Mon. Not. R. Astron. Soc. **312**, 116–122 (2000)

New *f*-values in neutral lead obtained by time-resolved laser spectroscopy, and astrophysical applications

E. Biémont,[1,2] H. P. Garnir,[1] P. Palmeri,[2] Z. S. Li[3] and S. Svanberg[3]
[1]*Institut de Physique Nucléaire Expérimentale (Bât. B15), Université de Liège, Sart Tilman, B-4000 Liège, Belgium*
[2]*Astrophysique et Spectroscopie, Université de Mons-Hainaut, Rue de la Halle, 15, B-7000 Mons, Belgium*
[3]*Department of Physics, Lund Institute of Technology, PO Box 118, S-221 00 Lund, Sweden*

Accepted 1999 September 8. Received 1999 August 23; in original form 1999 May 6

ABSTRACT

Natural radiative lifetimes have been measured for three odd-parity levels of neutral lead using time-resolved UV laser-induced fluorescence from a laser-produced plasma. These new lifetimes, as well as additional recent values obtained by laser spectroscopy, combined with theoretical branching ratios deduced from a relativistic Hartree–Fock calculation taking core polarization effects into account, have allowed the deduction of a new set of accurate *f*-values of astrophysical interest. Using the new lifetime value for 6p7s $(1/2, 1/2)^{\circ}_{0}$, a refined value of the lead abundance in the solar photosphere is deduced: $A_{\mathrm{Pb}} = 2.00 \pm 0.06$ on the usual logarithmic scale, allowing the resolution of the long-standing discrepancy previously observed between the solar photosphere and meteorites.

Key words: atomic data – methods: laboratory – Sun: abundances – Sun: photosphere – meteors, meteorites.

1 INTRODUCTION

The oscillator strengths of the heavy elements are important in astrophysics for the determination of the chemical composition of astrophysical objects, for the development of models of the atmospheres and interiors of stars, and also for testing theories of nucleosynthesis. In the latter field, the importance of lead has been stressed by many astrophysicists (see e.g. Burbidge et al. 1957). Lead occurs in the form of four different stable isotopes: ^{204}Pb (1 per cent) is produced by the s-process, while ^{206}Pb (24 per cent), ^{207}Pb (22 per cent) and ^{208}Pb (52 per cent) are produced by either the r- or s-process (Jaschek & Jaschek 1995). As ^{208}Pb is the end-product of radioactive ^{232}Th, the solar Th/Pb ratio is also of particular interest, as pointed out by Hauge & Sorli (1973).

Lead has been identified in different astrophysical objects. Pb I has been observed in the solar spectrum (see e.g. Peach 1968; Grevesse 1969; Hauge & Sorli 1973), and five lines (some of them being strongly blended) have been used for photospheric abundance determination. The 3683.463-Å transition has been identified in the solar chromosphere (Pierce 1968). Pb I has been detected in M-type stars (Fay, Fredrick & Johnsson 1968) and in Ap stars (see e.g. Burbidge et al. 1957; Guthrie 1972). Pb II is also present in Ap stars (Severny & Lyubimkov 1985) and in Am stars (Sadakane 1991), as well as in the interstellar medium (Welty et al. 1995).

In theoretical atomic physics, the calculation of radiative lifetimes for excited states of the column IV elements of the periodic table is useful for testing the adequacy of theoretical models in relation to the increasing importance of relativistic effects and of the progressive transition from *LS* to *jj* coupling. In addition, a detailed investigation of correlation effects in neutral lead is now possible in view of recent experimental analyses of the Rydberg series up to high *n*-values (see e.g. Young, Mirza & Duley 1980; Buch, Nellessen & Ertmer 1988; Ding et al. 1989; Dembczynski et al. 1994; Hasegawa & Suzuki 1996).

In Pb I, the transition probabilities available in the literature concern only a limited number of transitions, generally connecting levels of low excitation, and their reliability is difficult to assess. In addition, large discrepancies are frequently observed when comparing the different sets of data. In addition to the measurements reported in the present paper, the recent availability of an unprecedentedly large number of accurate radiative lifetimes measured by laser spectroscopy (Li et al. 1998b), combined with adequate theoretical branching ratios, provides the possibility of establishing in the present paper a reliable scale of absolute *f*-values for Pb I, particularly for some transitions of astrophysical interest. This paper is part of a general project of lifetime measurements being carried out at the Lund Laser Centre (Sweden) with the purpose of providing the scientific community with accurate atomic data needed in many fields of astrophysics (see e.g. Berzinsh et al. 1997a; Berzinsh, Svanberg & Biémont 1997b; Biémont et al. 1998b, 1999; Li et al. 1998a,b; Li et al. 1999a,b).

2 EXPERIMENTAL MEASUREMENTS

In the present work, radiative lifetimes have been measured for three odd-parity levels by time-resolved spectroscopy. For the two

7s $(1/2, 1/2)^{\circ}_{0,1}$ levels, a Q-switched and mode-locked Nd:YAG laser pumped by a distributed feedback dye laser (DFDL) was used for the excitation, which provided tuneable 60-ps laser pulses (see Biémont et al. 1999 for details). For the 7s $(3/2, 1/2)^{\circ}_1$ level, a 1-ns tunable laser system including a stimulated Brillouin scattering (SBS) compressor was employed for excitation (see Li et al. 1999a for details). Free lead atoms with sufficient populations in the metastable states were prepared in a laser-induced plasma in the vacuum chamber. The short UV laser pulses were sent across the plasma, and the free lead atoms were excited to the desired upper levels. The atomization and excitation pulses were synchronized by external triggering from the same delay generator. Fluorescence from the upper levels was collected by a fused-silicate lens and wavelength-selected by a monochromator. Finally, it was detected by a multichannel plate photomultiplier tube (MCP-PMT) connected to a TDS 602 transient digitizer. The temporal shape of the excitation pulse was recorded by the same detection system as for the fluorescence, and fitting of a convolution system between the detected excitation laser pulse and a pure exponential decay to the experimental curve yielded the lifetime values. Lifetime evaluations were performed on an IBM PC in direct connection with the experiment, and a series of measurements under different conditions was performed for each level to eliminate the systematic errors.

