

Radiative lifetimes, branching fractions and transition probabilities in Ge I – solar implications

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ABSTRACT

New radiative lifetimes have been measured for the $5s\ ^3P^o_{0,1,2}$ and $5s\ ^1P^o_1$ levels of Ge I using a laser-produced plasma subject to selective laser excitation. A diffraction grating based emission spectrometer of moderately high resolution has been used to remeasure the branching ratios of the 4p–5s depopulating transitions. The oscillator strengths of astrophysical interest, which have been derived from these new data, are compared with theoretical values calculated within a pseudo-relativistic Hartree–Fock approach. The new set of f -values has been compared with the few results available in the literature, which are generally characterized by a large scatter and a low accuracy. The solar photospheric abundance of germanium deduced from the new atomic data of the present work is $A_{\text{Ge}} = 3.58 \pm 0.05$, on the usual logarithmic scale, in agreement with the meteoritic value.

Key words: atomic data – methods: laboratory – methods: numerical – Sun: abundances.

1 INTRODUCTION

Germanium is observed in the spectra of various stellar objects: Ge I is likely to be present in some stars of the Cr–Eu–Sr variety of Ap stars (Adelman, Bidelman & Pyper 1979), while Ge II has been observed in Bp stars of the Hg–Mn subgroup (see e.g. Leckrone et al. 1991). Ge I has also been identified in the solar photospheric spectrum (see e.g. Moore, Minnaert & Houtgast 1966).

Germanium has been observed in the interstellar medium (ISM) predominantly in the form of Ge II in the direction of the ζ Pup (Morton 1978), ζ Oph and χ Per (Cardelli, Savage & Ebberts 1991), 15 Mon, π Aqr, 23 Ori, π Sco and I Sco (Hobbs et al. 1993) stars. Investigation of the heavy element content ($Z \geq 30$) of the ISM provides information on the effects of local chemical enrichment and mixing in the interstellar gas where most atoms and ions are observed in their ground energy states, the resonance lines generally appearing in the UV region. ISM germanium abundances, deduced from Ge I or Ge II absorption lines, show deviations when compared with those of the Solar system, and these deviations are generally explained by the formation of dust grains in the ISM with different degrees of incorporation of elements into dust.

The determination of the chemical composition of the stars relies heavily upon the availability of accurate transition probabilities, and the refinement of the ISM abundance analyses is strongly dependent upon the atomic oscillator strengths used for the calculations [see e.g. Johansson et al. (1994) for a recent discussion in the case of χ Lupi].

For Ge I, the available f -values are frequently inaccurate or lacking. This is because the published theoretical and experimental data, even for the resonance transitions, show rather large discrepancies (see Section 5).

For these reasons, we have undertaken in the present study a theoretical and experimental investigation of oscillator strengths for some Ge I transitions of astrophysical interest. This paper is limited to the discussion of allowed (E1) transitions. Forbidden lines (M1 and E2 types) have been considered and discussed elsewhere (see e.g. Biémont & Hansen 1986). This paper complements recent data of astrophysical interest obtained for UV transitions of Ge II (Biémont, Morton & Quinet 1998b).

2 RADIATIVE LIFETIME MEASUREMENTS

Lifetimes of the 4p5s configuration levels of Ge I have been measured by time-resolved spectroscopy at the Lund High Power Laser Facility (Svanberg et al. 1994). The same method has recently been used in lifetime measurements of Pt II (Larsson, Zerne & Lundberg 1996), Pb I (Li et al. 1998a) and Si I (Li et al. 1998b).

The experimental set-up is shown in Fig. 1. In order to obtain laser pulses of relatively short duration but with a small spectral bandwidth, a distributed-feedback dye laser (DFDL) oscillator (Schade, Garbe & Helbig 1990) was pumped by a small fraction of the frequency-doubled output from a mode-locked and Q-switched Nd:YAG laser. The DFDL oscillator, together with two dye amplifiers pumped by the same Nd:YAG laser, provides tunable radiation from 745 to 815 nm with a pulse energy just above 1 mJ. The radiation from the dye laser was frequency-tripled

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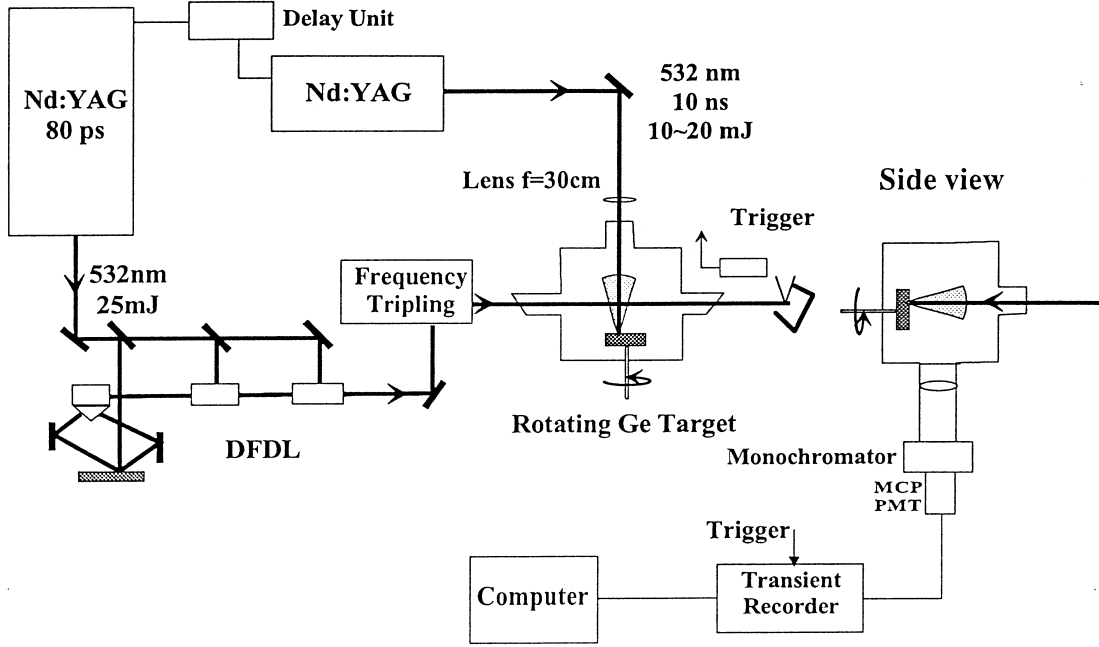


Figure 1. The experimental set-up for lifetime measurements.

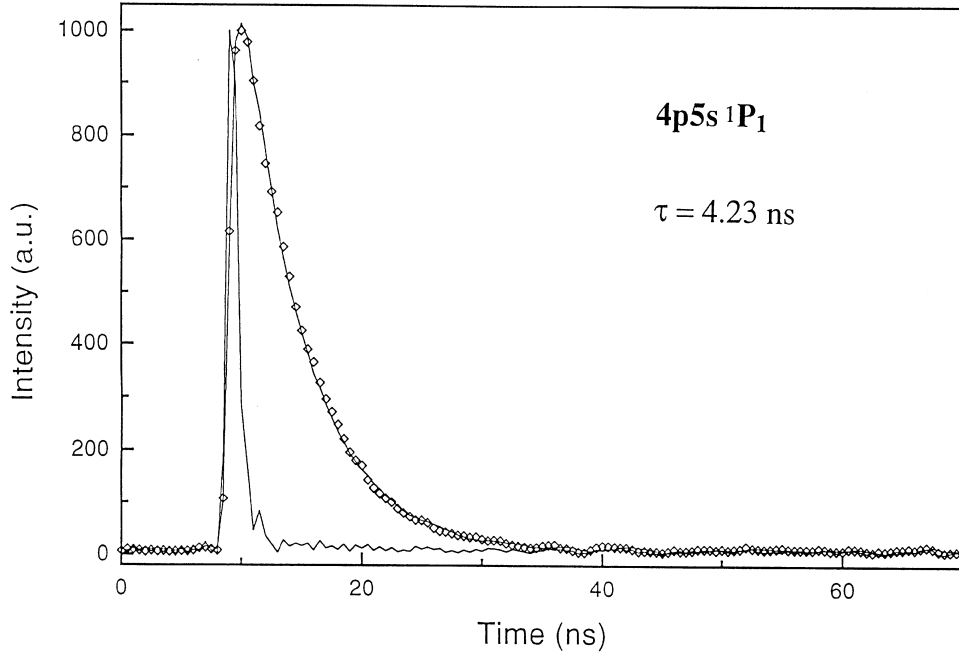


Figure 2. The fluorescence signal (open diamonds) of the $4p5s\ ^1P_1$ state, fitted with the convolution of the excitation laser pulse and an exponential with a decay constant of 4.23 ns; and the excitation laser pulse.

in KDP and BBO crystals, yielding pulses of a few tens of μJ and 60-ps duration, tunable in the region 249–279 nm.

Free germanium atoms were obtained in a laser-produced plasma. Radiation from a Q-switched Nd:YAG laser (Continuum Surelite¹), producing pulses of 10-ns duration and an output energy of 10–20 mJ, was focused with a 30-cm focal-length lens on to a rotating germanium target. Atoms in the laser-produced plasma

entered the excitation laser beam, which was about 2 cm above the surface of the germanium target. Both Nd:YAG lasers were triggered from a common unit (Stanford Research Systems² Model 535). This allowed us to change the time delay between the laser pulses used for atomization and excitation. Effective population of metastable states occurred and, by waiting until the plasma density was sufficiently low, perturbation-free measurements

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²Stanford Research Systems, 1290-D Reamwood Avenue, Sunnyvale, CA 97089, USA.

Table 1. Ge I: calculated and measured lifetimes, and comparison with previous measurements.

Level	Energy* (cm ⁻¹)	Excitation		Observed fluor. (nm)	Lifetime value (ns)		Previous
		Origin	λ (nm)		This work Exp.	HFR	
5s ¹ P ₁ ^o	40020.5604	4p ² ³ P ₀	249.87	304.0	4.23 ± 0.14	3.66	4.0 ± 0.3 ^a , 3.9 ± 0.5 ^b , 4.4 ± 0.9 ^c , 6.2 ± 0.6 ^d
5s ³ P ₀ ^o	37451.6809	4p ² ³ P ₁	271.04	271.0	4.81 ± 0.14	4.12	4.9 ± 0.6 ^a , 3.6 ± 0.4 ^b , 6.0 ± 0.5 ^d
5s ³ P ₁ ^o	37702.3054	4p ² ³ P ₁	269.21	275.5	4.68 ± 0.20	3.99	4.4 ± 0.6 ^a , 3.7 ± 0.5 ^b , 6.8 ± 0.7 ^d
5s ³ P ₂ ^o	39117.9021	4p ² ³ P ₁	265.20	265.2	4.50 ± 0.18	3.79	4.2 ± 0.5 ^a , 4.0 ± 0.4 ^b , 6.0 ± 1.2 ^c , 7.4 ± 0.6 ^d

*Sugar & Musgrove (1993); ^aTint et al. (1990) (delayed coincidence technique); ^bAndersen et al. (1975) (beam-foil spectroscopy); ^cLawrence (1967) (phase-shift method); ^dKomarovskii & Verolainen (1989) (delayed coincidence method).

Table 2. