Theoretical Stark broadening parameters of Pb V spectral lines

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ABSTRACT

In this paper, we report calculated values of the Stark widths and shifts for 72 spectral lines of Pb V. They were calculated using the Griem semi-empirical approach. A set of wavefunctions obtained from Hartree–Fock relativistic calculations including core polarization effects was used. Stark widths and shifts corresponding to lines arising from $5d^9ns$ ($n = 7, 8$), $5d^9$ 6p, $5d^9$ 6d and $5d^9$ 5f configurations of Pb V. Stark widths and shifts are presented for an electron density of 10^{17} cm^{-3} and temperatures $T = 1.6$–5.0 (10^4 K). The 2142.5, 2167.9 and 2278.6 Å lines of Pb V recently measured are included in our calculations. In this case, we have included for comparison calculations without core polarization effects. There is good agreement between our calculations and the above-cited experimental values.

Key words: atomic data – atomic processes.

1 INTRODUCTION

Data on Stark broadening parameters of spectral lines are relevant not only for atomic structure research but also for astrophysics and analytical techniques in plasma diagnosis. In astrophysics, calculations of stellar opacities, stellar atmospheres modelling and abundances determinations depend on an extensive list of broadening parameters of different spectral lines of several atomic species. Lead is an important element because it belongs to the group of heavy elements produced by nucleosynthesis in the supernovae.

In a recent work, Bukvić et al. (2011) have measured the Stark broadening of several spectral lines of Pb IV and Pb V in a pulsed helium plasma discharge. The presence of Pb IV in stellar spectra has been reported in a few different types of stars: Proffitt, Sansonetti & Reader (2001) have determined the abundance of lead in the early B main-sequence star AV 304 in the Small Magellanic Cloud by measuring the 1313.1 Å resonance line of Pb IV. The lines of Pb V, which have been measured in this work, are very close to those of Pb IV and may be expected to play an important role in further astrophysical studies.

Theoretical Stark broadening for Pb IV lines was present in a previous work for these authors (Alonso-Medina et al. 2010).

In this paper, we present semi-empirical approximate values of the Stark broadening parameters for 72 lines of Pb V arising from $5d^9ns$ ($n = 7, 8$), $5d^9$ 6p, $5d^9$ 6d and $5d^9$ 5f configurations. The results have been obtained by using Griem's (1968) semi-classical calculations. Stark widths and shifts are presented for an electron density of 10^{17} cm^{-3} and temperatures $T = 1.6$–5.0 (10^4 K). The values presented in this work are compared with the values presented by Bukvić et al. (2011) for the 2142.5, 2167.9 and 2278.6 Å lines of Pb V.

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We describe in Section 2 the theoretical calculations and in Section 3 the results and discussion. We also present the variation of the Stark broadening parameters versus the temperature.

2 THEORETICAL CALCULATIONS

The Stark line widths and Stark line shifts can be calculated from the following semi-empirical formulas:

$$\omega_{\rm se} \approx 8 \left(\frac{\pi}{3}\right)^{3/2} \frac{\hbar}{m a_0} N_{\rm e} \left(\frac{E_H}{kT}\right)^{1/2} \left[\sum_{i'} |\langle i'|\boldsymbol{r}|i\rangle|^2 g_{\rm se}\left(\frac{E}{\Delta E_{i'i}}\right) + \sum_{f'} |\langle f'|\boldsymbol{r}|f\rangle|^2 g_{\rm se}\left(\frac{E}{\Delta E_{f'f}}\right)\right] \quad (1)$$

$$d \approx -8 \left(\frac{\pi}{3}\right)^{3/2} \frac{\hbar}{m a_0} N_{\rm e} \left(\frac{E_H}{kT}\right)^{1/2} \left[\sum_{i'} \left(\frac{\Delta E_{i'i}}{|\Delta E_{i'i}|}\right) |\langle i'|\ \boldsymbol{r}\ |i\rangle|^2\, g_{\rm sh}\left(\frac{E}{\Delta E_{i'i}}\right) - \sum_{f'} \left(\frac{\Delta E_{f'f}}{|\Delta E_{f'f}|}\right) |\langle f'|\ \boldsymbol{r}\ |f\rangle|^2\, g_{\rm sh}\left(\frac{E}{\Delta E_{f'f}}\right)\right]. \quad (2)$$

These formulas are derived of a simple semi-empirical impact approximation suggested by Griem (1968) and based on Baranger's original formulation (Baranger 1958) and the use of an effective Gaunt factor, proposed by Seaton (1962) and Van Regemorter (1962).

