 - 219,430	$1s2p^2$ - $1s^2 2p$	$^2D_{3/2}$ - $^2P_{3/2}$	[11]
0.7635		5.8365	5.8358	17,355,065 - 219,430	$1s2p^2$ - $1s^2 2p$	$^2D_{5/2}$ - $^2P_{3/2}$	[11]
0.0000		5.8365	*5.8366	2,788,650 - 19,921,845	$1s3s$ - $1s2s3p$	$^2S_{1/2}$ - $^4P_{1/2}$	[11]
0.0000		5.8365	*5.8370	2,788,650 - 19,920,720	$1s3s$ - $1s2s3p$	$^2S_{1/2}$ - $^4P_{3/2}$	[11]
0.0000		5.869	5.8675	17,251,290 - 208,204	$1s2p^2$ - $1s^2 2p$	$^4P_{3/2}$ - $^2P_{1/2}$	[11]
0.0005		5.869	5.8689	17,246,905 - 208,204	$1s2p^2$ - $1s^2 2p$	$^4P_{1/2}$ - $^2P_{1/2}$	[11]
0.0028		5.869	5.8692	17,257,990 - 219,430	$1s2p^2$ - $1s^2 2p$	$^4P_{5/2}$ - $^2P_{3/2}$	[11]
0.0010		5.869	5.8713	17,251,290 - 219,430	$1s2p^2$ - $1s^2 2p$	$^4P_{3/2}$ - $^2P_{3/2}$	[11]
0.0000		5.869	5.8729	17,246,905 - 219,430	$1s2p^2$ - $1s^2 2p$	$^4P_{1/2}$ - $^2P_{3/2}$	[11]
0.0002		5.869	*5.8726	0 - 17,028,110	$1s2s$ - $1s2s2p$	$^2S_{1/2}$ - $^4P_{3/2}$	[11]

