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Lifetimes in Fe II and the solar abundance of iron

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Abstract. New atomic lifetimes have been determined for eight quartet ($z\,^4$D, $z\,^4$F) levels and ten sextet ($z\,^6$D, $z\,^6$F, $z\,^6$P) levels in Fe II and the results for seven of these levels have been combined with existing experimental branching fractions to obtain a revised set of log *gf*-values for 15 solar lines in Fe II. The new log *gf* data are used together with equivalent widths determined from the Liège solar atlas to derive a value for the iron photospheric abundance: $A_{\rm Fe} = \log N_{\rm Fe} = 7.48 \pm 0.04$ (relative to $\log N_{\rm H}$ taken as 12.00), which is consistent with the currently accepted meteoritic result, 7.51 ± 0.01. The results are compared with the atomic lifetime data, log *gf* data and solar analyses used in three other recent solar abundance determinations based on Fe II lines.

Key words: atomic lifetimes – transition probabilities – solar abundance

1. Introduction

Iron is the most abundant of the heavier ($Z > 14$) elements in the Sun, and yet its photospheric abundance has proven to be one of the most elusive to determine with high accuracy. The difficulty lies in the fact that the most reliable abundance determinations are provided by Fe II lines which are extremely weak ($f < 0.001$) or which originate from very weakly populated lower levels (see e.g. Pauls et al. 1990; Holweger et al. 1990; Biémont et al. 1991), and the oscillator strengths (*f*-values) of such lines are very difficult to measure accurately. Moreover, many of the suitable, weak Fe II lines are LS-forbidden transitions, for which it is often difficult to calculate reliable theoretical *f*-values owing to uncertainties in the amount of mixing between the levels.

Recent solar abundance determinations based on Fe II lines have yielded differing values for the iron solar abundance. Pauls et al. (1990), using a sample of three near-infrared solar lines and *f*-values derived from their experimental branching ratio data and the lifetime data of Hannaford & Lowe (1983; hereafter HL), obtained $A_{\rm Fe} = 7.66 \pm 0.06$, which is in agreement with the result (7.67 ± 0.03) deduced from rather low excitation Fe I lines by Blackwell et al. (1984, 1986) but is significantly higher than the currently accepted meteoritic value (7.51 ± 0.01; Anders & Grevesse 1989). Holweger et al. (1990), using a sample of 13 solar lines and new experimental *f*-values normalised with an optimised set of lifetime values similar to the HL lifetimes, obtained $A_{\rm Fe} = 7.48 \pm 0.09$[1], which is in agreement with the meteoritic result. Very recently, Biémont et al. (1991) have used a large sample (39) of Fe II lines together with the new theoretical *f*-values of Kurucz (1988) and obtained $A_{\rm Fe} = 7.54 \pm 0.03$. In the latter investigation the lifetimes deduced from Kurucz's theoretical *f*-values were found to be about 10% shorter on average than the experimental lifetimes obtained by Biémont et al. for the sextet levels $z\,^6{\rm D}_J$, $z\,^6{\rm F}_J$ and $z\,^6{\rm P}_J$ by the accurate beam-laser technique, and a scaling factor of -0.05 dex was applied to Kurucz's log *gf*-values in their determination of the iron solar abundance. Most of the Fe II lines retained in the three recent solar abundance determinations, however, originate from the quartet levels $z\,^4{\rm D}_J$, $z\,^4{\rm F}_J$ and $z\,^4{\rm P}_J$ rather than from the sextet levels, and Kurucz's theoretical lifetimes for these quartet levels are 17–34% (0.08–0.18 dex) shorter than existing experimental lifetimes (Hannaford & Lowe 1983; Salih & Lawler 1983) determined from pulsed-laser fluorescence measurements. The solar abundance results of the three groups of workers, however, do not appear to reflect these differences in lifetimes, viz., the *uncorrected* abundance result of Biémont et al. (7.49 ± 0.03, not including the scaling factor of -0.05 to allow for differences in the lifetimes) is in fact in good agreement with the result of Holweger et al. (7.48 ± 0.09), which in turn is in rather poor agreement with the result of Pauls et al. (7.66 ± 0.06). It is worth noting that the use of the new lifetimes in a recalculation of the abundance derived by Pauls et al. leads to a value (Sect. 5) which is consistent with that reported in this paper.

