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Radiative lifetimes, branching fractions and oscillator strengths in Pd I and the solar palladium abundance

H. L. Xu[1,2], Z. W. Sun[1], Z. W. Dai[1], Z. K. Jiang[1], P. Palmeri[3], P. Quinet[3,4], and É. Biémont[3,4]

[1] Department of Physics, Jilin University, Changchun 130023, PR China
e-mail: jzk@jlu.edu.cn
[2] Department of Physics, Laval University, Quebec city, G1K 7P4, Canada
e-mail: huailiang.xu@gmail.com
[3] Astrophysique et Spectroscopie, Université de Mons-Hainaut, 7000 Mons, Belgium
e-mail: P.Quinet@umh.ac.be
[4] IPNAS, Université de Liège, Sart Tilman (Bât. B15), 4000 Liège, Belgium
e-mail: E.Biemont@ulg.ac.be

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ABSTRACT

Transition probabilities have been derived for 20 5s−5p transitions of Pd I from a combination of radiative lifetime measurements for 6 odd-parity levels with time-resolved laser-induced fluorescence spectroscopy and of branching fraction determination using a hollow cathode discharge lamp. Additional oscillator strengths for 18 transitions have been determined from measured lifetimes and theoretical branching fractions obtained from configuration interaction calculations with core-polarization effects included. These new results have allowed us to refine the palladium abundance in the solar photosphere: $A_{\rm Pd} = 1.66 \pm 0.04$, in the usual logarithmic scale, a result in close agreement with the meteoritic value.

Key words. atomic data – techniques: spectroscopic – stars: abundances

1. Introduction

In astrophysics, accurate atomic data (radiative lifetimes, branching fractions (BF) and oscillator strengths (gf)) are useful in determining the chemical composition of the stars, in modeling the stellar atmospheres and to understand the buildup of the elements in nucleosynthesis. Many atomic parameters are required for the interpretation of astrophysical observations, particularly to disentangle the blends that frequently complicate the analysis of the spectra.

Palladium is a fifth row element ($Z = 46$; $A = 106.42$) with 6 stable isotopes. ^{105}Pd (22.33%), ^{106}Pd (27.33%) and ^{108}Pd (26.46%) are produced by both the r and the s processes, ^{110}Pd (11.72%) is a pure r-process isotope, ^{104}Pd (11.14%) is a pure s-product and ^{102}Pd (1.02%) is resulting only from the p process. All isotopes have a nuclear spin $I = 0$, except ^{105}Pd which has $I = 5/2$. Consequently, hyperfine structure only affects this last isotope.

The emission lines of neutral palladium have been observed in the spectra of many different stellar objects, including the stars of the CP magnetic sequence. Identifications of Pd I transitions have been reported in the optical spectrum of γ Equ (Adelman et al. 1979), of HR 465 (Bidelman 1966; Bidelman et al. 1995; Cowley et al. 1973), of Procyon (Orlov & Shavrina 1991) and in the spectrum of metal-poor stars (Johnson & Bolte 2002, 2004). These last authors found a [Pd/Ag] ratio larger than predicted from the solar system r-process abundances but similar to those measured in r-process rich stars CS 22892-052 (Sneden et al. 2000) and CS 31082-001 (Hill et al. 2002). This ratio might indicate one r-process pattern in the intermediate-mass elements in metal-poor stars but this conclusion is based on the use of only one Pd and one Ag line and is, consequently, strongly dependent upon the accuracy of the atomic data (gf) used.

Pd II has been observed in Bp stars by Adelman (1974), Adelman et al. (1979) and in the chemically peculiar HgMn star χ Lupi (Lundberg et al. 1996). In the latter case, the authors find a palladium abundance of $\log N_{\rm Pd} = 5.0$, which is considerably above (3.3 dex) the solar abundance. The most recent determination of the solar abundance of palladium is by Biémont et al. (1982) who found $A_{\rm Pd} = 1.69 \pm 0.04$ (in the usual logarithmic scale). These authors used f-values for eight Pd I lines derived from a combination of lifetime measurements with a time-resolved laser-induced fluorescence (TR-LIF) technique and Corliss & Bozman (CB) (1962) branching fractions. This result is thus strongly dependent upon these last values but, as pointed out by Doidge (1995), the accuracy of the CB BFs is seriously questioned and those imprecisions are responsible for large errors affecting the f-values.