Continued

0.0009		5.869	*5.8740	0 - 17,024,200	1s2s - 1s2s2p	$^2S_{1/2}$ - $^4P_{1/2}$	[11]
0.0284	1	22.64/.678	22.6545	4,633,565 - 219,430	$1s^28d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[4] [5]
0.0032	1	22.64/.678*	22.6549	4,633,486 - 219,430	$1s^28d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[4] [5]
0.0452	1	23.08/.075	23.0752	4,553,085 - 219,430	$1s^27d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[4] [5]
0.0050	1	23.08/.075	*23.0764	4,552,860 - 219,430	$1s^27d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[4] [5]
0.0440	50	23.75	23.7465	4,419,350 - 208,204	$1s^26d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{1/2}$	[5]
0.0790 50	50	23.810	23.8100	4,419,350 - 219,430	$1s^26d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[5]
0.0088 50	50	23.810	23.8100	4,419,350 - 219,430	$1s^26d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[5]
0.0899	3	25.103	25.0998	4,192,300 - 208,204	$1s^25d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{1/2}$	[5]
0.1613	4	25.169	25.1707	4,192,300 - 219,430	$1s^25d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[5]
0.0179	4	25.169	25.1707	4,1923,00 - 219,430	$1s^25d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[5]
0.0033	4	25.169	*25.1693	4,181,300 - 208,204	$1s^25s$ - $1s^22p$	$2S_{1/2}$ - $2P_{1/2}$	[5]
0.1219	5	26.608	26.6087	0 - 3,758,169	$1s^22s$ - $1s^24p$	$^2S_{1/2}$ - $^2P_{3/2}$	[5]
0.0609	5	26.608	26.6091	0 - 3,758,112	$1s^22s$ - $1s^24p$	$^2S_{1/2}$ - $^2P_{1/2}$	[5]
0.2435	6	28.044	28.0482	3,773,500 - 208,204	$1s^24d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{1/2}$	[5]
0.4369	6	28.128	28.1328	3,774,000 - 219,430	$1s^24d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[5]
0.0485	6	28.128	*28.1368	3,773,500 - 219,430	$1s^24d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[16] [17]
0.0085	2	28.337	*28.3139	3,740,040 - 208,204	$1s^24s$ - $1s^22p$	$^2S_{1/2}$ - $^2P_{1/2}$	[5]
0.0169	2	28.337	*28.4042	3,740,040 - 219,430	$1s^24s$ - $1s^22p$	$^2S_{1/2}$ - $^2P_{3/2}$	[5]
0.4817	5	35.095	35.0950	0 - 2,849,410	$1s^22s$ - $1s^23p$	$^2S_{1/2}$ - $^2P_{3/2}$	[5]
0.2406	7	35.136	35.1361	0 - 2,846,080	$1s^22s$ - $1s^23p$	$^2S_{1/2}$ - $^2P_{1/2}$	[5]
1.3341	7	37.561	37.5610	2,870,540 - 208,204	$1s^23d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{1/2}$	[5]
2.3922	8	37.706	37.7060	2,871,530 - 219,430	$1s^23d$ - $1s^22p$	$^2D_{5/2}$ - $^2P_{3/2}$	[5]
0.2657	0	37.723	37.7201	2,870,540 - 219,430	$1s^23d$ - $1s^22p$	$^2D_{3/2}$ - $^2P_{3/2}$	[5]
0.0397	3	38.754	38.7530	2,788,650 - 208,204	$1s^23s$ - $1s^22p$	$^2S1_{/2}$ - $^2P_{1/2}$	[5]
0.0791	3	38.921	38.9223	2,788,650 - 219,430	$1s^23s$ - $1s^22p$	$^2S_{1/2}$ - $^2P_{3/2}$	[5]
0.2693	1	74.357	74.2820	4,192,300 - 2,846,080	$1s^25d$ - $1s^23p$	$^2D_{3/2}$ - $^2P_{1/2}$	[5]
0.0537	2	74.563	*74.4662	4,192,300 - 2,849,410	$1s^25d$ - $1s^23p$	$2D_{3/2}$ - $2P_{3/2}$	[5]
0.4836	2	74.563	74.4662	4,192,300 - 2,849,410	$1s^25d$ - $1s^23p$	$^2D_{5/2}$ - $^2{}_{3/2}$	[5]
0.1331	10	455.67/.73	455.7256	0 - 219,430	$1s^22s$ - $1s^22p$	$^2S1_{/2}$ - $^2P5_{/2}$	[6]-[8]
0.6310	-	480.42/.298	480.2973	0 - 208,204	$1s^22s$ - $1s^22p$	$^2S_{1/2}$ - $^2P_{1/2}$	[6]-[8]
0.2259	-	1645.8	1645.8343	2,788,650 - 2,849,410	$1s^23s$ - $1s^23p$	$^2S_{1/2}$ - $^2P_{3/2}$	[15] [16]
0.1068	-	1741.3	1741.2672	2,788,650 - 2,846,080	$1s^23s$ - $1s^23p$	$^2S_{1/2}$ - $^2P_{1/2}$	[15] [16]
0.3068	-	4087.	4079.096	3,740,040 - 3,764,550	$1s^24s$ - $1s^24p$	$^2S_{1/2}$ - $^2P_{3/2}$	[15] [16]
0.0969	-	4520.	4519.470	2,871,530 - 2,849,410	$1s^23d$ - $1s^23p$	$^2D_{5/2}$ - $^2P_{3/2}$	[15] [16]
0.0103	-	4731.	4731.222	2,870,540 - 2,849,410	$1s^23d$ - $1s^23p$	$^2D_{3/2}$ - $^2P_{3/2}$	[15] [16]

Table 2. (a) Even configurations. (b) Odd configurations.

(a)

Lifetimes (s)	Energy levels (cm^{-1})	Configurations	Terms	Percentage Composition
	0	$1s^2 2s$	$^2S_{1/2}$	100%
3.812×10^{-12}	2,788,650	$1s^2 3s$	$^2S_{1/2}$	100%
5.296×10^{-13}	2,870,540	$1s^2 3d$	$^2D_{3/2}$	100%
5.346×10^{-13}	2,871,530	$1s^2 3d$	$^2D_{5/2}$	100%
5.693×10^{-12}	3,740,040	$1s^2 4s$	$^2S_{1/2}$	100%
1.229×10^{-12}	3,773,500	$1s^2 4d$	$^2D_{3/2}$	100%
1.239×10^{-12}	3,774,000	$1s^2 4d$	$^2D_{5/2}$	100%
8.880×10^{-12}	4,181,300	$1s^2 5s$	$^2S_{1/2}$	100%
3.508×10^{-12}	4,192,300	$1s^2 5d$	$^2D_{3/2}$	100%
3.533×10^{-12}	4,192,300	$1s^2 5d$	$^2D_{5/2}$	100%
7.800×10^{-12}	*4,199,270	$1s^2 5g$	$^2G_{5/2}$	100%
7.804×10^{-12}	*4,199,330	$1s^2 5g$	$^2G_{7/2}$	100%
1.379×10^{-11}	*4,415,640	$1s^2 6s$	$^2S_{1/2}$	100%
6.412×10^{-12}	4,419,350	$1s^2 6d$	$^2D_{3/2}$	100%
6.455×10^{-12}	4,419,350	$1s^2 6d$	$^2D_{5/2}$	100%
1.384×10^{-11}	*4,425,975	$1s^2 6g$	$^2G_{5/2}$	100%
1.384×10^{-11}	*4,426,010	$1s^2 6g$	$^2G_{7/2}$	100%
2.046×10^{-11}	*4,556,200	$1s^2 7s$	$^2S_{1/2}$	100%
6.284×10^{-12}	*4,552,860	$1s^2 7d$	$^2D_{3/2}$	100%
6.319×10^{-12}	4,553,085	$1s^2 7d$	$^2D_{5/2}$	100%
2.916×10^{-11}	*4,647,077	$1s^2 8s$	$^2S_{1/2}$	100%
9.419×10^{-12}	*4,633,445	$1s^2 8d$	$^2D_{5/2}$	100%
9.369×10^{-12}	4,633,565	$1s^2 8d$	$^2D_{5/2}$	100%
4.314×10^{-13}	*16,971,300	$1s2s^2$	$(^2S)\,^2S_{1/2}$	92% + 8% $1s2p^2(^1S)\,^2S$
2.060×10^{-11}	17,246,905	$1s2p^2$	$(^3P)\,^4P_{1/2}$	100%
1.987×10^{-11}	17,251,290	$1s2p^2$	$(^3P)\,^4P_{3/2}$	100%
1.075×10^{-11}	17,257,990	$1s2p^2$	$(^3P)\,^4P_{5/2}$	100%
3.789×10^{-14}	17,353,875	$1s2p^2$	$(^1D)\,^2D_{3/2}$	97%
4.011×10^{-14}	17,355,065	$1s2p^2$	$(^1D)\,^2D_{5/2}$	100%
1.299×10^{-14}	17,378,605	$1s2p^2$	$(^3P)\,^2P_{1/2}$	100%
1.319×10^{-14}	17,388,180	$1s2p^2$	$(^3P)\,^2P_{3/2}$	97%
4.198×10^{-14}	17,498,570	$1s2p^2$	$(^1S)\,^2S_{1/2}$	91% + 8% $1s2s^2(^2S)$