In this paper we compare and critically examine the atomic lifetimes, *f*-values, solar data and solar analysis calculations used in the recent iron solar abundance determinations of Pauls et al. (1990), Holweger et al. (1990) and Biémont et al. (1991) in an attempt to resolve some of the apparent inconsistencies. The outcome of this investigation emphasised the need for a new set of experimental lifetimes for the quartet levels of Fe II which are reported here. The new experimental lifetimes are used together with the experimental branching ratio data of Heise & Kock (1990) and Pauls et al. (1990) to obtain a revised set of log *gf*-values for 15 Fe II solar lines, which in turn are combined with new solar data taken from the Liège solar atlas (Delbouille et al. 1973) to derive an improved value for the solar photospheric abundance of iron.

2. Lifetime results

The early HL lifetime measurements for the important $z\,^4{\rm D}_J$ and $z\,^4{\rm F}_J$ quartet levels have been repeated under somewhat improved conditions. The same technique of laser-induced fluorescence from sputtered metal vapour has been used, but in the

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[1] The uncertainty (± 0.09) quoted by Holweger et al. (1990) reduces to ± 0.05 when defined in the same manner as in Biémont et al. (1991), i.e. twice the standard deviation of the mean.

present experiment a β-barium borate crystal, which enabled the exciting laser radiation to be frequency-doubled down to wavelengths of about 230 nm, was employed instead of a KDP crystal. In this way, the $z\,^4D_J$ and $z\,^4F_J$ levels could be excited from the low-lying $a\,^4F_J$ metastable levels near 3000 cm^{-1}, rather than having to resort to the higher-lying $a\,^4D_J$ metastable levels near 8000 cm^{-1} as in the early work of HL. Thus, the signal-to-noise of the fluorescence decay curves was greatly enhanced and background emission from the sputtering discharge was significantly reduced. The background emission was further reduced by incorporating a narrow-band interference filter in the fluorescence channel.

As the lifetimes of the Fe II quartet levels are comparable with the duration of the exciting laser pulse (≈ 3 ns), consideration has to be given to the possible contribution of the laser excitation pulse and the system response time to the detected fluorescence decay curves. For the decay curves recorded in this work, however, the signal-to-noise is sufficiently high for the analyses to be readily performed by fitting a pure exponential to the lower half of the decay curves. The accuracy of this procedure has been checked by recording the laser pulse (as modified by the system response time) and then convoluting this recorded pulse with exponentials of varying decay constant. Figure 1 shows the result of such a fit to the recorded fluorescence decay for the short-lived (2.9 ns) $z\,^4D_{1/2}$ level. The level of agreement between the lifetime values obtained by direct analysis of the decay curves and by the convolution procedure described above indicates that the contribution of the excitation pulse and the system response time to the measured lifetimes is less than 2% for lifetimes of 2.9 ns and longer.

The lifetime values determined for eight quartet and ten sextet Fe II levels are presented in Table 1 along with various Fe II lifetime results reported in the literature and some preliminary beam-laser results of Guo et al. (1991). These lifetime results include the upper levels of all of the transitions that we have used (Sect. 4) in determining the solar abundance and include the first reported lifetime for the important $z\,^4D_{1/2}$ level. The experimental lifetimes for the four recent sets of measurements (columns 2–5) are in excellent agreement for all sextet and quartet levels and are also in reasonable agreement with the four earlier sets of experimental lifetimes (columns 6–9), with the exception of the HL lifetime for the $z\,^4D_{7/2}$ level which is high by about 20%. The latest lifetimes also suggest that the earlier results of HL and Brzozowski et al. (1976) are slightly long by about 6% on an average, though within the experimental uncertainties. The "optimised" lifetime values (Kroll & Kock 1987) given in column 10, which are very close to the early HL values, were the lifetimes used in the normalisation of the f-values employed in the solar abundance determination of Holweger et al. (1990).

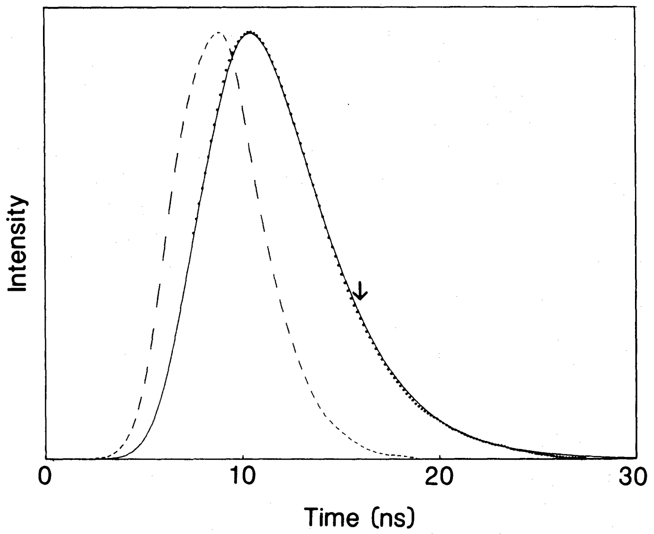

Fig. 1. Fluorescence decay curve for the Fe II $z\,^4D_{1/2}$ level. The points represent the experimental data. Analysis of the tail of the curve (i.e. to the right of the arrow) gives $\tau = 2.95$ ns. The full curve represents a convolution of the recorded laser pulse (broken curve) with a pure exponential of decay constant (2.90 ns)$^{-1}$