The 7s $(1/2, 1/2)^{\circ}_0$ level was excited from the $6p^2$ $(1/2, 3/2)_1$ level, and the fluorescence on the same transition was detected; the 7s $(1/2, 1/2)^{\circ}_1$ level was excited from the $6p^2$ $(1/2, 3/2)_2$ level, and the fluorescence of the decay to $6p^2$ $(1/2, 1/2)_0$ was detected. Finally, the 7s $(3/2, 1/2)^{\circ}_1$ state was excited from $6p^2$ $(1/2, 1/2)_0$, and the fluorescence in the decay to $6p^2$ $(1/2, 1/2)_2$ was detected. We found the following lifetimes: $\tau[7s(1/2,\ 1/2)^{\circ}_0] = 6.8 \pm 0.3$ ns, $\tau[7s(1/2, 1/2)^{\circ}_1] = 6.0 \pm 0.3$ ns and $\tau[7s(3/2,\ 1/2)^{\circ}_1] = 4.9 \pm 0.3$ ns. Statistical errors and possible remaining systematic shifts have been included in the error bar.

3 THEORETICAL CALCULATIONS

Theoretical transition probabilities have been calculated for all the transitions (allowed by the selection rules for electric dipole radiation) depopulating the levels for which radiative lifetimes have been measured by Li et al. (1998b) or in the present work.

The now 'classical' relativistic Hartree–Fock method (HFR), originally introduced by Cowan & Griffin (1976), was used for the calculations. The suite of computer programs has been described by Cowan (1981). Configuration interaction was considered among the following 42 configurations: $6s^26p^2 + 6s^26pnp$ $(7 \leq n \leq 13)$ + $6s^26pnf$ $(5 \leq n \leq 13)$ + $6p^4$ + $6s6p^2ns$ $(7 \leq n \leq 10)$ and $6s^26pns$ $(7 \leq n \leq 13)$ + $6s^26pnd$ $(6 \leq n \leq 13)$ + $6s6p^3$ + $6s6p^2np$ $(7 \leq n \leq 10)$, respectively. In order to reduce as much as possible the discrepancies between computed and observed level values, the HFR method was used in combination with a least-squares optimization of the average energies (E_{av}), direct and exchange Slater integrals (F^k and G^k), spin–orbit integrals (ζ_k), configuration interaction integrals (R^k) and effective interaction operator (α). All the F^k, G^k and R^k integrals, not optimized in the fitting procedure, were scaled down by a factor of 0.80, while the spin–orbit integrals, ζ_{nl}, were left at their *ab initio* values.

The experimental energy levels used for the fitting procedure were essentially taken from the spectral analyses published by Wood & Andrew (1968), Brown, Tilford & Ginter (1977) and Hasegawa & Suzuki (1996). Throughout the present work, *jj* coupling has been used for the level designations, even for the ground configuration, according to the analysis of Wood & Andrew (1968).

In a heavy element such as Pb I, polarization effects are expected to play a role (Bieron, Marcinek & Migdalek 1991), and should be incorporated in atomic structure calculations. They were not considered in our previous work (Li et al. 1998b) in view of the huge amount of configuration interaction considered in the calculations. However, as has been shown recently (Biémont & Quinet 1998; Biémont et al. 1998a; Biémont, Quinet & Van Renterghem 1998c; Biémont & Zeippen 1999; Li et al. 1999b), the inclusion of polarization effects in the HFR calculations leads to an improvement of the agreement between theoretical lifetime values and accurate laser measurements in heavy neutrals or singly ionized elements like Yb II, Fr I or In II. As a consequence, an additional calculation was performed taking these effects into account. One- and two-electron contributions as well as core penetration effects were introduced in the calculations in the manner described by Migdalek & Baylis (1978, 1986) and Hibbert (1989). According to that procedure, core-valence correlation was approximated by a core polarization term depending upon two parameters: i.e. α_{d}, the static dipole polarizability of the core; and r_{c}, the cut-off radius which is arbitrarily chosen as a measure of the size of the ionic core. This parameter is usually taken as the expectation value of r for the outermost core orbital. Cowan's code was modified accordingly. For Pb I, in view of the large sets of configurations introduced in the calculations, the dipole polarizability of the ionic core, α_{d} (corresponding to the Pb V ion), was chosen equal to 3.98 a.u. which corresponds to the values reported by Fraga, Karwowski & Saxena (1976); for the cut-off, we used $r_{\mathrm{c}} = 1.29$ a.u. which is the HFR value of the mean radius of 5d, i.e. $\langle 5d|r|5d\rangle$. It was verified also that consideration of the parameters $\alpha_{\mathrm{d}} = 22.33$ a.u. and $r_{\mathrm{c}} = 2.39$ a.u. (calculated with the HFR approach) of the Pb III ion leads to an overestimate of the polarization effects (the lifetime values are generally too large).

The adopted parameters for both parities and the comparison between calculated eigenvalues and observed energy levels are not tabulated in the present paper, but the numerical values are available upon request. For 65 and 50 levels of the even and odd parities, the average deviations $E_{\mathrm{obs}} - E_{\mathrm{calc}}$ reach 41 and 65 cm^{-1}, respectively.

4 THE LIFETIME VALUES

A comparison of the HFR lifetime values of Pb I with laser measurements has been discussed in a recent publication (Li et al. 1998b) and is shown in Table 1 for the odd-parity levels. For the 6pns $(1/2, 1/2)^{\circ}_1$ series, the mean ratio $\tau_{\mathrm{HFR}}/\tau_{\mathrm{exp}}$ is 1.02 ± 0.09 for seven levels (the quoted uncertainty representing twice the standard deviation of the mean). For the 6pnd $1/2[3/2]^{\circ}_1$ levels, the ratio is somewhat lower (0.76 ± 0.12 for six levels). The largest discrepancies are observed for the first members ($n = 7$–9) of the series 1/2 $[3/2]^{\circ}_2$ and also for $n = 13$ in the same series. The overall agreement is, however, good, the mean ratio being 1.04 ± 0.10 for 27 levels if we exclude from the mean the five levels for which this ratio is larger than 2 or smaller than 0.5.

When the core polarization (CP) effects are included in the model, the agreement between theory and experiment is still somewhat improved for some levels, as shown in Table 1. It is observed that the lifetime values are generally slightly increased

Table 1. Pb I: calculated and observed lifetime values (in ns). The theoretical results have been calculated with (HFR + CP) and without (HFR) inclusion of core polarization effects (see the text).