The radiative parameters of Pd I are still poorly known and there are only a few sets of results reported in the literature. Budick (1969) measured the lifetime of the first excited state of Pd I (^{3}P$_1$) using the level crossing technique. With the same method, Baumann & Liening (1971) determined 6 lifetimes of Pd I belonging to the 4d^{9}5p configuration. Additional measurements, in the same configuration, are by Liening (1974) and by Bauman et al. (1981). Biémont et al. (1982) measured 9 lifetimes of Pd I with a LIF technique. Van Duijn et al. (2002) published 3 lifetime values of Pd I using laser spectroscopy and analyzing the profiles of the lines.

Absolute oscillator strengths in the spectra of ten elements were reported by Lawrence et al. (1965) but their paper contains information for only one Pd I transition at 276.308 nm. In a well known work, Corliss & Bozman (1962) contributed to the determination of oscillator strengths for 70 elements, including Pd I, using arc measurements. CB values have been proven to be very uncertain and affected by significant excitation-dependent, wavelength-dependent and intensity-dependent errors resulting from the use of arc spectra (see e.g. Bell & Upson II 1971; Corliss & Tech 1976).

Doidge (1995) reported three f-values for Pd I deduced from CB branching fractions and the lifetimes values of Baumann & Leining (1971) or of Biémont et al. (1982). This author emphasizes also the need for further measurements of this atom.

A versatile method for obtaining reliable transition probabilities consists of combining lifetime measurements with laser spectroscopy and BF determination using either experimental measurements or theoretical calculations. The new experimental or partly experimental f-values presented in the present paper for 38 Pd I transitions have been determined from a combination of lifetime measurements with a TR-LIF approach applied on a laser-produced plasma and BF determination using either laser spectroscopy measurements or calculations with a relativistic approach including correlation and core-polarization effects. The new oscillator strengths have allowed us to revise and to refine the solar photospheric abundance of palladium.

2. Radiative lifetimes

Radiative lifetimes of 6 levels of Pd I, belonging to the $4d^95p$ configuration, have been measured using the TR-LIF technique. The experimental setup used in the present work has been described in detail elsewhere, and only a brief description is given here. For more details, the reader is referred to recent work in Gd I and II (Xu et al. 2003a), and Sm II (Xu et al. 2003b). Free palladium atoms were generated in a laser-produced plasma. A 532-nm pulse, emitted from a Nd:YAG laser (Continuum Surelite) with 10 ns pulse duration was focused onto a rotating palladium foil located in a vacuum chamber with 10^{-6}–10^{-5} mbar background pressure. Neutral palladium atoms were produced and expanded from the foil for subsequent laser excitation.

The excitation radiation originated from a pulsed dye laser. The pulses emitted from a 532 nm Nd:YAG pumping laser (Continuum NY-82) with an 8-ns pulse duration and a single pulse energy of 400 mJ were shortened by a stimulated Brillouin scattering (SBS) cell filled with water. This results in a compression of the pulse duration to about 1 ns. The compressed laser pulse was then used to pump a dye laser (Continuum Nd-60), in which a DCM dye was used. In order to obtain the required excitation, the radiation from the dye laser could be frequency doubled in a KDP crystal, and then mixed with the fundamental frequency in a BBO crystal in order to produce the third harmonic of the dye laser frequency. A stimulated Stokes Raman Scattering (SSRS) cell with hydrogen at about 10 bars was used in this experiment to extended the tunable range of the dye laser source. The Stokes and anti-Stokes components of Raman shifting were produced by focusing the second harmonic (2ω), or the third harmonic (3ω) of the dye laser radiation into the SSRS cell. The two Nd:YAG lasers were controlled externally by a digital delay generator (Stanford Research Systems Model DG 535), which was used to adjust the delay time between the excitation and ablation lasers.

The fluorescence was detected with a Hamamatsu R1564U photomultiplier tube with a rise time of 0.2 ns. The signal was averaged in a Tektronix Model DSA 602 oscilloscope. Lifetimes were estimated with a deconvolution procedure. The temporal shape of the excitation pulses needed in the fitting process was recorded by inserting a metal rod into the interaction zone of the excitation laser and the plasma when the ablation beam was blocked. The evaluation process was performed by fitting the experimental fluorescence decay curve to a convolution of the recorded excitation pulse and of a pure exponential function.