In these formulas, $\omega_{\rm se}$ and d are the Stark line width and shifts, respectively, in angular frequency units, $E_{\rm H}$ is the hydrogen ionization energy, $N_{\rm e}$ is the free electron perturber density, T is the electron

temperature, $E = \frac{3}{2}kT$ is the mean energy of the perturbing electron, and g_{se} and g_{sh} are the effective Gaunt factors. These factors are slowly varying functions of $x_{i'i} = E/\Delta E_{i'i}$, where $\Delta E_{i'i}$ is the energy difference between a perturbing level i' and the perturbed level i. The indices i and f denote the initial (upper) and final (lower) levels of the transitions, respectively. This approximation depends therefore on the Gaunt factor precision. We have chosen the Gaunt factors suggested by Niemann et al. (2003) because these factors give us theoretical values more close to the experimental values. ω_{se} is the half-width at half-maximum (HWHM) of the Lorentz profile in frequency units. ω_{se} is proportional to the full width at half-maximum (FWHM) line ω in wavelength units, through the expression $\omega = \omega_{se}\lambda^2/(\pi c)$.

The calculated atomic matrix elements $\langle i|\boldsymbol{r}|i'\rangle$ also appear in these formulas. The atomic matrix elements were obtained using Hartree–Fock relativistic (HFR) calculations and configuration interaction in an intermediate coupling (IC) scheme. For the IC calculations, we used the standard method of least-squares fitting of experimental energy levels by means of computer programs of Cowan (1981). The basis set used in this work consists of seven configurations of even parity, namely $5d^{10}$, $5d^9ns$ (n = 6, 7, 8 and 9), $5d^9$ 6d and $5d^8$ $6s^2$ and four configurations of odd

Table 1. Pb v $5d^9$ 6p–$5d^9ns$ line widths (FWHM), ω (pm) and shifts, d (pm), normalized to $N_e = 10^{17}$ cm^{-3}.

Wavelength	Transition levels		T (10^4 K)	ω (pm)	d (pm)
λ (Å)[a]	Upper	Lower			
697.2	$5d^9$ 7s 1.5(0.5) $J = 1$	$5d^9$ 6p 1.5(0.5) $J = 2$	1.6	1.40	1.00
			2.0	1.20	0.86
			2.52	1.03	0.75
			3.3	0.87	0.63
			5.0	0.67	0.49
694.4	$5d^9$ 7s 1.5(0.5) $J = 2$	$5d^9$ 6p 1.5(0.5) $J = 2$	1.6	1.99	1.49
			2.0	1.71	1.29
			2.52	1.48	1.11
			3.3	1.24	0.94
			5.0	0.96	0.73
706.3	$5d^9$ 7s 1.5(0.5) $J = 2$	$5d^9$ 6p 1.5(0.5) $J = 1$	1.6	1.84	1.44
			2.0	1.59	1.25
			2.52	1.37	1.08
			3.3	1.15	0.91
			5.0	0.90	0.71
859.0	$5d^9$7s 1.5(0.5) $J = 2$	$5d^9$6p 1.5(1.5) $J = 3$	1.6	3.30	2.41
			2.0	2.85	2.08
			2.52	2.45	1.80
			3.3	2.06	1.52
			5.0	1.60	1.19
696.2	$5d^9$ 7s 2.5(0.5) $J = 3$	$5d^9$ 6p 2.5(0.5) $J = 2$	1.6	2.58	2.00
			2.0	2.23	1.73
			2.52	1.92	1.50
			3.3	1.62	1.27
			5.0	1.26	0.99
707.7	$5d^9$ 7s 2.5(0.5) $J = 3$	$5d^9$ 6p 2.5(0.5) $J = 3$	1.6	2.89	2.18
			2.0	2.49	1.89
			2.52	2.15	1.63
			3.3	1.81	1.38
			5.0	1.40	1.07
703.7	$5d^9$ 7s 2.5(0.5) $J = 2$	$5d^9$ 6p 2.5(0.5) $J = 3$	1.6	2.25	1.65
			2.0	1.94	1.43
			2.52	1.67	1.23
			3.3	1.41	1.04
			5.0	1.09	0.81
431.9	$5d^9$ 8s 2.5(0.5) $J = 3$	$5d^9$ 6p 2.5(1.5) $J = 4$	1.6	2.51	2.01
			2.0	2.19	1.76
			2.52	1.70	1.54
			3.3	1.63	1.32
			5.0	1.29	1.06
390.9	$5d^9$8s 2.5(0.5) $J = 2$	$5d^9$6p 2.5(0.5) $J = 3$	1.6	2.00	1.66
			2.0	1.75	1.46
			2.52	1.52	1.27
			3.3	1.30	1.09
			5.0	1.03	0.87

Note. A positive shift is blue.
[a]Moore (1958).

parity, namely $5d^9\ np$ ($n = 6, 7$), $5d^9\ 5f$ and $5d^8\ 6s\,6p$. The experimental levels used for the calculations have been taken from the Moore (1958) tables, Gutmann (1969) and Wyart et al. (1992).