Level	$E_{\rm exp}$	Lifetime value (ns)		
	(cm^{-1})	Experiment[a]	HFR[b]	HFR + CP
6p7s (1/2, 1/2)$^\circ_0$	34 960	6.8 ± 0.3*	7.65	7.07
6p7s (1/2, 1/2)$^\circ_1$	35 287	6.0 ± 0.3*	5.47	5.12
6p7s (3/2, 1/2)$^\circ_2$	48 189	6.5 ± 0.3	4.97	4.55
6p7s (3/2, 1/2)$^\circ_1$	49 440	4.9 ± 0.3*	3.37	3.25
6p8s (1/2, 1/2)$^\circ_1$	48 687	14.7 ± 0.5	15.29	14.26
6p9s (1/2, 1/2)$^\circ_1$	53 511	33.1 ± 0.8	29.69	28.05
6p10s (1/2, 1/2)$^\circ_1$	55 720	69 ± 1	66.67	63.28
6p11s (1/2, 1/2)$^\circ_1$	56 942	116 ± 3	120.0	116.2
6p12s (1/2, 1/2)$^\circ_1$	57 689	185 ± 5	208.6	204.2
6p13s (1/2, 1/2)$^\circ_1$	58 178	275 ± 15	330.4	333.9
6p6d 1/2 [5/2]$^\circ_2$	45 443	24.5 ± 1.2	24.75	23.93
6p6d 1/2 [3/2]$^\circ_2$	46 061	4.4 ± 0.3	3.81	3.72
6p6d 1/2 [3/2]$^\circ_1$	46 068	4.1 ± 0.4	2.43	2.41
6p6d 1/2 [5/2]$^\circ_3$	46 329		5.82	5.97
6p6d 3/2 [5/2]$^\circ_2$	58 518	9.2 ± 0.6	4.24	3.94
6p7d 1/2 [3/2]$^\circ_2$	52 311	15.7 ± 0.6	24.24	25.34
6p7d 1/2 [3/2]$^\circ_1$	52 500	10.2 ± 0.9	5.97	6.15
6p7d 1/2 [5/2]$^\circ_2$	52 102	53.7 ± 1.1	66.44	66.35
6p8d 1/2 [3/2]$^\circ_1$	55 158	17.9 ± 0.5	14.42	15.04
6p8d 1/2 [3/2]$^\circ_2$	55 084	35.4 ± 0.9	88.02	90.56
6p8d 1/2 [5/2]$^\circ_2$	55 003	94.5 ± 2.1	121.9	120.2
6p9d 1/2 [3/2]$^\circ_1$	56 605	32 ± 1	27.63	28.99
6p9d 1/2 [3/2]$^\circ_2$	56 563	72 ± 2	30.94	36.09
6p9d 1/2 [5/2]$^\circ_2$	56 526	169 ± 10	195.9	199.2
6p10d 1/2 [3/2]$^\circ_1$	57 471	52.1 ± 1.5	45.02	47.39
6p10d 1/2 [3/2]$^\circ_2$	57 444	105 ± 15	94.79	106.6
6p10d 1/2 [5/2]$^\circ_2$	57 424	187 ± 5	324.4	325.9
6p11d 1/2 [3/2]$^\circ_1$	58 030	73 ± 3	63.34	67.17
6p11d 1/2 [3/2]$^\circ_2$	58 012	199 ± 9	201.7	230.2
6p11d 1/2 [5/2]$^\circ_2$	57 996	182 ± 18	411.4	391.6
6p12d 1/2 [3/2]$^\circ_2$	58 399	176 ± 16	496.1	578.4
6p12d 1/2 [5/2]$^\circ_2$	58 379	94.2 ± 3.1	127.3	75.56
6p13d 1/2 [5/2]$^\circ_2$	58 667	152 ± 4	206.5	208.0

*Measured in the present work. [a]From Li et al. (1998b) except where otherwise indicated. [b]From Li et al. (1998b).

when the CP effects are included in the calculations, although not in a dramatic way, the mean ratio for 27 levels being 1.03 ± 0.10. For the 6p7s (1/2, 1/2)$^\circ_0$ levels measured in the present work, the HFR+CP lifetimes are smaller than the HFR results, leading to a better agreement for the $J = 0$ level, while the agreement is somewhat worse for the $J = 1$ level. For the 6pns levels, the mean ratio $\tau_{\rm (HFR\ +CP)}/\tau_{\rm exp} = 0.96 \pm 0.10$ (nine levels), while the same ratio is 1.06 ± 0.14 for the 6pnd series (18 levels) if we exclude from the mean the 5 levels for which large discrepancies between theory and experiment are observed.

This gratifying agreement for a heavy element like Pb indicates that both correlation and relativistic effects have been properly taken into account in the physical model adopted for the calculations. This has prompted us to use the new lifetime measurements in order to normalize the HFR results, i.e. to combine the experimental lifetimes with the theoretical branching fractions in order to deduce a new scale of reliable absolute transition probabilities. Although the agreement of the lifetimes is not sufficient to guarantee that the branching ratios are accurate, the adequacy of the adopted procedure appears sufficient according to the discussions of the following sections. This normalization process has been applied only to the levels for which theoretical and experimental lifetime values agree roughly within 30 per cent (i.e. for 23 levels).

For the six levels at 35 287, 45 443, 46 061, 46 068, 46 329 and 48 189 cm^{-1}, the ratio $\tau_{\rm HFR}\,{+}_{\rm CP}/\tau$ (Garpman et al. 1971) has been found to be systematically lower than unity, with a mean value of 0.857. The Hanle effect measurements of Garpman et al. (1971) are, however, systematically lower by 5–10 per cent than the measurements of Li et al. (1998b), except for the level 6p6d 1/2[5/2]$^\circ_2$ for which they agree. A satisfying agreement is also found when comparing the HFR+CP lifetimes with the delayed-coincidence measurements of Gorshov & Verolainen (1985) ($\tau_{\rm HFR}\ {+}_{\rm CP}/\tau_{\rm exp} = 0.85 \pm 0.14$ for 12 levels).

The normalized results are reported in Table 2, where we give successively the upper (column 1) and lower (column 2) levels of the transitions, the observed wavelengths (in Å, $\lambda < 1.0\,\mu$m) (column 3) where they exist (Wood & Andrew 1968; Brown et al. 1977) or the air wavelengths calculated from the energy level scheme proposed by Wood & Andrew (1968), the oscillator strengths (log *gf*, columns 4 and 5) and the transition probabilities (*gA*, in s^{-1}, columns 6 and 7), calculated with the optimized parameters and with inclusion of core polarization effects.