Possible systematic errors, which potentially affect the accuracy of the lifetimes, were carefully investigated. Attempts were made to observe lifetime variations by changing various experimental parameters. The delay times between the ablation and the excitation pulses were varied and could be as long as 10 μs for Pd I. In this way, the detected fluorescence intensity was varied by a factor of 10, but the lifetime values were found to be nearly identical. This indicates that radiation trapping and collisional quenching effects were absent for the experimental conditions selected.

An important aspect in lifetime measurements is to avoid the flight-out-of-view effects, especially when the measured lifetimes are long. In our experiment, the radiative lifetimes were shorter than 10 ns. The distance between the foil and the interaction zone is about 10 mm. The speed of atoms is of the order of 1 km s^{-1} and, for a lifetime of 10 ns, the distance reached by the ions can be about 0.01 mm. Therefore, flight-out-of-view effects for these lifetimes could be eliminated by using long delay times and a wide entrance slit for the monochromator.

A possible presence of quantum beats due to the Zeeman effects was checked by adding and removing a magnetic field over the laser-induced plasma. No observable effects were found. In addition, saturation effects in the detection system were carefully avoided by inserting different neutral density filters in the exciting laser light path and, for each pulse, only weak fluorescence signals were detected during the measurements.

The lifetimes measured are included in Table 1, with their error bars corresponding to the statistical uncertainties and they are compared to the previous data when they exist. As it can be seen from Table 1, the new lifetime values agree quite well (within the error bars) with the previous measurements performed by Biémont et al. (1982) using a LIF technique with a thermal oven source. An excellent agreement (also within the error bars) is observed when comparing our measurements (for 4 levels) with the Hanle-effect results obtained by Baumann & Liening (1971). For the level at 36180.677 cm^{-1}, the older measurement by Budick (1968) is somewhat higher [8.7 (9) ns] but the origin of this discrepancy is not clear because the Hanle effect technique was also used by this author. Our results are clearly in favour of those of Baumann & Liening (1971).

Recent lifetime results based on natural linewidth measurements have been published by van Duijn et al. (2002) for three levels, but, surprinsingly, they disagree considerably from the present measurements and also from the other previous results. In their paper, these authors noticed the discrepancy between their lifetimes and those of Liening (1974) for the level at 36180.677 cm^{-1} but were unable to find an explanation. The fact that their results appear systematically smaller than the other measurements could eventually originate from an overestimation of the full width at half maximum (FWHM) of the optical transitions used in their analysis (according to the relation $2\pi\tau = 1/\Delta\nu$, where τ is the lifetime and $\Delta\nu$ is the FWHM). In the linewidth measurements, special care has indeed to be exercised concerning the Doppler broadening and also the broadening contributions due to collisions or other residual mechanisms, which might affect the accuracy of the calculated radiative lifetimes. Therefore, the discrepancy could possibly originate from

Table 1. Calculated and observed radiative lifetimes for $4d^95p$ levels of Pd I and comparison with previous results.

$E(\mathrm{cm}^{-1})^f$	Origin^f	J_{upp}	Excit^f λ_{vac}(nm)	Observ. λ_{vac}(nm)	Lifetime value (ns) HFR This work	EXP This work	EXP Previous
34 068.977		2			8.41		6.90(76)^a, 8.9(4)^b
35 451.443		3			7.96		8.2(4)^b
35 927.948		4			7.22		7.09(46)^a, 7.4(4)^b
36 180.677	0.0	1	276.30899	352	7.31	7.6(3)	7.46(32)^a, 7.7(4)^b, 5.2(3)^c, 8.7(9)^d
36 975.973		2			7.29		8.2(4)^b
37 393.763	6564.148	3	324.26983	337	6.68	7.2(3)	6.99(49)^a, 7.5(4)^b
38 088.192	10093.992	0	357.11489	357	8.21	8.4(4)	
38 811.896		2			7.65		8.0(4)^b
39 858.361		3			7.47		7.8(4)^b
40 368.796	0.0	1	247.64127	330	5.19	5.0(2)	4.89(40)^a, 3.1(2)^c
40 771.510	10093.992	2	325.87765	344	6.89	7.2(3)	
40 838.874	10093.992	1	325.16361	343	4.94	4.8(2)	4.99(35)^a, 4.8(3)^b, 4.3(2)^c

[a] Hanle effect (Baumann & Liening 1971);
[b] LIF method (Biémont et al. 1982);
[c] Laser spectroscopy and linewidths measurements (Van Duijn et al. 2002);
[d] Hanle effect (Budick 1968);
[f] Engleman et al. (1998).

an underestimation of residual broadening contributions to the FWHMs of the lines.