We have taken into account all Wyart et al. considerations regarding the evaluation of the levels presented in the tables of Moore. In this way, we use the allocation made by Wyart et al. (1992)

Table 2. Pb v $5d^9\ 6s$–$5d^9\ 6p$ and $5d^{10}$–$5d^9\ 6p$ line widths (FWHM), ω (pm) and shifts, d (pm), normalized to $N_e = 10^{17}$ cm^{-3}.

Wavelength	Transition levels		T (10^4 K)	ω(pm)	d (pm)
λ (Å)[a]	Upper	Lower			
1189.9	$5d^9\ 6p\ 2.5(0.5)\ J = 2$	$5d^9\ 6s\ 2.5(0.5)\ J = 3$	1.6	4.75	4.11
			2.0	4.06	3.51
			2.52	3.45	2.98
			3.3	2.87	2.47
			5.0	2.17	1.87
954.3	$5d^9\ 6p\ 1.5(0.5)\ J = 1$	$5d^9\ 6s\ 2.5(0.5)\ J = 2$	1.6	2.07	1.83
			2.0	1.77	1.56
			2.52	1.51	1.33
			3.3	1.25	1.10
			5.0	0.94	0.83
906.6	$5d^9\ 6p\ 2.5(1.5)\ J = 4$	$5d^9\ 6s\ 2.5(0.5)\ J = 3$	1.6	3.41	2.65
			2.0	2.92	2.27
			2.52	2.48	1.93
			3.3	2.07	1.60
			5.0	1.56	1.21
915.7	$5d^9\ 6p\ 2.5(1.5)\ J = 2$	$5d^9\ 6s\ 2.5(0.5)\ J = 2$	1.6	2.23	1.87
			2.0	1.91	1.60
			2.52	1.63	1.36
			3.3	1.35	1.13
			5.0	1.02	0.86
863.9	$5d^9\ 6p\ 2.5(1.5)\ J = 3$	$5d^9\ 6s\ 2.5(0.5)\ J = 3$	1.6	2.77	2.33
			2.0	2.37	1.99
			2.52	2.02	1.70
			3.3	1.68	1.41
			5.0	1.27	1.07
438.9	$5d^9\ 6p\ 2.5(1.5)\ J = 1$	$5d^{10}\ ^1S_0$	1.6	0.29	0.19
			2.0	0.25	0.16
			2.52	0.21	0.13
			3.3	0.17	0.11
			5.0	0.13	0.08
883.9	$5d^9\ 6p\ 2.5(1.5)\ J = 1$	$5d^9\ 6s\ 2.5(0.5)\ J = 2$	1.6	1.90	1.48
			2.0	1.63	1.27
			2.52	1.38	1.08
			3.3	1.15	0.90
			5.0	0.87	0.68
952.8	$5d^9\ 6p\ 1.5(1.5)\ J = 0$	$5d^9\ 6s\ 1.5(0.5)\ J = 1$	1.6	1.09	1.01
			2.0	0.93	0.86
			2.52	0.79	0.73
			3.3	0.66	0.61
			5.0	0.50	0.46
920.3	$5d^9 6p\ 1.5(1.5)\ J = 3$	$5d^9 6s\ 1.5(0.5)\ J = 2$	1.6	2.60	2.02
			2.0	2.22	1.73
			2.52	1.89	1.47
			3.3	1.57	1.22
			5.0	1.19	0.92
407.7	$5d^9 6p\ 1.5(1.5)\ J = 1$	$5d^{10}\ ^1S_0$	1.6	0.13	0.13
			2.0	0.11	0.11
			2.52	0.09	0.09
			3.3	0.07	0.07
			5.0	0.06	0.06
888.4	$5d^9 6p\ 1.5(1.5)\ J = 1$	$5d^9 6s\ 1.5(0.5)\ J = 1$	1.6	0.80	0.80
			2.0	0.68	0.68
			2.52	0.58	0.58
			3.3	0.48	0.48
			5.0	0.36	0.36

Note. A positive shift is blue.
[a]Moore (1958).

Table 3. Pb v $5d^9$ 6p–$5d^9$ 6d line widths (FWHM), ω (pm) and shifts, d (pm), normalized to $N_e = 10^{17}$ cm^{-3}.