5 THE OSCILLATOR STRENGTHS

Strengths and Stark widths of the prominent visible lines of Pb I and Pb II have been measured in emission by Miller, Bengtson & Lindsay (1979) using a gas-driven shock tube. Although the experimental conditions of their experiment were deliberately tailored to enhance the Pb II spectrum, they were able to measure the relative intensities of the dominant Pb I lines in the range $3500 < \lambda < 4200$ Å. Their relative scale was normalized using the A_{ki} value ($A = 9.9 \times 10^7\ {\rm s}^{-1}$) of λ4057.8 [6p^2 (3/2, 1/2)$_2$ –6p7s (1/2, 1/2)$^\circ_1$] which is larger by about a factor of 1.5 than the present result. Consequently, their normalized data (for nine lines) are systematically larger than our results by factors ranging between 1.1 and 6.7. As their accuracy is expected to be low (the quoted uncertainties are between 30 and 60 per cent), these results will not be considered further in the present paper.

Relative *f*-values of the p^2–ps and p^2–pd transition arrays of Pb I have been measured via the hook method by Penkin & Slavenas (1963) (PS). The absolute scale was established through the line at 2833.053 Å ($f = 0.212 \pm 0.003$). When comparing with our data, it is observed that the ratio $f_{\rm HFR}\ {+}_{\rm CP}/f_{\rm PS}$ is scattered between 0.65 and 1.35 (except for $\lambda = 2613.655$ Å). Doidge (1995) has recently discussed the *f*-value of the resonance line at 2833 Å and adopted the result $f = 0.19 \pm 0.02$ according to the analyses of Lvov (1970) and DeZafra & Marshall (1968), which is somewhat lower than our normalized result ($f = 0.26$). It should be emphasized, however, that the line strengths measured by Penkin & Slavenas (1963) in Pb I are markedly different from the linestrengths calculated in either intermediate or *jj* coupling, and that the *J*-sum rules are not satisfied, indicating probably a lack of consistency in the experimental data.

Branching ratio measurements have been performed by Lotrian et al. (1979) for the transitions emitted from eight levels of Pb I excited in a hollow cathode discharge. A set of absolute transition probabilities has been derived for 28 lines using averaged available lifetimes (Saloman & Happer 1966; Saloman 1966; Savage & Lawrence 1966; Cunningham & Link 1967; DeZafra & Marshall 1968; Garpman et al. 1971; Svanberg 1972). For half of the lines, the transition probabilities of Lotrian et al. agree to

Table 2. Pb I: experimental energy levels (in cm^{-1}), observed wavelengths (in Å), calculated oscillator strengths ($\log g_i f_{ik}$) and transition probabilities ($g_k A_{ki}$, in s^{-1}). The depopulation branches situated at $\lambda > 1.0\,\mu$m are not quoted.