It should be emphasized that our calculations (see further Sect. 4) are in excellent agreement (see Col. 6 of Table 1) with the present measurements and those of Baumann & Liening (1971) but do not agree with the results of van Duijn et al. (2002).

3. Branching fraction and oscillator strength determination

In addition to the lifetime measurements, BFs of 20 Pd I lines have been obtained using emission spectroscopy with a hollow cathode discharge lamp. An Acton Research Corp. 1 m length spectrometer with a 2400 g mm^{-1} grating (SpectraPro-500i) was used to determine the BFs of Pd I in the UV and visible regions. The system has a spectral resolution of 0.03 nm, and it provides an optimal spectral coverage of 190−450 nm. The spectral response $E(\lambda)$ of the detection system has been calibrated with a standard lamp with radiance calibration uncertainties <4% for the spectral region 280 nm−750 nm and <10% for the spectral range 240 nm−275 nm.

The emission source was a palladium hollow cathode discharge lamp with a fused silica window containing argon as a carrier gas. Light from the hollow cathode lamps was focused using a fused silica lens (f = 10 cm) onto the entrance slit of the spectrometer. The signals were detected with a Hamamatsu R928 photomultiplier tube connected to a personal computer. The hollow cathode lamp can be operated with the discharge current in the region 5−8 mA. In order to test if re-absorption effects were present for strong Pd I lines, we measured the spectra at three different discharge currents (5, 6 and 7 mA). The ratios of the line intensities measured in different currents were found in good agreement indicating that no significant self-absorption effects were present. The Pd hollow cathode lamp showed a long-time intensity drift <0.5%. As an example, Fig. 1 shows a part of the Pd I spectrum recorded with the detection system described

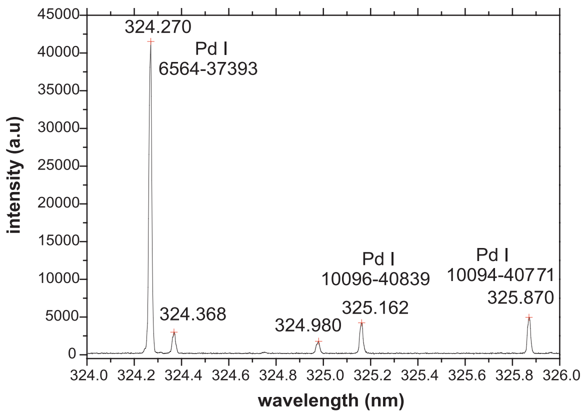

Fig. 1. Part of the Pd I spectrum of a hollow cathode lamp.

above. The branching fraction $R_{ki}(\lambda_{ki})$ for the transition $k \rightarrow i$ is given by:

$$R_{ki}(\lambda_{ki}) = \frac{\lambda_{ki} I(\lambda_{ki})}{\sum_i \lambda_{ki} I(\lambda_{ki})} \quad (1)$$

where the relative line intensity $I(\lambda) = A(\lambda)/E(\lambda)$, $A(\lambda)$ being the line intensity obtained by integrating the areas under the line profiles and $E(\lambda)$ the spectral response of the detection system. The sum in the denominator includes all the possible transitions (according to the selection rules) depopulating the same upper level. To identify the lines observed on the spectra, the wavelengths of the depopulating channels and the energy level positions were taken from the recent paper by Engleman et al. (1998).

The BFs measured in the present work are presented in Col. 5 of Table 2. The uncertainties of the BFs mainly originate from the intensity calibration of the spectral response of the detection system and from the long-time intensity drift of the hollow cathode lamp. The intensities of the transitions as observed by Engleman et al. (1998) are also given for comparison in Col. 3 of Table 2. In our experiment, BFs smaller than 0.5% could not be detected. In addition, infrared transitions of Pd I cannot be observed due to the low response of the detection system in the infrared range. However, according to our calculations (see Sect. 4), there are no significant missing branches for

Table 2. Branching ratios, transition probabilities and oscillator strengths of 5s−5p Pd I transitions.