On the basis of the latest experimental lifetimes, the theoretical lifetimes deduced from Kurucz's f-values are systematically short by 6 to 17% for the $z\,^6D$, $z\,^6F$ and $z\,^6P$ sextet levels and by 12 to 28% for the $z\,^4D$ and $z\,^4F$ quartet levels.

3. *gf*-values and branching fractions

The present lifetime results and the experimental branching ratio data of Heise & Kock (1990) and Pauls et al. (1990) have been used to determine log gf-values for the 15 solar lines listed in Table 2. In the case of the 457.633 and 751.583 nm lines, for which two experimental determinations of the branching fraction exist (Table 2, columns 7 and 8), the adopted branching fraction was taken to be the mean of the two values. The quoted uncertainties in the log gf-values arise mainly from the uncertainties in the branching fractions. If the apparently more accurate, preliminary lifetime results of Guo et al. (1991) were to be used instead of the lifetime values reported here, the log gf-values in Table 2 would be altered by ≤ 0.01 dex and the uncertainties reduced by less than 0.01 dex.

The present log gf-values are a little higher on average than the values used in the solar analyses of both Pauls et al. (mean difference +0.08 dex) and Holweger et al. (mean difference +0.04 dex, standard deviation 0.04 dex), mainly on account of the slightly shorter lifetime values found in the present work. In the solar abundance determination of Pauls et al., the f-values were determined for three solar lines using the early HL lifetime for the $z\,^4D_{5/2}$ level and assuming the lifetime of the $z\,^4D_{1/2}$ level to be the same as the $z\,^4D_{5/2}$ level for two of the lines.

For the 11 solar lines in common with the 39 lines used by Biémont et al., the mean of the difference, $\log gf_{\rm this\ work} - \log gf_{\rm Kurucz}$, is small (+0.01 dex) but the standard deviation is large (0.12 dex) owing to large discrepancies for some lines. Such a small mean difference is surprising in view of the fact that the difference between the experimental lifetimes and those deduced from Kurucz's theoretical f-values (Table 1) is rather large (mean difference for levels of 11 solar lines +17%, or +0.07 dex). As there is close agreement between the solar abundance result based on the data of Biémont et al. for the 11 common lines (7.51 ± 0.06, excluding the 0.05 scaling factor) and that obtained by Biémont et al. for all 39 lines (7.49 ± 0.03, excluding the scaling factor), it would appear that Kurucz's theoretical f-values are *on an average* reasonably accurate for the large sample of solar lines used by Biémont et al. However, the difference between the theoretical and experimental lifetimes implies that the theoretical f-values are systematically high for the strong shorter-wavelength lines that essentially determine the lifetimes of the levels. Such discrepancies are, of course, also reflected in the values of the branching

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Table 1. Comparison of atomic lifetimes in Fe II