Upper level	Lower level	λ_{exp}(Å)	log *gf*		*gA* (s^{-1})	
			CP	NORM	CP	NORM
6p7s (1/2, 1/2)$^\circ_0$	6p^2 (3/2, 1/2)$_1$	3683.463 a	−0.54	−0.52	1.41(8)	1.48(8)
$E = 34\,960$ cm^{-1}						
6p7s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	2833.053 a	−0.50	−0.58	2.62(8)	2.20(8)
$E = 35\,287$ cm^{-1}	6p^2 (3/2, 1/2)$_1$	3639.568 a	−0.80	−0.88	7.99(7)	6.70(7)
	6p^2 (3/2, 1/2)$_2$	4057.807 a	−0.22	−0.30	2.40(8)	2.01(8)
	6p^2 (3/2, 3/2)$_2$	7228.965 a	−1.62	−1.70	3.11(6)	2.61(6)
6p6d 1/2 [5/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2657.094 a	−2.47	−2.48	3.21(6)	3.14(6)
$E = 45\,443$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2873.311 a	−0.61	−0.62	1.98(8)	1.93(8)
	6p^2 (3/2, 3/2)$_2$	4168.033 a	−1.94	−1.95	4.45(6)	4.35(6)
6p6d 1/2 [3/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2614.175 a	0.10	0.03	1.22(9)	1.03(9)
$E = 46\,061$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2823.189 a	−0.81	−0.88	1.28(8)	1.08(8)
	6p^2 (3/2, 3/2)2	4063.39	−2.92	−2.99	4.87(5)	4.12(5)*
6p7s (3/2, 1/2)$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2476.378 a	−0.69	−0.85	2.24(8)	1.57(8)
$E = 48\,189$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2663.154 a	−0.17	−0.33	6.35(8)	4.45(8)
	6p^2 (3/2, 3/2)$_2$	3739.935 a	−0.31	−0.47	2.39(8)	1.67(8)
6p8s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	2053.284 a	−2.32	−2.33	7.52(6)	7.29(6)
$E = 48\,687$ cm^{-1}	6p^2 (3/2, 1/2)$_1$	2446.181 a	−1.04	−1.05	1.01(8)	9.80(7)
	6p^2 (3/2, 1/2)$_2$	2628.262 a	−3.07	−3.08	8.13(5)	7.89(5)*
	6p^2 (3/2, 3/2)$_2$	3671.491 a	−0.88	−0.89	6.61(7)	6.41(7)
	6p^2 (3/2, 3/2)$_0$	5201.437 a	−1.35	−1.36	1.09(7)	1.06(7)
6p7d 1/2 [5/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2257.534 a	−6.06	−5.97	1.14(3)	1.40(3)*
$E = 52\,102$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2411.734	−1.76	−1.67	1.98(7)	2.45(7)
	6p^2 (3/2, 3/2)$_2$	3262.355 a	−2.40	−2.31	2.55(6)	3.15(6)
6p9s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1868.764 a	−1.58	−1.65	5.04(7)	4.27(7)
$E = 53\,511$ cm^{-1}	6p^2 (3/2, 1/2)$_1$	2187.888 a	−3.30	−3.37	6.98(5)	5.91(5)
	6p^2 (3/2, 1/2)$_2$	2332.418 a	−1.55	−1.62	3.44(7)	2.91(7)
	6p^2 (3/2, 3/2)$_2$	3118.894 a	−2.39	−2.46	2.80(6)	2.37(6)
	6p^2 (3/2, 3/2)$_0$	4157.814 a	−3.55	−3.62	1.09(5)	9.23(4)*
	6p7p (1/2, 1/2)$_1$	9438.048 a	−1.22	−1.29	4.55(6)	3.85(6)
6p8d 1/2 [5/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2118.697 a	−2.20	−2.10	9.30(6)	1.18(7)
$E = 55\,003$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2253.943 a	−4.17	−3.97	8.90(4)	1.13(5)*
	6p^2 (3/2, 3/2)$_2$	2980.157 a	−2.44	−2.34	2.72(6)	3.46(6)
	6p7p (1/2, 1/2)$_1$	8272.690 a	−1.28	−1.18	5.13(6)	6.52(6)
	6p7p (1/2, 3/2)$_1$	9679.483 a	−0.81	−0.71	1.11(7)	1.41(7)
	6p7p (1/2, 3/2)$_2$	9807.054 a	−1.20	−1.10	4.34(6)	5.52(6)
6p8d 1/2 [3/2]$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1812.969 a	−1.18	−1.26	1.34(8)	1.13(8)
$E = 55\,158$ cm^{-1}	6p^2 (3/2, 1/2)$_1$	2111.758 a	−1.69	−1.77	3.08(7)	2.59(7)
	6p^2 (3/2, 1/2)$_2$	2246.100 a	−2.27	−2.35	7.09(6)	5.96(6)
	6p^2 (3/2, 3/2)$_2$	2966.460 a	−2.12	−2.20	5.81(6)	4.88(6)
	6p^2 (3/2, 3/2)$_0$	3891.235 a	−5.02	−5.10	4.19(3)	3.46(3)*
	6p7p (1/2, 1/2)$_1$	8168.001 a	−1.43	−1.51	3.67(6)	3.08(6)
	6p7p (1/2, 1/2)$_0$	9293.477 a	−0.88	−0.96	1.04(7)	8.74(6)
	6p7p (1/2, 3/2)$_1$	9536.461 a	−1.69	−1.77	1.52(6)	1.28(6)
	6p7p (1/2, 3/2)$_2$	9660.301 a	−2.16	−2.24	4.94(5)	4.15(5)
6p6f 1/2 [5/2]$_2$	6p7s (1/2, 1/2)$^\circ_1$	4980.462 a	−2.53	−2.48	8.05(5)	8.96(5)
$E = 55\,360$ cm^{-1}						
6p10s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1794.672 a	−2.00	−2.04	2.10(7)	1.93(7)
$E = 55\,720$ cm^{-1}	6p^2 (3/2, 1/2)$_1$	2086.968 a	−3.45	−3.49	5.45(5)	5.00(5)
	6p^2 (3/2, 1/2)$_2$	2218.075 a	−1.99	−2.03	1.38(7)	1.27(7)
	6p^2 (3/2, 3/2)$_2$	2917.777 a	−3.23	−3.27	4.67(5)	4.28(5)*
	6p^2 (3/2, 3/2)$_0$	3807.921 a	−2.93	−2.97	5.36(5)	4.92(5)
	6p7p (1/2, 1/2)$_1$	7809.259 a	−1.65	−1.69	2.45(6)	2.25(6)
	6p7p (1/2, 1/2)$_0$	8831.860 a	−2.36	−2.40	3.76(5)	3.45(5)
	6p7p (1/2, 3/2)$_1$	9050.998 a	−2.22	−2.26	4.90(5)	4.49(5)
	6p7p (1/2, 3/2)$_2$	9162.481 a	−1.47	−1.51	2.70(6)	2.48(6)
6p9d 1/2 [5/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2052.424 a	−3.19	−3.12	1.03(6)	1.21(6)
$E = 56\,526$ cm^{-1}	6p^2 (3/2, 1/2)$_2$	2179.099 a	−2.46	−2.39	4.87(6)	5.74(6)
	6p^2 (3/2, 3/2)$_2$	2850.707 a	−3.36	−3.29	3.59(5)	4.23(5)*
	6p7p (1/2, 1/2)$_1$	7346.676 a	−1.11	−1.04	9.62(6)	1.13(7)
	6p7p (1/2, 3/2)$_1$	8435.419 a	−2.47	−2.40	3.18(5)	3.75(5)
	6p7p (1/2, 3/2)$_2$	8532.172 a	−1.74	−1.67	1.65(6)	1.94(6)