E_k^c (cm^{-1})	E_i^c (cm^{-1})	Int^c	λ_{ik}^c (air) (nm)	R_{ki} EXP	R_{ki} HFR	g_kA_{ki} (10^8 s^{-1}) EXP	g_kA_{ki} HFR	log (g_if_{ik}) EXP	log (g_if_{ik}) HFR	Others
35 927.948	6564.148	58 000	340.45764	1.000	1.000	12.16(66)	12.47	0.33	0.34	0.32[a]
36 180.677	0.000	28 100	276.30899	0.079(5)	0.072	0.31(3)	0.295	−1.45	−1.47	−1.237[b]
	7755.025	61 000	351.69438	0.845(10)	0.857	3.34(17)	3.52	−0.21	−0.18	−0.24[a]
	10 093.992	27 700	383.22860	0.059(3)	0.056	0.23(2)	0.228	−1.29	−1.29	
	11 721.809	6500	408.73434	0.016(1)	0.015	0.063(6)	0.062	−1.80	−1.81	
37 393.762	6564.148	32 000	324.26983	0.768(12)	0.830	7.47(43)	8.695	0.07	0.14	−0.07[a]
	7755.025	43 600	337.29943	0.166(8)	0.124	1.61(15)	1.294	−0.56	−0.65	
	11 721.809	38 500	389.41988	0.064(4)	0.046	0.62(6)	0.484	−0.85	−0.96	−0.53[a]
38 088.192	10 093.992	49 700	357.11489	1.000	1.000	1.19(6)	1.218	−0.64	−0.63	
40 368.796	0.000	19 800	247.64127	0.265(20)	0.219	1.59(28)	1.264	−0.83	−0.93	−1.284[b]
	7755.025	17 100	306.52986	0.083(8)	0.102	0.50(10)	0.587	−1.15	−1.08	
	10 093.992	48 100	330.21262	0.444(15)	0.464	2.66(35)	2.678	−0.36	−0.35	
	11 721.809	47 200	348.97700	0.208(10)	0.216	1.25(19)	1.248	−0.64	−0.64	
40 771.510	6564.148	2730	292.24922	0.020(1)	0.026	0.13(1)	0.192	−1.77	−1.61	
	7755.025	14 600	302.79084	0.102(4)	0.092	0.67(6)	0.669	−1.03	−1.04	
	10 093.992	47 100	325.16361	0.252(8)	0.191	1.66(13)	1.390	−0.58	−0.65	
	11 721.809	43 300	344.13896	0.624(12)	0.690	4.11(26)	5.008	−0.14	−0.05	
40 838.874	0.000	20 700	244.79058	0.286(25)	0.269	1.87(33)	1.633	−0.78	−0.84	−1.523[b]
	10 093.992	47 100	325.16361	0.209(10)	0.239	1.36(19)	1.450	−0.67	−0.64	
	11 721.809	75 000	343.34278	0.505(15)	0.492	3.29(38)	2.989	−0.23	−0.28	

[a] Biémont et al. (1982) (obtained from LIF lifetimes and CB BFs);
[b] Doidge (1995) (Compilation);
[c] Engleman et al. (1998).

the levels of Table 1, the transition from the 40 838.874 cm^{-1} level to the level at 7755.025 cm^{-1} having a negligible f value ($\log gf = -4.92$) which does not affect the final results.

The transition probability, A_{ki}, for a transition from a level k to a level i can be defined in terms of the lifetime τ_k and the branching fraction R_{ki} according to:

$$A_{ki} = \frac{R_{ki}}{\tau_k}\cdot \quad (2)$$

The weighted oscillator strength, g_if_{ik}, can be obtained from the following relation:

$$g_if_{ik} = 1.4992.10^{-16}\lambda_{ki}^2 g_kA_{ki} \quad (3)$$

where g_i and g_k denote the statistical weights of the upper and of the lower levels, respectively, and λ_{ki} is the wavelength (in Å) of the transition.