Continued

1.422×10^{-12}	*19,974,700	1s2p3p	$(^3P)^4D_{1/2}$	95%
1.484×10^{-12}	*19,797,615	1s2p3p	$(^3P)^4D_{3/2}$	96%
1.612×10^{-12}	*19,802,455	1s2p3p	$(^3P)^4D_{5/2}$	99%
1.656×10^{-12}	*10,809,080	1s2p3p	$(^3P)^4D_{7/2}$	100%
1.289×10^{-12}	*19,816,705	1s2p3p	$(^3P)^4S_{3/2}$	56% + 39% 1s2p3p$(^3P)^2P$
5.117×10^{-14}	*19,867,315	1s2p3p	$(^3P)^2P_{3/2}$	50% + 41% 1s2p3p$(^3P)^4S$
5.114×10^{-14}	*19,867,440	1s2p3p	$(^3P)^2P_{1/2}$	89% + 5% 1s2p3p $(^3P)^4D$ + 5% 1s2p3p$(^1P)^2P$
1.850×10^{-14}	*20,021,950	1s2p3p	$(^1P)^2D_{3/2}$	89% + 9% 1s2p3p$(^3P)^2D$
1.836×10^{-14}	20,029,775	1s2p3p	$(^1P)^2D_{5/2}$	94% + 6% 1s2p3p$(^3P)^2D$
1.818×10^{-14}	20,040,625	1s2p3p	$(^1P)^2S_{1/2}$	79% + 19% 1s2p3p$(^3P)^2S$
9.880×10^{-12}	*20,322,915	1s2p3p	$(^3P)^4P_{1/2}$	99%
1.002×10^{-12}	*20,325,950	1s2p3p	$(^3P)^4P_{3/2}$	96%
9.924×10^{-13}	*20,330,500	1s2p3p	$(^3P)^4P_{5/2}$	99%
7.210×10^{-14}	*20,434,240	1s2p3p	$(^3P)^2D_{3/2}$	89% + 9% 1s2p3p$(^1P)^2D$
7.442×10^{-14}	*20,435,930	1s2p3p	$(^3P)^2D_{5/2}$	93% + 6% 1s2p3p$(^1P)^2D$
1.818×10^{-14}	*20,468,175	1s2p3p	$(^3P)^2S_{1/2}$	80% + 18% 1s2p3p$(^1P)^2S$
1.967×10^{-14}	*20,559,010	1s2p3p	$(^1P)^2P_{1/2}$	91% + 6% 1s2p3p$(^3P)^2P$
1.968×10^{-14}	*20,564,875	1s2p3p	$(^1P)^2P_{3/2}$	91% + 7% 1s2p3p$(^3P)^2P$
1.479×10^{-12}	*20,913,970	1s2p4p	$(^3P)^4D_{1/2}$	92% + 7% 1s2p4p$(^3P)^2P$
1.919×10^{-12}	*20,916,430	1s2p4p	$(^3P)^4D_{3/2}$	94%
2.164×10^{-12}	20,920,465	1s2p4p	$(^3P)^4D_{5/2}$	93% + 6% 1s2p4p$(^3P)^4P$
3.429×10^{-12}	*20,927,445	1s2p4p	$(^3P)^4D_{7/2}$	100%
5.873×10^{-13}	*20,922,595	1s2p4p	$(^3P)^4S_{3/2}$	49% + 25% 1s2p4p$(^3P)^2P$ + 24% 1s2p4p$(^3P)^4P$
2.679×10^{-13}	*20,925,580	1s2p4p	$(^3P)^2P_{1/2}$	74% + 20% 1s2p4p$(^3P)^4P$
7.846×10^{-13}	*20,927,915	1s2p4p	$(^3P)^4P_{1/2}$	77% + 16% 1s2p4p$(^3P)^2P$
2.711×10^{-13}	*20,930,500	1s2p4p	$(^3P)^2P_{3/2}$	60% + 19% 1s2p4p$(^3P)^4S$ + 12% 1s2p4p$(^3P)^2D$
2.952×10^{-12}	*20,933,730	1s2p4p	$(^3P)^4P_{3/2}$	67% + 31% 1s2p4p$(^3P)^4S$
2.444×10^{-12}	*20,934,970	1s2p4p	$(^3P)^4P_{5/2}$	92% + 6% 1s2p4p$(^3P)^4D$
1.880×10^{-13}	*20,939,950	1s2p4p	$(^3P)^2D_{3/2}$	85% + 12% 1s2p4p$(^3P)^2P$
2.190×10^{-13}	*20,946,885	1s2p4p	$(^3P)^2D_{5/2}$	97%
1.567×10^{-13}	*20,956,590	1s2p4p	$(^3P)^2S_{1/2}$	94%
1.836×10^{-14}	21,018,640	1s2p4p	$(^1P)^2D_{3/2}$	97%
1.812×10^{-14}	21,019,240	1s2p4p	$(^1P)^2D_{5/2}$	100%
1.801×10^{-14}	*21,020,865	1s2p4p	$(^1P)^2P_{1/2}$	97%
1.810×10^{-14}	*21,022,540	1s2p4p	$(^1P)^2P_{3/2}$	97%
1.828×10^{-14}	21,027,320	1s2p4p	$(^1P)^2S_{1/2}$	97%

(*) Indicates an attempt to identify.

(b)