Table 2 – *continued*

Upper level	Lower level	λ_{exp}(Å)	log *gf*		*gA* (s^{-1})	
			CP	NORM	CP	NORM
6p9d 1/2 [3/2]$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1766.637 a	−1.52	−1.56	6.50(7)	5.89(7)
$E = 56\,605\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	2049.136 a	−1.97	−2.01	1.70(7)	1.54(7)
	6p^2 (3/2, 1/2)$_2$	2175.391 a	−2.57	−2.61	3.80(6)	3.44(6)
	6p^2 (3/2, 3/2)$_2$	2844.364 a	−2.38	−2.42	3.44(6)	3.12(6)
	6p^2 (3/2, 3/2)$_0$	3683.834	−3.51	−3.55	1.50(5)	1.36(5)*
	6p7p (1/2, 1/2)$_1$	7304.683 a	−1.80	−1.84	1.95(6)	1.77(6)
	6p7p (1/2, 1/2)$_0$	8191.886 a	−1.24	−1.28	5.79(6)	5.25(6)
	6p7p (1/2, 3/2)$_1$	8380.105 a	−2.04	−2.08	8.68(5)	7.86(5)
	6p7p (1/2, 3/2)$_2$	8475.569 a	−2.46	−2.50	3.22(5)	2.92(5)
6p11s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1756.171 b	−2.30	−2.30	1.08(7)	1.08(7)
$E = 56\,942\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	2035.055 a	−3.64	−3.64	3.68(5)	3.69(5)
	6p^2 (3/2, 1/2)$_2$	2159.532 a	−2.32	−2.32	6.85(6)	6.86(6)
	6p^2 (3/2, 3/2)$_2$	2817.314 a	−4.10	−4.10	6.76(4)	6.77(4)*
	6p^2 (3/2, 3/2)$_0$	3638.596	−2.81	−2.81	7.83(5)	7.85(5)
	6p7p (1/2, 1/2)$_1$	7128.942 a	−1.90	−1.90	1.66(6)	1.66(6)
	6p7p (1/2, 1/2)$_0$	7971.498 a	−2.93	−2.93	1.25(5)	1.25(5)*
	6p7p (1/2, 3/2)$_1$	8149.616 a	−2.53	−2.53	2.96(5)	2.97(5)
	6p7p (1/2, 3/2)$_2$	8239.91 a	−1.80	−1.80	1.54(6)	1.54(6)
6p10d 1/2 [3/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	2014.452 a	−1.73	−1.72	3.03(7)	3.08(7)
$E = 57\,444\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_2$	2136.346	−2.72	−2.71	2.79(6)	2.83(6)
	6p^2 (3/2, 3/2)$_2$	2777.990 a	−2.51	−2.50	2.72(6)	2.76(6)
	6p7p (1/2, 1/2)$_1$	6882.390 a	−3.38	−3.37	5.94(4)	6.03(4)*
	6p7p (1/2, 3/2)$_1$	7829.008 a	−1.27	−1.26	5.83(6)	5.92(6)
	6p7p (1/2, 3/2)$_2$	7912.280	−2.28	−2.27	5.64(5)	5.72(5)
6p10d 1/2 [3/2]$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1740.003 b	−1.78	−1.82	3.70(7)	3.37(7)
$E = 57\,471\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	2013.371 a	−2.17	−2.21	1.12(7)	1.02(7)
	6p^2 (3/2, 1/2)$_2$	2135.145 a	−2.75	−2.79	2.57(6)	2.34(6)
	6p^2 (3/2, 3/2)$_2$	2775.932 a	−2.49	−2.53	2.85(6)	2.59(6)
	6p^2 (3/2, 3/2)$_0$	3569.865 a	−3.57	−3.61	1.39(5)	1.26(5)*
	6p7p (1/2, 1/2)$_1$	6869.775 a	−2.16	−2.20	9.79(5)	8.91(5)
	6p7p (1/2, 1/2)$_0$	7648.862 a	−1.47	−1.51	3.92(6)	3.57(6)
	6p7p (1/2, 3/2)$_1$	7812.710 a	−2.32	−2.36	5.25(5)	4.78(5)
	6p7p (1/2, 3/2)$_2$	7895.629 a	−2.69	−2.73	2.19(5)	1.99(5)
6p12s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1733.444 a	−2.61	−2.57	5.50(6)	6.07(6)
$E = 57\,689\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	2004.580 a	−4.04	−4.00	1.50(5)	1.66(5)
	6p^2 (3/2, 1/2)$_2$	2125.263 a	−2.68	−2.64	3.05(6)	3.37(6)
	6p^2 (3/2, 3/2)$_2$	2759.272 a	−6.50	−6.46	2.79(2)	3.08(2)*
	6p^2 (3/2, 3/2)$_0$	3542.358 a	−2.73	−2.69	9.94(5)	1.10(6)
	6p7p (1/2, 1/2)$_1$	6768.629 a	−2.02	−1.98	1.37(6)	1.51(6)
	6p7p (1/2, 1/2)$_0$	7523.679 a	−3.79	−3.75	1.93(4)	2.13(4)*
	6p7p (1/2, 3/2)$_1$	7682.151 a	−2.77	−2.73	1.94(5)	2.14(5)
	6p7p (1/2, 3/2)$_2$	7762.306 a	−2.08	−2.04	9.22(5)	1.02(6)
6p11d 1/2 [3/2]$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1723.249 b	−1.96	−2.00	2.46(7)	2.26(7)
$E = 58\,030\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	1991.604 a	−2.32	−2.36	8.01(6)	7.37(6)
	6p^2 (3/2, 1/2)$_2$	2109.946	−2.85	−2.89	2.11(6)	1.94(6)
	6p^2 (3/2, 3/2)$_2$	2733.516	−2.51	−2.55	2.78(6)	2.56(6)
	6p^2 (3/2, 3/2)$_0$	3500.026 a	−4.60	−4.64	1.36(4)	1.25(4)*
	6p7p (1/2, 1/2)$_1$	6615.743 a	−2.62	−2.66	3.64(5)	3.35(5)
	6p7p (1/2, 1/2)$_0$	7335.273 a	−1.58	−1.62	3.28(6)	3.02(6)
	6p7p (1/2, 3/2)$_1$	7485.83 a	−2.57	−2.61	3.19(5)	2.93(5)
	6p7p (1/2, 3/2)$_2$	7561.908	−2.86	−2.90	1.60(5)	1.47(5)
6p11d 1/2 [3/2]$^\circ_2$	6p^2 (3/2, 1/2)$_1$	1992.314 a	−2.22	−2.16	1.01(7)	1.16(7)
$E = 58\,012\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_2$	2110.737 a	−2.92	−2.86	1.77(6)	2.05(6)
	6p^2 (3/2, 3/2)$_2$	2734.837 a	−2.53	−2.47	2.67(6)	3.09(6)
	6p7p (1/2, 1/2)$_1$	6623.574 a	−3.03	−2.97	1.41(5)	1.63(5)*
	6p7p (1/2, 3/2)$_1$	7495.843 a	−1.55	−1.49	3.36(6)	3.89(6)
	6p7p (1/2, 3/2)$_2$	7572.134	−2.72	−2.66	2.23(5)	2.58(5)
6p13s (1/2, 1/2)$^\circ_1$	6p^2 (1/2, 1/2)$_0$	1718.864 b	−2.99	−2.91	2.35(6)	2.85(6)
$E = 58\,178\ \mathrm{cm}^{-1}$	6p^2 (3/2, 1/2)$_1$	1985.758 b	−4.67	−4.59	3.65(4)	4.43(4)*
	6p^2 (3/2, 1/2)$_2$	2103.368 a	−3.26	−3.18	8.31(5)	1.01(6)
	6p^2 (3/2, 3/2)$_2$	2722.489	−3.83	−3.75	1.34(5)	1.63(5)*
	6p^2 (3/2, 3/2)$_0$	3481.974 a	−2.57	−2.49	1.47(6)	1.78(6)
	6p7p (1/2, 1/2)$_1$	6551.538	−1.98	−1.90	1.61(6)	1.95(6)
	6p7p (1/2, 1/2)$_0$	7256.406	−3.81	−3.73	2.00(4)	2.43(4)*