Level	Experiment									Theory
	This work	Guo[a] (1991)	Biém[b] (1991)	Scha[c] (1988)	HL[d] (1983)	Sal[e] (1983)	Brz[f] (1976)	Ass[g] (1972)	Opt[h] (1987)	Kur[i] (1988)
$z\,^6D_{9/2}$	3.7(2)		3.70(6)	3.7(2)	3.9(2)			3.9(4)	3.9	3.41
$z\,^6D_{7/2}$	3.75(20)		3.68(7)	3.8(3)	4.0(2)		4.0(4)		4.2	3.43
$z\,^6D_{5/2}$	3.7(2)		3.63(8)	3.8(3)	4.0(2)			3.9(4)	4.1	3.44
$z\,^6D_{3/2}$	3.7(2)		3.83(10)	3.7(2)	3.9(3)				4.0	3.45
$z\,^6D_{1/2}$	3.8(2)		3.76(10)	3.8(3)	4.0(3)				3.9	3.45
$z\,^6F_{11/2}$	3.2(2)		3.19(4)	3.3(2)						2.83
$z\,^6F_{9/2}$	3.2(2)		3.24(6)	3.4(2)			3.5(4)	3.2(3)	3.4	2.89
$z\,^6F_{7/2}$			3.26(10)	3.3(2)				3.2(3)	3.6	2.92
$z\,^6F_{5/2}$			3.33(9)	3.3(2)					3.5	2.93
$z\,^6F_{3/2}$			3.34(10)	3.3(2)				3.2(3)	3.3	2.94
$z\,^6F_{1/2}$				3.3(3)				3.2(3)	3.2	2.94
$z\,^6P_{7/2}$	3.8(2)		3.73(5)	3.5(3)				3.8(4)	3.8	3.28
$z\,^6P_{5/2}$	3.7(2)		3.83(7)	3.5(3)						3.26
$z\,^6P_{3/2}$	3.6(2)			3.4(3)			4.0(4)	3.8(4)	4.0	3.25
$z\,^4D_{7/2}$	3.1(2)	3.02(6)			3.7(4)				3.7	2.43
$z\,^4D_{5/2}$	3.1(2)	3.10(8)			3.4(4)				3.2	2.44
$z\,^4D_{3/2}$	3.0(2)				3.4(4)				3.2	2.43
$z\,^4D_{1/2}$	2.9(2)									2.42
$z\,^4F_{9/2}$	3.7(2)	3.88(9)			4.1(3)	3.9(2)			4.3	3.34
$z\,^4F_{7/2}$	3.6(2)	3.63(11)			3.9(3)				3.9	3.22
$z\,^4F_{5/2}$	3.7(2)				4.0(3)				4.0	3.26
$z\,^4F_{3/2}$	3.7(2)				4.1(4)				4.1	3.30

[a] Preliminary results of Guo et al. (1991); [b] Biémont et al. (1991); [c] Schade et al. (1988); [d] Hannaford & Lowe (1983); [e] Salih & Lawler (1983); [f] Brzozowski et al. (1976); [g] Assousa & Smith (1972); [h] Optimised lifetime values used by Kroll & Kock (1987) to normalise their *f*-values; [i] Kurucz (1988)

fractions deduced from the theoretical *f*-values (Table 2, column 9), where the mean difference between the experimental branching fractions and the theoretical fractions is −21% (excluding the 552.513 nm line for which there is a very large discrepancy). Further evidence of Kurucz's *f*-values being systematically high for the strong shorter-wavelength lines is provided by the experimental log *gf*-values of Pauls et al. (see Fig. 2 of Biémont et al.), Kroll & Kock (1987; mean difference −0.07 dex for 81 lines with $\log gf > -2.0$ in the range 225–300 nm after rescaling using the new lifetime values) and Whaling (1983; mean difference −0.08 dex for 52 lines with $\log gf > -2.0$ in the range 225–300 nm after rescaling). Evidence of a wavelength dependence in Kurucz's *f*-values also seems to be apparent in the solar abundance data of Biémont et al., which show a systematic decrease with decreasing wavelength, that is not present when using the experimental log *gf*-values obtained in this work. For the data of Biémont et al., the 20 solar lines in the wavelength range 410–550 nm yield an average abundance value (7.45 ± 0.04, excluding the 0.05 scaling factor) which is somewhat lower than the value (7.53 ± 0.03) derived from the 19 lines in the range 550–780 nm.

If Kurucz's theoretical *f*-values are on an average correct for the large sample of solar lines used by Biémont et al., then it would seem that the scaling factor of −0.05 dex applied to the theoretical *f*-values in the solar abundance determination of Biémont et al. is too large.

4. Solar data and solar analysis

A new set of equivalent widths has been measured for the 15 solar lines for which log *gf*-values have been determined in this work, using solar spectra taken from the Liège solar atlas (Delbouille et al. 1973). These results are compared with the equivalent widths used in the three other recent solar abundance determinations in Table 3. In the case of the 552.513, 562.749 and 744.934 nm solar lines, which are significantly perturbed in the wings, the equivalent widths were determined by fitting Gaussian lineshapes to the observed profiles. The quoted uncertainties in the equivalent widths reflect the quality of the solar lines and the scatter between individual measurements. The equivalent widths used in the four recent solar abundance investigations are generally in good agreement, with the largest differences amounting to 9–12% for the 465.697 and 541.408 nm lines (Table 3).