Wavelength	Transition levels		T (10^4 K)	ω(pm)	d (pm)
λ (Å)[a]	Upper	Lower			
771.4	$5d^9$ 6d 2.5(1.5) J=1	$5d^9$ 6p 2.5(0.5) J=2	1.6	1.16	0.60
			2.0	1.00	0.52
			2.52	0.85	0.44
			3.3	0.71	0.37
			5.0	0.54	0.29
749.4	$5d^9$ 6d 2.5(1.5) J=2	$5d^9$ 6p 2.5(0.5) J=2	1.6	1.44	0.74
			2.0	1.24	0.64
			2.52	1.06	0.55
			3.3	0.89	0.46
			5.0	0.68	0.36
762.7	$5d^9$ 6d 2.5(1.5) J=2	$5d^9$ 6p 2.5(0.5) J=3	1.6	1.75	0.90
			2.0	1.50	0.77
			2.52	1.29	0.66
			3.3	1.08	0.56
			5.0	0.83	0.43
741.0	$5d^9$ 6d 2.5(2.5) J=1	$5d^9$ 6p 2.5(0.5) J=2	1.6	1.07	0.54
			2.0	0.92	0.47
			2.52	0.79	0.40
			3.3	0.66	0.34
			5.0	0.50	0.26
906.9	$5d^9$ 6d 2.5(2.5) J=1	$5d^9$ 6p 1.5(0.5) J=1	1.6	1.26	0.63
			2.0	1.09	0.54
			2.52	0.93	0.46
			3.3	0.78	0.39
			5.0	0.60	0.60
981.1	$5d^9$ 6d 2.5(2.5) J=1	$5d^9$ 6p 2.5(1.5) J=1	1.6	1.63	0.63
			2.0	1.40	0.54
			2.52	1.20	0.47
			3.3	1.00	0.40
			5.0	0.77	0.31
742.0	$5d^9$ 6d 2.5(1.5) J=3	$5d^9$ 6p 2.5(0.5) J=2	1.6	1.75	0.88
			2.0	1.50	0.76
			2.52	1.29	0.65
			3.3	1.07	0.55
			5.0	0.53	0.43
755.0	$5d^9$ 6d 2.5(1.5) J=3	$5d^9$ 6p 2.5(0.5) J=3	1.6	2.07	1.04
			2.0	1.78	0.90
			2.52	1.52	0.77
			3.3	1.27	0.65
			5.0	0.98	0.50
923.4	$5d^9$6d 2.5(2.5) J=3	$5d^9$6p 2.5(1.5) J=2	1.6	2.68	1.40
			2.0	2.21	1.21
			2.52	1.98	1.04
			3.3	1.66	0.88
			5.0	1.28	0.68
946.2	$5d^9$6d 2.5(2.5) J=3	$5d^9$6p 2.5(1.5) J=3	1.6	3.16	1.66
			2.0	2.72	1.43
			2.52	2.33	1.24
			3.3	1.95	1.04
			5.0	1.50	0.81
920.9	$5d^9$6d 2.5(2.5) J = 2	$5d^9$6p 2.5(1.5) J = 2	1.6	2.15	1.13
			2.0	1.84	0.97
			2.52	1.58	0.84
			3.3	1.33	0.71
			5.0	1.02	0.55
891.7	$5d^9$6d 2.5(2.5) J = 4	$5d^9$6p 2.5(1.5) J = 4	1.6	3.64	1.79
			2.0	3.13	1.55
			2.52	2.68	1.33
			3.3	2.25	1.12
			5.0	1.73	0.87

Table 3 – *continued*

Wavelength	Transition levels		T (10^4 K)	ω(pm)	d (pm)
λ (Å)[a]	Upper	Lower			
937.1	$5d^9$ 6d 2.5(2.5) J=4	$5d^9$ 6p 2.5(1.5) J=3	1.6	3.63	1.88
			2.0	3.13	1.63
			2.52	2.68	1.41
			3.3	2.25	1.19
			5.0	1.73	0.93
772.3	$5d^9$ 6d 1.5(1.5) J=1	$5d^9$ 6p 1.5(0.5) J=1	1.6	0.90	0.44
			2.0	0.78	0.38
			2.52	0.67	0.33
			3.3	0.56	0.28
			5.0	0.43	0.21
825.5	$5d^9$ 6d 1.5(1.5) J=1	$5d^9$ 6p 2.5(1.5)J=1	1.6	1.14	0.43
			2.0	0.98	0.37
			2.52	0.84	0.32
			3.3	0.70	0.27
			5.0	0.54	0.21
755.8	$5d^9$ 6d 1.5(1.5) J=3	$5d^9$ 6p 1.5(0.5) J=2	1.6	1.79	0.86
			2.0	1.54	0.75
			2.52	1.33	0.65
			3.3	1.12	0.55
			5.0	0.86	0.43
797.0	$5d^9$ 6d 1.5(1.5) J=3	$5d^9$ 6p 2.5(1.5) J=2	1.6	1.96	0.97
			2.0	1.69	0.84
			2.52	1.45	0.73
			3.3	1.22	0.62
			5.0	0.94	0.49
877.3	$5d^9$ 6d 1.5(2.5) J=1	$5d^9$ 6p 1.5(1.5) J=0	1.6	0.84	0.41
			2.0	0.72	0.36
			2.52	0.62	0.31
			3.3	0.52	0.26
			5.0	0.42	0.21
739.5	$5d^9$ 6d 1.5(1.5) J=2	$5d^9$ 6p 1.5(0.5) J=2	1.6	1.38	0.67
			2.0	1.19	0.58
			2.52	1.02	0.50
			3.3	0.86	0.42
			5.0	0.66	0.33
752.9	$5d^9$ 6d 1.5(1.5) J=2	$5d^9$ 6p 1.5(0.5) J=1	1.6	1.19	0.58
			2.0	1.02	0.50
			2.52	0.88	0.43
			3.3	0.74	0.37
			5.0	0.57	0.29
803.4	$5d^9$6d 1.5(1.5) J = 2	$5d^9$6p 1.5(1.5) J = 3	1.6	1.86	0.90
			2.0	1.60	0.78
			2.52	1.37	0.67
			3.3	1.15	0.57
			5.0	0.89	0.45
920.6	$5d^9$6d 1.5(2.5) J = 2	$5d^9$6p 1.5(1.5) J = 1	1.6	1.26	0.61
			2.0	1.09	0.53
			2.52	0.94	0.43
			3.3	0.79	0.40
			5.0	0.62	0.32
905.6	$5d^9$6d 1.5(2.5) J = 3	$5d^9$6p 1.5(1.5) J = 3	1.6	2.83	1.39
			2.0	2.44	1.21
			2.52	2.09	1.05
			3.3	1.76	0.89
			5.0	1.36	0.70
930.3	$5d^9$6d 1.5(2.5) J = 3	$5d^9$6p 1.5(1.5) J = 2	1.6	2.61	1.32
			2.0	2.26	1.14
			2.52	1.94	0.99
			3.3	1.63	0.84
			5.0	1.27	0.67