Table 2 – *continued*

Upper level	Lower level	$\lambda_{\rm exp}$(Å)	log *gf*		*gA* (s^{-1})	
			CP	NORM	CP	NORM
	6p7p $(1/2, 3/2)_1$	7403.704	−2.93	−2.85	1.44(5)	1.75(5)
	6p7p $(1/2, 3/2)_2$	7478.123 a	−2.35	−2.27	5.37(5)	6.52(5)
6p12d 1/2 $[5/2]^{\circ}_2$	$6\mathrm{p}^2$ $(3/2, 1/2)_1$	1977.876 a	−3.50	−3.60	5.36(5)	4.30(5)
$E = 58\,379\ \mathrm{cm}^{-1}$	$6\mathrm{p}^2$ $(3/2, 1/2)_2$	2094.531 a	−2.76	−2.86	2.64(6)	2.12(6)
	$6\mathrm{p}^2$ $(3/2, 3/2)_2$	2707.708 a	−2.64	−2.74	2.12(6)	1.70(6)
	6p7p $(1/2, 1/2)_1$	6466.572 a	−5.27	−5.37	8.52(2)	6.83(2)*
	6p7p $(1/2, 3/2)_1$	7295.380 a	−1.99	−2.09	1.31(6)	1.05(6)*
	6p7p $(1/2, 3/2)_2$	7367.636 a	−4.23	−4.33	7.24(3)	5.81(3)
6p13d 1/2 $[5/2]^{\circ}_2$	$6\mathrm{p}^2$ $(3/2, 1/2)_1$	1966.667 a	−2.94	−2.80	1.97(6)	2.69(6)
$E = 58\,667\ \mathrm{cm}^{-1}$	$6\mathrm{p}^2$ $(3/2, 1/2)_2$	2081.949 a	−2.57	−2.43	4.10(6)	5.60(6)
	$6\mathrm{p}^2$ $(3/2, 3/2)_2$	2686.76 a	−2.82	−2.68	1.42(6)	1.94(6)
	6p7p $(1/2, 1/2)_1$	6348.239	−1.15	−1.01	1.17(7)	1.60(7)
	6p7p $(1/2, 3/2)_1$	7145.123	−2.74	−2.60	2.41(5)	3.30(5)
	6p7p $(1/2, 3/2)_2$	7214.411	−3.34	−3.20	5.85(4)	8.00(4)*

(a) From Wood & Andrew (1968); (b) from Brown et al. (1977). The wavelengths not observed by Wood & Andrew (1968) have been calculated on the basis of the energy levels determined by these authors. *Cancellation factor $|\mathrm{CF}| < 0.0050$. CP: this work; HFR results with core polarization effects included. NORM: this work; normalized results (see the text).

within 20 per cent with the HFR data, but, for the other transitions, large discrepancies are observed in an erratic way. New accurate experimental branching ratios are needed to check the accuracy of Lotrian et al.'s results.

Multiconfiguration Dirac–Fock (Extended Average Level Approximation + Configuration Interaction) [MCDF (EAL+CI)] calculations have been reported by Bieron et al. (1991), but large discrepancies are observed when comparing length and velocity forms of the dipole operator, indicating a lack of accuracy of the wavefunctions used in the calculations. For most of the transitions common to both works, our results are in between the length and velocity results.

6 ASTROPHYSICAL APPLICATIONS

Lead is observed in the solar photosphere and has been the subject of many abundance determinations (see e.g. Peach 1968; Grevesse 1969; Lambert, Mallia & Warner 1969; Ross & Aller 1976). In the compilation of Anders & Grevesse (1989), the adopted photospheric result is 1.85 ± 0.05 on the usual logarithmic scale, while the meteoritic result is substantially higher: 2.05 ± 0.03.

Five Pb I lines have been identified in the photospheric spectrum at 3639.568, 3683.463, 3739.935, 4057.807 and 7228.965 Å, the identification of the latter two lines being doubtful. As the two lines at 3639.568 and 3739.935 Å are strongly perturbed, we are left with the line at 3683.463 Å which is the best abundance indicator. The equivalent width of this line has been measured by many authors and the results show some scatter: $W_\lambda = 7.7 \pm 0.4\ \mathrm{m\AA}$ (Grevesse & Meyer 1985); $W_\lambda = 7.0\ \mathrm{m\AA}$ (Goldberg, Müller & Aller 1960); $W_\lambda = 8.3\ \mathrm{m\AA}$ (Mutschlecner 1963); $W_\lambda = 7.8\ \mathrm{m\AA}$ (Grevesse 1969). Somewhat larger values have been measured by Helliwell (1961) ($W_\lambda = 11\ \mathrm{m\AA}$) and by Moore, Minnaert & Houtgast (1966) ($W_\lambda = 10.0\ \mathrm{m\AA}$). We have remeasured the line on the Jungfraujoch spectra (Delbouille, Neven & Roland 1973) and have obtained $W_\lambda = 9.1 \pm 1.0\ \mathrm{m\AA}$. The quoted uncertainty of our measurement is a reasonable estimate of the error bar based on the dispersion of the published measurements (the mean value obtained from seven different authors being $8.7 \pm 1.4\ \mathrm{m\AA}$) and on the fact that the 3683.463-Å line is blended in the wings by strong Fe I contributions at 3683.092 and 3683.623 Å (Moore et al. 1966). Using this last value, new partition functions for Pb I and Pb II recalculated on the basis of all the available energy levels, and ionization potentials equal to 7.4166 and 15.032 eV, we have recalculated the abundance of lead in the solar photosphere. On the basis of the Holweger & Müller (1974) solar model with an isotropic microturbulence ($0.85\ \mathrm{km\,s^{-1}}$) and a macroturbulence of $1.8\ \mathrm{km\,s^{-1}}$, we have obtained $A_{\rm Pb} = 2.00 \pm 0.06$ on the usual logarithmic scale (using the normalized *g*-value of Table 2). As the line is weak, this result is independent of the approximations used for calculating the damping. In addition, adopting a microturbulence of $0.5\ \mathrm{km\,s^{-1}}$ would increase the result by 0.024 dex, while using $1.0\ \mathrm{km\,s^{-1}}$ would decrease the final result by only 0.007 dex. This abundance value is now only 0.05 dex lower than, but in agreement within the errors with the meteoritic value ($A_{\rm Pb} = 2.05 \pm 0.03$) as adopted by Anders & Grevesse (1989) in their compilation. According to these authors, an enrichment process for Pb, which is highly volatile in chondrites, although it has been considered as a possibility by some authors, seems to be unlikely. Our present result confirms this point of view.

ACKNOWLEDGMENTS

This work was financially supported by the Swedish Natural Science Research Council. Financial support from the European Community Access to Large-Scale Facilities Programme (contract ERBFMGECT 950020) and from the Belgian National Fund for Scientific Research (FNRS) is also acknowledged. EB is grateful for the warm hospitality enjoyed during several stays at the Lund Laser Centre.