The solar analysis was performed using the solar photospheric model of Holweger & Müller (1974), together with values of the microturbulence ($\xi = 1$ km s^{-1}) and damping enhancement factor ($\Delta = 2$) which permitted the smallest dispersion in the abundance results and an updated solar chemical composition

Table 2. Comparison of log *gf*-values and branching fractions used in the recent iron solar abundance determinations based on lines in Fe II. Only lines in common with those used in the present investigation are included. Values in square brackets are for lines not used in the actual solar abundance determinations

λ (nm)		log *gf*				Branching fractions ($\times 10^{-5}$)		
		This work[a]	Pauls et al.	Holweger et al.[b]	Biémont et al.[c]	Pauls et al.	Heise & Kock	Kurucz
457.633	$b\,^4F_{5/2}$–$z\,^4D_{5/2}$	−2.94 (10)	[−2.97 (16)]	−2.94	−2.822	[19 (8)]	19 (4)	19.5
462.051	$b\,^4F_{7/2}$–$z\,^4D_{7/2}$	−3.21 (9)		−3.29	−3.079		7.5 (1.4)	7.9
465.697	$a\,^6S_{5/2}$–$z\,^4D_{5/2}$	−3.59 (10)		−3.61	−3.552		4.1 (9)	3.5
523.462	$a\,^4G_{7/2}$–$z\,^4F_{5/2}$	−2.23 (10)		−2.27	−2.151		87 (20)	93
526.479	$a\,^4G_{5/2}$–$z\,^4D_{3/2}$	−3.25 (8)		−3.27	[−3.303]		10.2 (1.8)	[7.3]
541.408	$a\,^4G_{7/2}$–$z\,^4D_{7/2}$	−3.50 (10)		−3.58	−3.750		2.8 (6)	1.2
552.513	$b\,^2H_{9/2}$–$z\,^4D_{7/2}$	−3.95 (11)		−4.04	[−4.609]		0.94 (24)	[0.16]
562.749	$a\,^2F_{7/2}$–$z\,^4F_{5/2}$	−4.10 (10)		−4.14	[−4.171]		1.0 (2)	[0.77]
643.267	$a\,^6S_{5/2}$–$z\,^6D_{5/2}$	−3.50 (9)		−3.55	−3.708		3.1 (6)	1.8
651.607	$a\,^6S_{5/2}$–$z\,^6D_{7/2}$	−3.38 (7)		−3.44	−3.450		3.1 (5)	2.4
722.239	$b\,^4D_{3/2}$–$z\,^4D_{1/2}$	−3.36 (6)	−3.43 (7)		−3.295	8.1 (1.0)		7.8
722.449	$b\,^4D_{1/2}$–$z\,^4D_{1/2}$	−3.28 (6)	−3.35 (6)		−3.243	9.8 (1.1)		8.8
744.934	$b\,^4D_{3/2}$–$z\,^4D_{5/2}$	−3.09 (12)		−3.10	[−3.308]		5.0 (1.3)	[2.4]
751.583	$b\,^4D_{7/2}$–$z\,^4D_{5/2}$	−3.44 (14)	−3.53 (8)	−3.41	−3.432	2.0 (3)	2.4 (6)	1.8
771.173	$b\,^4D_{7/2}$–$z\,^4D_{7/2}$	−2.47 (9)		−2.55	−2.543		15 (3)	9.7

[a] Using lifetimes found in this work (Table 1, column 2) and experimental branching fractions of Heise & Kock (1990) (column 8) and Pauls et al. (1990) (column 7). For the 457.633 and 751.583 nm lines, the mean of the two results has been used

[b] Taken from the experimental data of Heise & Kock (1990)

[c] Taken from the theoretical calculations of Kurucz (1988)

Table 3. Comparison of equivalent widths (W_λ) and log gfN_{Fe}-values for the recent solar abundance determinations based on Fe II lines