Note. A positive shift is blue.

[a] Moore (1958).

Table 4. Pb v $5d^9$ 6s–$5d^9$ 5f, $5d^9$ 6d–$5d^9$ 5f and $5d^{10}$–$5d^9$ 5f line widths (FWHM), ω (pm) and shifts, d (pm), normalized to $N_e = 10^{17}$ cm^{-3}.

Wavelength	Transition levels		T (10^4 K)	ω(pm)	d (pm)
λ (Å)[a]	Upper	Lower			
424.4	$5d^9$ 5f 2.5(0.5) J=0	$5d^9$ 6s 1.5(0.5) J=1	1.62	0.19	0.17
			2.0	0.16	0.15
			2.52	0.14	0.12
			3.3	0.12	0.10
			5.02	0.09	0.08
2277.6*	$5d^9$ 5f 2.5(0.5) J=0	$5d^9$ 6d 2.5(1.5) J=1	1.62	5.21	2.09
			2.0	4.52	1.48
			2.3*	4.12	1.67
			2.52	3.88	1.58
			3.3	3.26	1.35
			5.02	2.51	1.06
271.1	$5d^9$ 5f 2.5(0.5) J=1	$5d^{10}$ $^1S_0$	1.62	0.08	0.03
			2.0	0.07	0.03
			2.52	0.06	0.02
			3.3	0.05	0.02
			5.02	0.03	0.01
393.4	$5d^9$ 5f 2.5(0.5) J=1	$5d^9$ 6s 2.5(0.5) J=2	1.62	0.30	0.22
			2.0	0.26	0.19
			2.52	0.22	0.16
			3.3	0.18	0.13
			5.02	0.14	0.10
423.3	$5d^9$ 5f 2.5(0.5) J=1	$5d^9$ 6s 1.5(0.5) J=1	1.62	0.23	0.13
			2.0	0.20	0.11
			2.52	0.17	0.09
			3.3	0.14	0.08
			5.02	0.11	0.06
429.3	$5d^9$ 5f 2.5(0.5) J=1	$5d^9$ 6s 1.5(0.5) J=2	1.62	0.36	0.26
			2.0	0.31	0.22
			2.52	0.27	0.19
			3.3	0.22	0.16
			5.02	0.17	0.12
390.0	$5d^9$ 5f 2.5(1.5) J=1	$5d^9$ 6s 2.5(0.5)J=2	1.62	0.30	0.21
			2.0	0.26	0.18
			2.52	0.22	0.15
			3.3	0.18	0.13
			5.02	0.14	0.10
419.5	$5d^9$5f 2.5(1.5) J=1	$5d^9$6s 1.5(0.5) J=1	1.62	0.23	0.13
			2.0	0.20	0.11
			2.52	0.17	0.09
			3.3	0.14	0.08
			5.02	0.11	0.06
2143.5*	$5d^9$5f 2.5(1.5) J=1	$5d^9$6d 2.5(1.5) J=1	1.62	5.74	0.82
			2.0	4.98	0.72
			23	4.54	0.67
			2.52	4.28	0.63
			3.3	3.60	0.54
			5.02	2.77	0.44
384.4	$5d^9$5f 2.5(1.5) J=2	$5d^9$6s 2.5(0.5) J=3	1.62	0.42	0.28
			2.0	0.36	0.24
			2.52	0.31	0.21
			3.3	0.26	0.17
			5.02	0.19	0.13
390.8	$5d^9$5f 2.5(1.5) J=2	$5d^9$6s 2.5(0.5) J=2	1.62	0.33	0.19
			2.0	0.29	0.17
			2.52	0.24	0.14
			3.3	0.20	0.12
			5.02	0.15	0.09