The transition probabilities and oscillator strengths deduced in the present work are listed in the Cols. 7 and 9 of Table 2. We adopted the lifetime value measured by Biémont et al. (1982) to obtain the transition probability and oscillator strength for the transition depopulating the 35927.95 cm^{-1} level [$\tau = 7.4 \pm 4$ ns] of Pd I. The uncertainties of g_kA_{ki} and g_if_{ik} values have been evaluated from the uncertainties of the measured lifetimes and BFs. For comparison, we list in the last column of Table 2 the previous values of the oscillator strengths obtained by Biémont et al. from a combination of LIF lifetimes and CB BFs and also, for three transitions, the values adopted by Doidge (1995) in his compilation.

4. Relativistic calculations

The ground-state level of Pd I is 4d^{10} ^{1}S$_0$ and the first experimentally determined excited configurations are 4d^9ns ($n \geq 5$), 4d^{8}5s^2, 4d^9nd ($n \geq 5$) (even parity) and 4d^9np ($n \geq 5$), 4d^{8}5s5p, 4d^9nf ($n \geq 4$) (odd parity). The most comprehensive spectral analysis of neutral palladium has been published by Engleman et al. (1998) who analyzed the spectrum emitted from a hollow cathode discharge using the Fourier transform spectroscopy in the region 175.0−5500 nm and identified 684 transitions between 67 even and 76 odd levels.

As in previous publications on heavy elements, the calculations of the present paper were performed within the framework of the relativistic Hartree-Fock (HFR) approach (Cowan 1981) which has appeared reliable for calculations in atoms or ions for which both relativity and correlation effects are important. In this method, the relativistic corrections are the Blume-Watson spin-orbit, the mass-velocity and one-body Darwin terms. The Blume-Watson spin-orbit term includes the part of the Breit interaction that can be reduced to a one-body operator. Core-valence interactions were taken into account through a polarization model potential and a correction to the dipole operator following a well-established approach (see e.g. Quinet et al. 1999) giving rise to the HFR+CP method. We considered a 4d^9 Pd$^+$ ionic core. The dipole polarizability was adopted from tabulated values (Fraga et al. 1976), i.e. 11.405 au. The cut-off radius used was the HFR mean radius of the 4d orbital in the Pd I ground configuration, i.e. 1.550 au.

Concerning the valence-valence interactions, we included in the vectorial basis the following even and odd configurations, respectively, i.e. 4d^{10} + 4d^{9}5s + 4d^{9}6s +4d^{9}5d + 4d^{9}6d + 4d^{8}5s^2 + 4d^{8}5p^2 + 4d^{8}5d^2 + 4d^{8}5s5d + 4d^{8}5s6d + 4d^{8}6s6d and 4d^{9}5p + 4d^{9}6p + 4d^{9}4f + 4d^{9}5f + 4d^{9}6f + 4d^{8}5s5p + 4d^{8}5s6p + 4d^{8}5s4f + 4d^{8}5s5f + 4d^{8}5s6f + 4d^{8}5p5d + 4d^{8}5p6d. In order to take into account the remaining interactions with far configurations not considered explicitly by the vectorial basis or implicitly by the polarization model, all the radial Coulomb parameters were first scaled down by 0.8 (see Cowan 1981 for a discussion). The HFR+CP method was then combined with a least-squares optimization routine minimizing the discrepancies between calculated and experimental energy levels published by Engleman et al. (1998). 51 even-parity levels below 64 000 cm^{-1}

Table 3. Calculated HFR transition probabilities (A_{ki}) and oscillator strengths ($\log gf$) for additional 5s−5p transitions of Pd I and comparison with previous results.

$E^a_{\rm upp}$ (cm^{-1})	$E^a_{\rm low}$ (cm^{-1})	$\lambda^a_{\rm air}$ nm	Int^a	$A_{ki}(10^8$ s) HFR	$\log gf$ HFR	BGKZ
34 068.977	6564.148	363.46884	72000	5.687	0.05	
	7755.025	379.91867	26 100	0.232	−1.31	
	10 093.992	416.98388	1900	0.009	−2.59	
	11 721.809	447.35857	1360	0.018	−2.29	
36 975.973	6564.148	328.72480	5900	0.207	−1.47	
	7755.025	342.12215	39 300	6.132	0.03	
	10 093.992	371.89062	21 700	0.216	−1.35	
	11 721.809	395.86232	29 200	0.307	−1.15	−0.83
38 811.896	6564.148	–	–	0.004	−3.27	
	7755.025	321.89698	455	0.032	−2.31	
	10 093.992	348.11516	49 000	5.195	−0.03	
	11 721.809	369.03368	56 000	1.309	−0.58	−0.34
35 451.443	6564.148	346.07381	62 000	1.576	−0.55	−0.42
	7755.023	360.95457	54 000	6.915	0.13	0.05
	11 721.809	421.29537	30 900	0.304	−1.10	
39 858.361	6564.148	300.26500	7200	0.264	−1.44	
	7755.023	311.40380	30 800	1.004	−0.83	
	11 721.809	355.30803	57 000	8.102	0.19	