Lifetimes (s)	Energy levels (cm^{-1})	Configurations	Terms	Leading Percentage
1.096×10^{-9}	208,204	$1s^2 2p$	$^2P_{1/2}$	100%
9.360×10^{-10}	219,430	$1s^2 2p$	$^2P_{3/2}$	100%
1.539×10^{-12}	2,846,080	$1s^2 3p$	$^2P_{1/2}$	100%
1.533×10^{-12}	2,849,410	$1s^2 3p$	$^2P_{3/2}$	100%
2.613×10^{-12}	3,756,701	$1s^2 4p$	$^2P_{1/2}$	100%
2.608×10^{-12}	3,764,548	$1s^2 4p$	$^2P_{3/2}$	100%
2.547×10^{-12}	*3,774,240	$1s^2 4f$	$^2F_{5/2}$	100%
2.553×10^{-12}	*3,774,380	$1s^2 4f$	$^2F_{7/2}$	100%
4.396×10^{-12}	*4,193,330	$1s^2 5p$	$^2P_{1/2}$	100%
4.392×10^{-12}	*4,193,980	$1s^2 5p$	$^2P_{3/2}$	100%
4.773×10^{-12}	*4,199,015	$1s^2 5f$	$^2F_{5/2}$	100%
4.783×10^{-12}	*4,199,115	$1s^2 5f$	$^2F_{7/2}$	100%
7.060×10^{-12}	*4,422,548	$1s^2 6p$	$^2P_{1/2}$	100%
7.055×10^{-12}	*4,422,920	$1s^2 6p$	$^2P_{3/2}$	100%
8.124×10^{-12}	*4,425,825	$1s^2 6f$	$^2F_{5/2}$	100%
8.135×10^{-12}	*4,425,885	$1s^2 6f$	$^2F_{7/2}$	100%
2.126×10^{-11}	*4,426,025	$1s^2 6h$	$^2H_{9/2}$	100%
2.127×10^{-11}	*4,426,050	$1s^2 6h$	$^2H_{11/2}$	100%
1.071×10^{-11}	*4,560,525	$1s^2 7p$	$^2P_{1/2}$	100%
1.070×10^{-11}	*4,560,760	$1s^2 7p$	$^2P_{3/2}$	100%
1.554×10^{-11}	*4,649,965	$1s^2 8p$	$^2P_{1/2}$	100%
1.554×10^{-11}	*4,650,120	$1s^2 8p$	$^2P_{3/2}$	100%
6.017×10^{-11}	17,024,200	1s2s2p	$(^3S)\,^4P_{1/2}$	100%
2.245×10^{-11}	17,028,110	1s2s2p	$(^3S)\,^4P_{3/2}$	100%
4.400×10^{-3}	*17,035,000	1s2s2p	$(^3S)\,^4P_{5/2}$	100%
2.219×10^{-14}	17,186,895	1s2s2p	$(^1P)\,^2P_{1/2}$	61% + 39% $1s2s2p(^3S)\,^2P$
2.067×10^{-14}	17,191,815	1s2s2p	$(^3S)\,^2P_{3/2}$	50% + 50% $1s2s2p(^1S)\,^2P$
1.461×10^{-13}	17,261,115	1s2s2p	$(^3S)\,^2P_{1/2}$	61% + 39% $1s2s2p(^1S)\,^2P$
2.860×10^{-13}	17,264,350	1s2s2p	$(^1P)\,^2P_{3/2}$	50% + 50% $1s2s2p(^3S)\,^2P$
6.847×10^{-11}	19,920,720	1s2s3p	$(^3S)\,^4P_{1/2}$	100%
2.375×10^{-11}	19,921,845	1s2s3p	$(^3S)\,^4P_{3/2}$	100%
3.585×10^{-9}	*19,923,960	1s2s3p	$(^3S)\,^4P_{5/2}$	100%
9.801×10^{-14}	19,949,895	1s2s3p	$(^3S)\,^2P_{3/2}$	99%
9.787×10^{-14}	19,951,015	1s2s3p	$(^3S)\,^2P_{1/2}$	100%
2.294×10^{-13}	*20,054,080	1s2s3p	$(^1P)\,^2P_{1/2}$	100%

Continued

2.300×10^{-13}	*20,057,670	1s2s3p	$(^1P)^2P3/2$	100%
1.247×10^{-9}	*20,851,270	1s2s4p	$(^3S)^4P1/2$	100%
4.749×10^{-10}	*20,851,760	1s2s4p	$(^3S)^4P3/2$	100%
1.054×10^{-7}	*20,852,600	1s2s4p	$(^3S)^4P5/2$	100%
2.236×10^{-13}	20,886,130	1s2s4p	$(^3S)^2P3/2$	99%
2.236×10^{-13}	20,886,620	1s2s4p	$(^3S)^2P1/2$	99%
3.982×10^{-13}	*20,987,940	1s2s4p	$(^1P)^2P1/2$	99%
3.982×10^{-13}	*20,989,430	1s2s4p	$(^1P)^2P3/2$	99%

(*) Indicates an attempt to identify.

spectra, as also phosphorus is an astrophysically important element. The present work is part of an ongoing program, whose goal is to obtain weighted oscillator strength, *gf*, and lifetimes for elements of astrophysical importance. Phosphorus occupies the fifteenth place with respect to cosmic distribution [26].

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