Table 4 – *continued*

Wavelength	Transition levels		T (10^4 K)	ω (pm)	d (pm)
λ (Å)[a]	Upper	Lower			
420.4	$5d^9$ 5f 2.5(1.5) J=2	$5d^9$ 6s 1.5(0.5) J=1	1.62	0.26	0.10
			2.0	0.23	0.09
			2.52	0.20	0.07
			3.3	0.16	0.06
			5.02	0.12	0.05
426.3	$5d^9$ 5f 2.5(1.5) J=2	$5d^9$ 6s 1.5(0.5) J=2	1.62	0.40	0.23
			2.0	0.34	0.20
			2.52	0.29	0.17
			3.3	0.24	0.14
			5.02	0.18	0.10
2168.7*	$5d^9$ 5f 2.5(1.5) J=2	$5d^9$ 6d 2.5(1.5) J=1	1.62	6.78	0.22
			2.0	5.89	0.20
			2.15	5.61	0.20
			2.52	5.06	0.18
			3.3	4.25	0.17
			5.02	3.27	0.14
386.8	$5d^9$ 5f 2.5(2.5) J=3	$5d^9$ 6s 2.5(0.5) J=2	1.62	0.36	0.15
			2.0	0.31	0.13
			2.52	0.27	0.11
			3.3	0.22	0.09
			5.02	0.17	0..7
2222.2	$5d^9$ 5f 2.5(2.5) J=3	$5d^9$ 6d 2.5(1.5) J=2	1.62	11.26	0.59
			2.0	9.79	0.53
			2.52	8.42	0.48
			3.3	7.09	0.42
			5.02	5.47	0.35
2290.4	$5d^9$ 5f 2.5(2.5) J=3	$5d^9$ 6d 2.5(1.5) J=3	1.62	15.15	2.10
			2.0	13.17	1.86
			2.52	11.33	1.63
			3.3	9.54	1.40
			5.02	7.34	1.13
380.3	$5d^9$ 5f 2.5(2.5) J=2	$5d^9$ 6s 2.5(0.5) J=3	1.62	0.42	0.27
			2.0	0.36	0.23
			2.52	0.31	0.19
			3.3	0.25	0.16
			5.02	0.19	0.12
414.9	$5d^9$ 5f 2.5(2.5) J=2	$5d^9$ 6s 1.5(0.5) J=1	1.62	0.26	0.09
			2.0	0.23	0.07
			2.52	0.20	0.06
			3.3	0.16	0.05
			5.02	0.12	0.04
420.6	$5d^9$5f 2.5(2.5) J=2	$5d^9$6s 1.5(0.5) J=2	1.62	0.39	0.21
			2.0	0.34	0.18
			2.52	0.29	0.15
			3.3	0.24	0.12
			5.02	0.18	0.09
2424.8	$5d^9$5f 2.5(2.5) J=2	$5d^9$6d 2.5(2.5) J=2	1.62	12.22	1.63
			2.0	10.62	1.44
			2.52	9.14	1.26
			3.3	7.69	1.09
			5.02	5.94	0.87
3828.4	$5d^9$5f 2.5(3.5) J = 4	$5d^9$6d 1.5(1.5) J = 2	1.62	34.01	1.95
			2.0	29.70	1.65
			2.52	25.68	1.37
			3.3	21.76	1.10
			5.02	16.98	0.78
377.7	$5d^9$5f 2.5(3.5) J = 3	$5d^9$6s 2.5(0.5) J = 3	1.62	0.41	0.25
			2.0	0.36	0.22
			2.52	0.30	0.18
			3.3	0.25	0.15
			5.02	0.19	0.11