[a] Engleman et al. (1998);
HFR: Relativistic Hartree-Fock results (This work).
BGKZ: Biémont et al. (1982).

and 71 odd-parity levels below the same limit were included in the fitting process. These levels belong to the $4d^{10}$, $4d^9 5s$, $4d^9 6s$, $4d^9 5d$, $4d^9 6d$, $4d^8 5s^2$ and $4d^9 5p$, $4d^9 6p$, $4d^9 4f$, $4d^8 5s5p$ configurations. The standard deviations of the fits were found to be equal to 61 cm^{-1} and 86 cm^{-1} for the even and odd parities, respectively.

The HFR lifetime values are reported in Col. 6 of Table 1 for the 12 levels of the $4d^9 5p$ configuration including those for which the lifetime values have been measured in the present work. They agree quite well with the LIF values (present work and Biémont et al. 1982) and with the Hanle effect measurements. The values reported by van Duijn et al. (2002) are however systematically lower than the HFR results but, as discussed above, the problem probably arises from the measurements of these authors.

The corresponding HFR BFs and oscillator strengths are reported in Table 2. They agree well with the experimental results for all the transitions. Larger discrepancies are observed when comparing with the f values adopted in Doidge's (1995) compilation but these last values are dependent upon the accuracy of CB BFs.

For the 5s−5p transitions depopulating the levels for which the lifetimes have not been measured in the present work, the HFR results are reported in Table 3. For 4 transitions, the results are compared with the values taken from the paper of Biémont et al. (1982). The agreement is reasonable but it must be emphasized that the latter results are dependent upon the BFs of CB whose accuracy, as discussed in the introduction, is hard to assess.

5. Solar implications of the results

The solar photospheric abundance of Pd has been found equal to 1.69 ± 0.04 (in the logarithmic scale where the abundance of hydrogen is 12.00) by Biémont et al. (1982). This result, deduced from a set of 8 solar lines, is however strongly dependent upon the CB BFs and, consequently, dependent upon their limitations. This abundance value was itself an update of previous results (Müller 1967; Grevesse et al. 1968; Ross & Aller 1976; Hauge & Engvold 1977) which were all dependent upon CB f values. It is therefore entirely justified, on the basis of the present results, to reconsider the solar abundance of Pd in order to better assess this value.

We have retained in the present analysis the sample of lines considered by Biémont et al. (1982) but we have excluded from their list the two very weak intercombination lines at 389.4201 and 395.8642 nm whose accuracy of gf values is harder to assess. For the remaining transitions, we observe that the line at 346.0774 nm is leading to a substantially higher result (1.89) than the other transitions, indicating a possible blend. This is confirmed by the fact that this line is reported by Moore et al. (1966) as blended with a Co I line (at 346.0719 nm). The remaining five lines at 324.2703, 340.4580, 351.6943, 360.9548 and 369.0341 nm lead to a mean value of the solar abundance of Pd equal to 1.66 ± 0.04, where the uncertainty corresponds to twice the standard deviation of the mean. This result has been obtained with the same equivalent widths as used by Biémont et al. (1982) and the same solar model (Holweger & Müller 1974). This solar content is in very close agreement with the meteoric value as recently reported by Asplund et al. (2005): $A_{\rm Pd}$ = 1.67 ± 0.02. Although derived from a small number of lines, this result confirms the accuracy of the scale of oscillator strengths obtained in the present work.