λ (nm)	W_λ (mÅ)			log gfN_{Fe}						
	This work (a)	Holweger et al.	Biémont et al.	This work	Pauls et al.		Holweger et al.		Biémont et al.	
					(a)	(c)	(b)	(c)	(d)	(c)
				$\xi=1$	$\xi=0.85$	$\xi=1$	$\xi=1$	$\xi=1$	$\xi=1$	$\xi=1$
				$\Delta=2$	$\Delta=1$	$\Delta=2$	$\Delta=2.5$	$\Delta=2$	$\Delta=1.5$	$\Delta=2$
457.633	68 (1)	67.0	67.0	4.54 (2)			4.49	4.54	4.58	4.58
462.051	54.0 (1.5)	56.5	55.2	4.20 (4)			4.23	4.19	4.27	4.23
465.697	38 (3)	33.7	36.9	3.89 (7)			3.77	3.88	3.89	3.91
523.462	89.2 (1.0)	88.3	88.8	5.23 (2)			5.16	5.21	5.30	5.26
526.479	47.4 (5)	48.0		4.37 (1)			4.36	4.36		
541.408	27.6 (1.5)	29.8	26.6	3.89 (4)			3.94	3.89	3.89	3.91
552.513	12.7 (1.0)	13.1		3.47 (4)			3.49	3.47		
562.749	8.6 (1.0)	7.5		3.38 (6)			3.31	3.38		
643.267	43.4 (5)	44.2	42.9	3.90 (1)			3.91	3.90	3.92	3.92
651.607	57.5 (1.0)	57.6	55.8	4.18 (2)			4.17	4.18	4.19	4.21
722.239	20.0 (5)		19.5	4.22 (2)	4.27	4.26			4.25	4.26
722.449	20.7 (5)		20.7	4.24 (1)	4.29	4.28			4.28	4.28
744.934	19.5 (2.0)	19.2		4.20 (6)			4.19	4.20		
751.583	14.9 (2)	15.1	14.9	4.05 (8)	4.10	4.09	4.06	4.05	4.08	4.08
771.173	50.6 (1.0)	49.5	49.1	4.92 (2)			4.88	4.92	4.94	4.96

Notes: (a) Equivalent widths obtained by Pauls et al. (1990) for the 722.239, 722.449 and 751.583 nm lines are the same as in this work; (b) log gfN_{Fe}-values obtained by Holweger et al. (1990); (c) Original log gfN_{Fe}-values adjusted so that ξ, Δ and W_λ are the same as in this work ($\xi = 1$ km s^{-1}, $\Delta = 2$); (d) log gfN_{Fe}-values obtained by Biémont et al. (1991)

Table 4. Iron solar abundance results obtained in this investigation

λ (nm)		Lower E.P. (eV)	W_λ (mÅ)	$\log gf^{a}$	A_{Fe}
457.633	$b\,^4\mathrm{F}_{5/2}$–$z\,^4\mathrm{D}_{5/2}$	2.84	68 (1)	−2.94 (10)	7.48 (10)
462.051	$b\,^4\mathrm{F}_{7/2}$–$z\,^4\mathrm{D}_{7/2}$	2.83	54.0 (1.5)	−3.21 (9)	7.42 (9)
465.697	$a\,^6\mathrm{S}_{5/2}$–$z\,^4\mathrm{D}_{5/2}$	2.89	38 (3)	−3.59 (10)	7.48 (12)
523.462	$a\,^4\mathrm{G}_{7/2}$–$z\,^4\mathrm{F}_{5/2}$	3.22	89.2 (1.0)	−2.23 (10)	7.46 (10)
526.479	$a\,^4\mathrm{G}_{5/2}$–$z\,^4\mathrm{D}_{3/2}$	3.23	47.4 (0.5)	−3.25 (8)	7.62 (8)
541.408	$a\,^4\mathrm{G}_{7/2}$–$z\,^4\mathrm{D}_{7/2}$	3.22	27.6 (1.5)	−3.50 (10)	7.40 (10)
552.513	$b\,^2\mathrm{H}_{9/2}$–$z\,^4\mathrm{D}_{7/2}$	3.27	12.7 (1.0)	−3.95 (11)	7.42 (12)
562.749	$a\,^2\mathrm{F}_{7/2}$–$z\,^4\mathrm{F}_{5/2}$	3.39	8.6 (1.0)	−4.10 (10)	7.48 (11)
643.267	$a\,^6\mathrm{S}_{5/2}$–$z\,^6\mathrm{D}_{5/2}$	2.89	43.4 (0.5)	−3.50 (9)	7.40 (9)
651.607	$a\,^6\mathrm{S}_{5/2}$–$z\,^6\mathrm{D}_{7/2}$	2.89	57.5 (1.0)	−3.38 (7)	7.56 (8)
722.239	$b\,^4\mathrm{D}_{3/2}$–$z\,^4\mathrm{D}_{1/2}$	3.89	20.0 (0.5)	−3.36 (6)	7.58 (6)
722.449	$b\,^4\mathrm{D}_{1/2}$–$z\,^4\mathrm{D}_{1/2}$	3.89	20.7 (0.5)	−3.28 (6)	7.52 (6)
744.934	$b\,^4\mathrm{D}_{3/2}$–$z\,^4\mathrm{D}_{5/2}$	3.89	19.5 (2.0)	−3.09 (12)	7.29 (13)
751.583	$b\,^4\mathrm{D}_{7/2}$–$z\,^4\mathrm{D}_{5/2}$	3.90	14.9 (0.2)	−3.44 (14)	7.49 (14)
771.173	$b\,^4\mathrm{D}_{7/2}$–$z\,^4\mathrm{D}_{7/2}$	3.90	50.6 (1.0)	−2.47 (9)	7.39 (9)