Table 4 – *continued*

Wavelength	Transition levels		T (10^4 K)	ω (pm)	d (pm)
λ (Å)[a]	Upper	Lower			
417.5	$5d^9$ 5f 2.5(3.5) J=3	$5d^9$ 6s 1.5(0.5)J=2	1.62	0.39	0.20
			2.0	0.34	0.17
			2.52	0.29	0.14
			3.3	0.24	0.12
			5.02	0.18	0.09
2324.2	$5d^9$ 5f 2.5(3.5) J=3	$5d^9$ 6d 2.5(2.5) J=2	1.62	11.36	1.21
			2.0	9.88	1.07
			2.52	8.50	0.94
			3.3	7.16	0.81
			5.02	5.53	0.65
255.1	$5d^9$ 5f 1.5(1.5) J=1	$5d^{10}$ $^1S_0$	1.62	0.07	0.03
			2.0	0.06	0.03
			2.52	0.06	0.02
			3.3	0.05	0.02
			5.02	0.03	0.01
385.7	$5d^9$ 5f 1.5(1.5) J=1	$5d^9$ 6s 1.5(0.5) J=1	1.62	0.21	0.11
			2.0	0.18	0.10
			2.52	0.15	0.08
			3.3	0.13	0.07
			5.02	0.10	0.05
390.6	$5d^9$ 5f 1.5(1.5) J=1	$5d^9$ 6s 1.5(0.5) J=2	1.62	0.32	0.22
			2.0	0.27	0.19
			2.52	0.23	0.16
			3.3	0.19	0.13
			5.02	0.15	0.10

Note. A positive shift is blue.
[a]Moore (1958).
*Lines with experimental value.

for the levels of the configurations $5d^9$ 6p, $5d^9$ 6d and $5d^9$ 7s as a starting point for our calculations. Also, we used the levels of the configuration $5d^9$ 7p and $5d^9$ 5f provided by Gutmann (1969). We consider that levels allocation made by Gutmann for these configurations is safe. The levels of these configurations were established from transitions to the $5d^9$ 6s configuration and to the $5d^9$ 6d configuration, respectively. But we do not consider safe the allocation made by Gutmann for levels of the configurations $5d^8$ $6s^2$ and $5d^8$ 6s 6p that comprise levels built from a scarce number of transitions without a sufficient theoretical grounds. So we have introduced $5d^9$ 9s, $5d^8$ $6s^2$ and $5d^8$ 6s 6p but we have not assigned levels for these configurations in the HFR calculations.

Following the suggestions of Migdalek & Baylis (1978), we have included in our calculations the core-polarization effects. A more detailed description about these calculations is presented in Colón, Alonso-Medina & Porcher (in preparation).

3 RESULTS AND DISCUSSION

As has been indicated above, in this work we have calculated the Stark broadening parameters for 72 spectral lines of Pb v. The Stark line widths (FWHM) and line shifts are displayed in Tables 1–4. Data are presented at an electron density of 10^{17} cm^{-3} and several temperatures T = 1.6–5.0 (10^4 K). The first three columns denote the corresponding wavelengths (in Å; Moore 1958) and the transition level for each transition following the allocation made by Gutmann (1969) and Wyart et al. (1992). Temperatures are shown in column 4. Stark broadening line widths (in Å) are displayed in

Table 5. Comparison between our values of FWHM Pb v spectral lines and the experimental values of Bukvić et al. (2011).

λ (Å)[a]	Transition levels		T (10^4 K)	ω(pm)		
	Upper	Lower		This work		Other author
2143.5	$5d^9$ 5f 2.5(1.5) J=1	$5d^9$ 6d 2.5(1.5) J=1	2.3	4.54[b]	5.94[c]	6.7 ± 1.7[d]
2277.6	$5d^9$ 5f 2.5(0.5) J=0	$5d^9$ 6d 2.5(1.5) J=1	2.3	4.12[b]	5.43[c]	8.3 ± 2.1[d]
2168.7	$5d^9$ 5f 2.5(1.5) J=2	$5d^9$ 6d 2.5(1.5) J=1	2.15	5.61[b]	7.18[c]	7.9 ± 1.6[d]
2425.5	$5d^8$ 6s6p (5) J=3[e]	$5d^8$ $6s^2$ (7) J=4[e]	2.26	16.1[b]	18.1[c]	3.8 ± 1.0[d]

[a]Moore (1958).
[b]Theoretical value taken into account the core polarization effects.
[c]Theoretical value without core polarization effects.
[d]Bukvić (2011).
[e]Gutmann (1969).

column 5. The last column displays the theoretical Stark line shift (a positive shift is indicated in blue).

In Table 5, we present a comparison between our values of FWHM of Pb v spectral lines and the four experimental values of Bukvić et al. (2011). In this table, we present our calculated values in two columns: the first are the theoretical FWHM that are displayed in Table 4. The second value is a value obtained with the matrix element calculated without core polarization (CP) effects.