REFERENCES

Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197

Berzinsh U., Caiyan L., Zerne R., Svanberg S., Biémont E., 1997a, Phys. Rev. A, 55, 1836

Berzinsh U., Svanberg S., Biémont E., 1997b, A&A, 326, 412

Biémont E., Quinet P., 1998, Phys. Rev. Lett., 81, 3345

Biémont E., Zeippen C. J., 1999, At. Data Nucl. Data Tables, 72, 101
Biémont E., Dutrieux J.-F., Martin I., Quinet P., 1998a, J. Phys. B: At. Mol. Opt. Phys., 31, 3321
Biémont E., Garnir H. P., Federman S. R., Li Z. S., Svanberg S., 1998b, ApJ, 502, 1010
Biémont E., Quinet P., Van Renterghem V., 1998c, J. Phys. B: At. Mol. Opt. Phys., 31, 5301
Biémont E., Lyngå C., Li Z. S., Svanberg S., Garnir H. P., Doidge P. S., 1999, MNRAS, 303, 721
Bieron J. R., Marcinek R., Migdalek J., 1991, J. Phys. B, 24, 31
Brown C. M., Tilford S. G., Ginter M. L., 1977, J. Opt. Soc. Am., 67, 1240
Buch P., Nellessen J., Ertmer W., 1988, Phys. Scr., 38, 664
Burbidge E. M., Burbidge G. R., Fowler W. A., Hoyle F., 1957, Rev. Mod. Phys., 29, 547
Cowan R. D., 1981, The Theory of Atomic Structure and Spectra. Univ. California Press, Berkeley
Cowan R. D., Griffin D. C., 1976, J. Opt. Soc. Am., 66, 1010
Cunningham P. T., Link J. K., 1967, J. Opt. Soc. Am., 57, 1000
Delbouille L., Neven L., Roland G., 1973, Photometric Atlas of the Solar Photospheric Spectrum from $\lambda 3000$ to $\lambda 10000$. Institut d'Astrophysique, Université de Liège, Liège
Dembczynski J., Stachowska E., Wilson M., Buch P., Ertmer W., 1994, Phys. Rev. A, 49, 745
DeZafra R. L., Marshall A., 1968, Phys. Rev., 170, 28
Ding D., Jin M., Liu H., Liu X., 1989, J. Phys. B: At. Mol. Opt. Phys., 22, 1979
Doidge P. S., 1995, Spectrochim. Acta B, 50, 209
Fay F. D., Fredrick L. W., Johnsson H. R., 1968, ApJ, 152, 151
Fraga S., Karwowski J., Saxena K. M. A., 1976, Handbook of Atomic Data. Elsevier, Amsterdam
Garpman S., Lidö G., Rydberg S., Svanberg S., 1971, Z. Phys., 241, 217
Goldberg L., Müller E. A., Aller L. H., 1960, ApJS, 45, 1
Gorshov V. N., Verolainen Ya. F., 1985, Opt. Spectrosc. (USSR), 58, 848
Grevesse N., 1969, Sol. Phys., 6, 381
Grevesse N., Meyer J. P., 1985, in Editor X., Editor Y., eds, 19th Intern. Cosmic Ray Conf. NASA Conf. Publication No. 2376, La Jolla, California
Guthrie B. N. B., 1972, Ap&SS, 15, 214
Hasegawa S., Suzuki A., 1996, Phys. Rev. A, 53, 3014
Hauge O., Sorli H., 1973, Sol. Phys., 30, 301
Helliwell T. M., 1961, ApJ, 133, 566
Hibbert A., 1989, Phys. Scr., 39, 574
Holweger H., Müller E. A., 1974, Sol. Phys., 39, 19
Jaschek C., Jaschek M., 1995, The Behaviour of Chemical Elements in Stars. Cambridge Univ. Press, Cambridge
Lambert D. L., Mallia E. A., Warner B., 1969, MNRAS, 142, 71
Li Z. S., Persson A., Svanberg S., Garnir H. P., Biémont E., 1998a, Euro. Phys. J., D2, 11
Li Z. S., Svanberg S., Biémont E., Palmeri P., Jiang Z., 1998b, Phys. Rev. A, 57, 3443
Li Z. S., Norin J., Persson A., Wahlström C.-G., Svanberg S., Doidge P. S., Biémont E., 1999a, Phys. Rev. A, 60, 198
Li Z. S., Svanberg S., Quinet P., Tordoir X., Biémont E., 1999b, J. Phys. B: At. Mol. Opt. Phys., 32, 1731
Lotrian J., Guern Y., Cariou J., Johannin-Gilles A., 1979, J. Quant. Spectrosc. Radiat. Transfer, 21, 143
Lvov B. V., 1970, Atomic Absorption Spectrochemical Analysis. Adam Hilger Ltd, London, p. 278
Migdalek J., Baylis W. E., 1978, J. Phys. B, 11, L497
Migdalek J., Baylis W. E., 1986, J. Phys. B, 19, 1
Miller M. H., Bengtson R. D., Lindsay J. M., 1979, Phys. Rev. A, 20, 1997
Moore C. E., Minnaert M. G. J., Houtgast J., 1966, Natl. Bur. Stand., Monograph 61. National Bureau of Standards, Washington, DC
Mutschlecner J. P., 1963, PhD Thesis, University of Michigan
Peach J. V., 1968, MNRAS, 140, 43
Penkin N. P., Slavenas J. J., 1963, Opt. Spectrosc., 15, 83
Pierce K., 1968, ApJS, 17, 1
Ross J. E., Aller L. H., 1976, Sci, 191, 1223
Sadakane K., 1991, PASP, 103, 355
Saloman E. B., 1966, Bull. Am. Phys. Soc., 11, 327
Saloman E. B., Happer W., 1966, Phys. Rev., 144, 7
Savage C. B., Lawrence G. M., 1966, ApJ, 146, 490
Severny A. S., Lyubimkov L. S., 1985, in Cowley C., Dworets M. M. Mégessier C., eds, Proc. IAU Colloq. 90, Upper Main Sequence Stars with Anomalous Abundances. Kluwer, Dordrecht, p. 327
Svanberg S., 1972, Phys. Scr., 5, 73
Welty D. E., Hobbs L. M., Lauroesch J. T., Morton D. C., York D. G., 1995, ApJ, 449, L1
Wood D. R., Andrew K. L., 1968, J. Opt. Soc. Am., 58, 818
Young W. A., Mirza M. Y., Duley W. W., 1980, J. Phys. B: At. Mol. Phys., 13, 3175