6. Conclusions

Radiative lifetime measurements have been performed with a TR-LIF technique for 6 odd-parity levels of Pd I. Branching ratios for 20 5s−5p transitions have been measured from spectra of Pd I emitted from a hollow cathode discharge. By combining the lifetime values with BFs measured in the present work, absolute oscillator strengths have been deduced for 20 lines of astrophysical interest. The LIF results compare well with HFR + CP calculations performed with adjusted parameters resulting from a least-squares fit of the calculated eigenvalues of the Hamiltonian to the observed energy levels. This has allowed us to extend the set of oscillator strengths available for Pd I to transitions of astrophysical interest depopulating the 5p levels for which the lifetimes have not been measured in the present work.

The photospheric abundance of palladium, as derived from the present work is in very close agreement with the meteoritic abundance of this element.

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References

Adelman, S. J. 1974, ApJS, 28, 51
Adelman, S. J., Bidelman, W. P., & Pyper, D. M. 1979, ApJS, 40, 371
Asplund, M., Grevesse, N., & Sauval, A. J. 2005, in Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, ASP Conf. Ser., Vol. XXX, ed. F. N. Bash, & T.G. Barnes
Baumann, M., & Liening, H. 1971, Phys. Lett. 36A, 329
Bauman, M., Liening, H., & Loos, H. 1981, Z. Naturforsch. Teil A, 36, 778
Bell, R. A., & Upson II, W. L. 1971, Astrophys. Lett., 9, 109
Bidelman, W. P. 1966, in Abundance Determination in Stellar Spectra, ed. H. Hubenet (London: Academic), IAU Symp., 26, 229
Bidelman, W. P., Cowley, C. R., & Iler, A. L. 1995, Pub. Obs. Univ. Michigan, 12, No. 3
Biémont, E., Grevesse, N., Kwiatkowski, M., & Zimmermann, P. 1982, A&A, 108, 127
Budick, B. 1968, Phys. Rev., 168, 89
Corliss, C. H., & Bozman, W. R. 1962, NBS monograph, No. 53
Corliss, C. H., & Tech, J. L. 1976, J. Res. Nat. Bur. Stand. A, 80, 787
Cowley, C. R., Hartoog, M. R., Aller, M. E., & Cowley, A. P. 1973, ApJ, 183, 127
Doidge, P. 1995, Spectrochimica Acta B 50, 209; 1995, ibid. 50, 1421; 1996, ibid. 51, 375
Engelman, R., Jr., Litzén, U., Lundberg, H., & Wyart, J.-F. 1998, Phys. Scr., 57, 345
Grevesse, N., Blanquet, G., & Boury, A. 1968, in Origin and Distribution of the Elements, ed. L. H. Ahrens (Pergamon Press), 177
Hauge, O., & Engvold, O. 1977, Report 49, Institute of Theoretical Astrophysics, Blindern-Oslo
Hill, V., Plez, B., Cayrel, R., et al. 2002, A&A, 387, 560
Holweger, H., & Müller, E. A. 1974, Sol. Phys., 39, 19
Johnson, J. A., & Bolte, M. 2002, ApJ, 579, 616
Johnson, J. A., & Bolte, M. 2004, ApJ, 605, 462
Lawrence, G. M., Link, J. K., & King, R. B. 1965, ApJ, 141, 293
Liening, H. 1974, Z. Phys., 266, 287
Lundberg, H., Johanssson, S. G., Larsson, J., et al. 1996, ApJ, 469, 388
Moore, C. E., Minnaert, M. G. J., & Houtgast, J. 1966, NBS Monograph 61, US Dptmt of Commerce, Washington DC
Müller, E. A. 1967, in Solar Physics, ed. J. N. Xanthakis (New York: Interscience Publishers), 33
Orlov, M. Ya, & Shavrina, A. V. 1991, Soviet Astron. Lett., 17, 227
Ross, J. E., & Aller, L. H. 1976, Science, 197, 1223
Sneden, C., Cowan, J. J., Ivans, I. I., et al. 2000, ApJ, 533, L139
Van Duijn, E. J., Witte, S., Zinkstok, R., & Hogervorst, W. 2002, Eur. Phys. J. D, 19, 25
Xu, H. L., Jiang, Z. K., & Svanberg, S. 2003a, J. Phys. B, 36, 411
Xu, H. L., Svanberg, S., Quinet, P. H. P., Garnir, H. P., & Biémont, É. 2003b, J. Phys. B, 36, 4773
Xu, H. L., Persson, A., Svanberg, S., et al. 2004, Phys. Rev. A, 70, 042508