There is good agreement, with the exception of the 2425.5 Å line, between our calculations and the experimental values within the limits of the approximation of Griem. This approach, besides depending on semi-empirical factors, ignores elastic collisions of

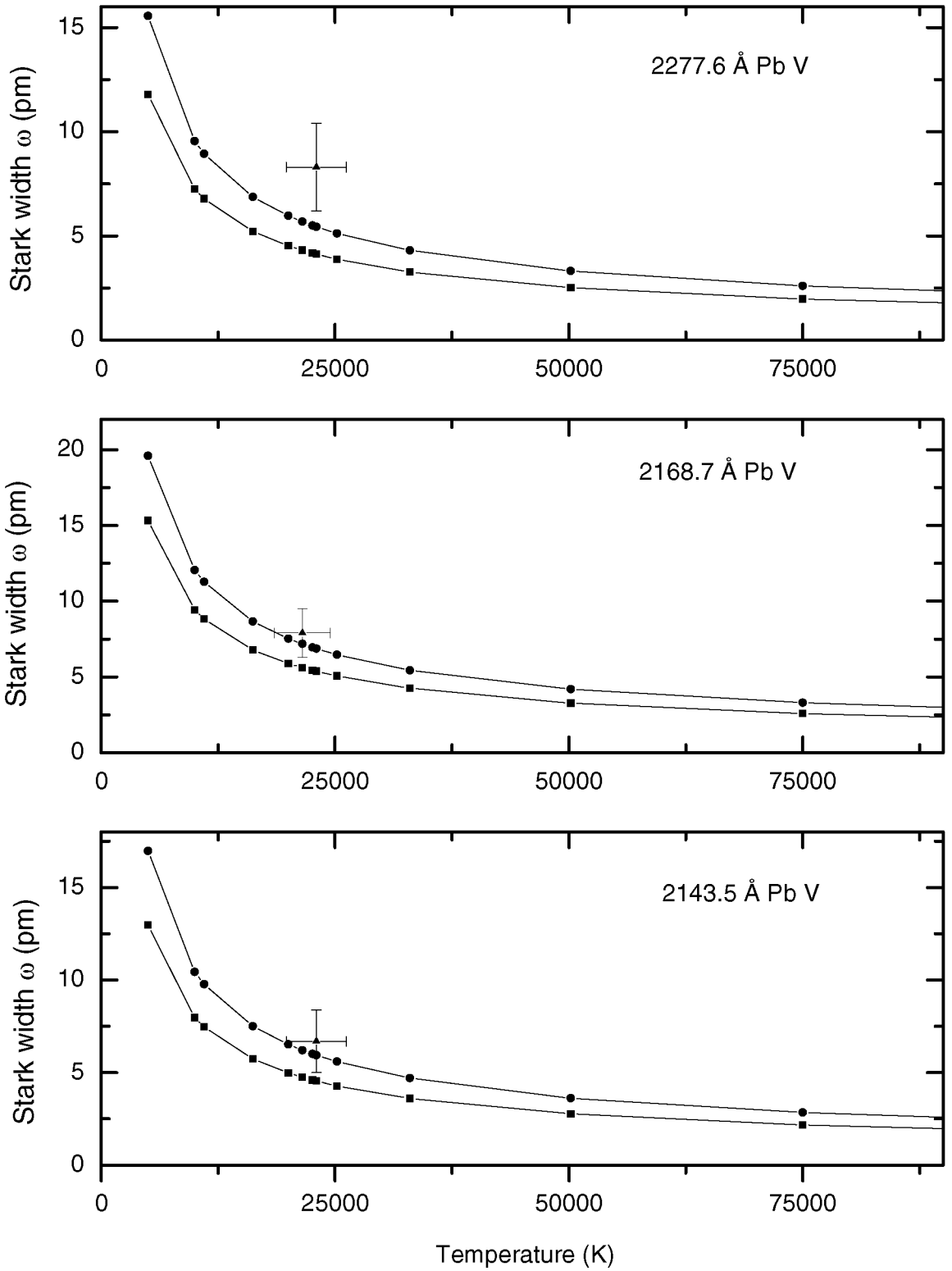

Figure 1. Calculated Stark width FWHM (ω(Å)) versus temperature for 2277.8 and 2168.7 Å and 2143.5 Pb v lines at an electron density of 10^{17} cm^{-3}.

electrons with the atomic target and therefore tends to underestimate the results.

In order to compare our theoretical values with the experimental ones, the dependence of the Stark parameters on the electron temperature, Fig. 1 displays calculated Stark widths FWHM (ω (pm)) versus temperature for 2277.8 Å and 2168.7 Å and 2143.5 Pb v lines.

In the case of line 2425.5 Å, there is not good agreement between the theoretical and experimental value. We think that it is due to difficulties in the identification of this line. The identification made by Gutmann (1969) to this line should be regarded as tentative: as we indicated above, we do not consider secure the allocation made for levels of the configurations $5d^8\,6s^2$ and $5d^8\,6s\,6p$. Also, there are no sufficient experimental levels corresponding to configurations $5d^8\,6s^2$ and $5d^8\,6s\,6p$ to establish a precise theoretical analysis of the 2425.5 Å line. Under these conditions, the matrix elements obtained are not in this case accurate enough to provide a good theoretical value.

In conclusion, by using the matrix elements calculated with the Cowan code, including core-polarization effects, we have obtained the Stark broadening parameters of Pb v spectral lines. Clear trends in the Stark widths are seen in our results.

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