[a] Using lifetimes obtained in this investigation and experimental branching fractions of Heise & Kock (1990) and Pauls et al. (1990)

used for the determination of the electronic and gaseous pressures. The $\log gfN_{\mathrm{Fe}}$-values thus deduced from the equivalent width data are summarised in Table 3 (column 5) along with the $\log gfN_{\mathrm{Fe}}$-values obtained in the three other solar abundance determinations (columns 6, 8 and 10). The second set of $\log gfN_{\mathrm{Fe}}$-values under the headings of Pauls et al. (column 7), Holweger et al. (column 9) and Biémont et al. (column 11) were obtained by making small adjustments to the original $\log gfN_{\mathrm{Fe}}$-values to correspond to the same values of W_λ, ξ and Δ as used in the present investigation. It is interesting to note that our results (column 5) agree remarkably well with the adjusted values of Holweger et al. (mean difference <0.01 dex), whereas the adjusted results of Pauls et al. and Biémont et al. are systematically lower (mean differences -0.04 and -0.03 dex, respectively) than our values even though similar solar models (Holweger–Müller) were used in all three analyses. The difference between the present $\log gfN_{\mathrm{Fe}}$-values and the adjusted values of Pauls et al. is attributed to differences in the electronic and gaseous pressures resulting from the updated solar chemical composition.

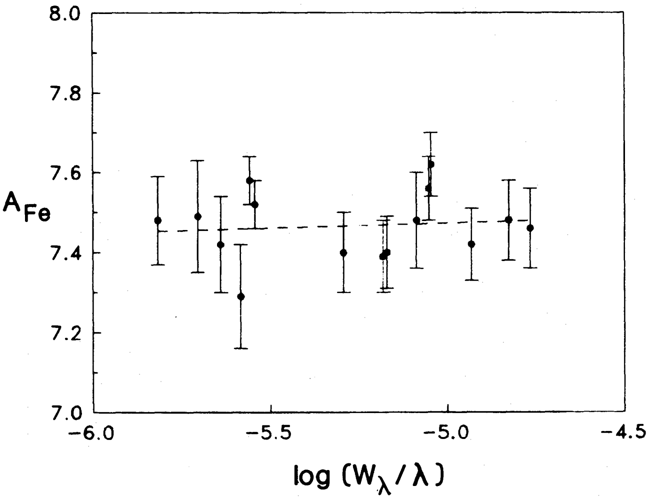

Fig. 2. Plot of the iron solar abundance values obtained in the present investigation for different solar lines against strength of the lines ($\log W_\lambda/\lambda$). The broken line is a straight-line fit to the points

5. The solar abundance of iron

Table 4 summarises the solar abundance data for the 15 Fe II lines used in this investigation. The abundance values derived from the individual solar lines are essentially independent of the strength ($\log W_\lambda/\lambda$) and wavelength of the solar lines, as illustrated in Figs. 2 and 3. The iron solar abundance, deduced from the weighted mean of the A_{Fe}-values for the 15 solar lines, is found to be

$$A_{\mathrm{Fe}} = 7.48 \pm 0.04,$$

where the uncertainty represents twice the standard deviation in the mean. This abundance value is in excellent agreement with the result of Holweger et al. (7.48 ± 0.09) and it is also consistent with the result of Biémont et al. (7.54 ± 0.03) and the currently accepted value for meteorites (7.51 ± 0.01; Anders & Grevesse 1989). When the abundance result of Pauls et al. is adjusted to allow for the new lifetime values and the updated electronic and gaseous pressures, it reduces to a value (7.54 ± 0.06) which is also consistent with the present result. Very recently, Holweger et al. (1991) have redetermined the solar abundance of iron from Fe I lines with new oscillator strengths measured by Bard et al. (1991), which are in agreement with the gf-values of Blackwell et al. (1984, 1986). They find $A_{\mathrm{Fe}} = 7.50 \pm 0.07$, in agreement with our value. The reason for the large difference between the recent results based on both Fe I and Fe II lines and the result of Blackwell et al. (7.67 ± 0.03) is not clear.

Taking an unweighted mean of the individual A_{Fe}-values, rather than a weighted mean, lowers the above abundance result

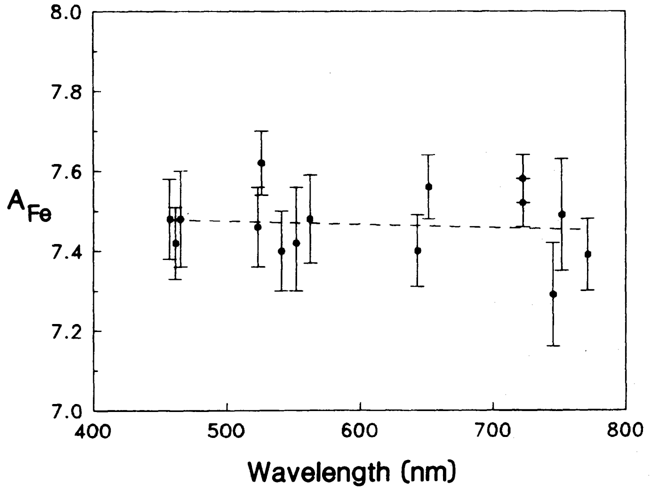

Fig. 3. Plot of the iron solar abundance values obtained in the present investigation for different solar lines against wavelength of the lines. The broken curve is a straight-line fit to the data

by only 0.01 dex. If we exclude the 744.934 nm line, which is strongly blended in the red wing, the abundance would be raised by only 0.01 dex. Finally, altering the microturbulance from $\xi = 1$ to $0.85\,\mathrm{km\,s^{-1}}$ would raise the abundance by 0.02 dex, while altering the damping enhancement factor from $\Delta = 2$ to 1.5 would raise the abundance by 0.01 dex.

6. Discussion and conclusions

The large difference (+0.18 dex) between the solar abundance result of Pauls et al. (1990) and the present value originates mainly from the difference in log *gf*-values (contribution +0.08 dex), a difference (+0.05 dex) resulting from the use of only three of the sample of 15 lines used in the present investigation, and a difference (+0.04 dex) resulting from the use of different electronic and gaseous pressures. As mentioned above, the difference arising from the log *gf*-values results mainly from the difference (contribution +0.06 dex) between the early HL lifetime for the $z\,^4\mathrm{D}_{5/2}$ level and the new lifetime values for the $z\,^4\mathrm{D}_{5/2}$ and $z\,^4\mathrm{D}_{1/2}$ levels. (In the investigation of Pauls et al. the lifetime of the $z\,^4\mathrm{D}_{1/2}$ level had been assumed to be the same as for the $z\,^4\mathrm{D}_{5/2}$ level). In the case of the 751.583 nm line, the difference in the log *gf*-value (+0.09 dex) is also partly the result of their smaller value for the branching fraction.

In the investigation of Holweger et al. (1990) the contributions arising from differences in the log *gf*-values (+0.04 dex) and the minor (negative) contributions arising from the effect of differences in the values of ξ and Δ and in the sample of solar lines used exactly cancel to give the same abundance result as in the present investigation.

The difference between the solar abundance result of Biémont et al. (1991) and the present result (+0.06 dex) originates from differences in the log *gf*-values (mean difference +0.06 dex, including the 0.05 dex scaling factor), a difference (+0.03 dex) originating from differences in the solar analysis calculations (see Table 3), and the combined effect of small contributions arising from differences in the equivalent widths, the values of ξ and Δ, and the sample of solar lines used in the determination.

The satisfactory agreement between the five recent iron abundance determinations (Holweger et al. 1990, 1991; Pauls et al. 1990 (after applying the corrections discussed above); Biémont et al. 1991; this work) now seems to provide strong evidence in favour of the lower value of the iron solar abundance. Very recently, Feldman (1991) has derived Fe/Mg and Fe/O ratios from solar flare spectra. He shows that no fractionation process is operating in the flares under investigation and that the iron abundance is equal to the meteoritic value, thus lending further support to the low abundance value for iron. As with nearly all non-volatile elements studied to date, there is now good agreement between the solar photospheric abundance of iron (7.48 ± 0.04) and the currently accepted value for the meteoritic abundance (7.51 ± 0.01; Anders & Grevesse 1989).

The accuracy of the present iron solar abundance determination is limited mainly by the relatively large uncertainties in the experimental branching fractions for the very weak Fe II solar lines and the fairly small sample of 15 solar lines for which branching fractions have been measured. Accurate lifetimes are now available for the upper levels of 32 of the 39 solar lines used in the solar abundance investigation of Biémont et al. and there is a need for accurate measurements of the branching fractions for a large number of these very weak solar lines.

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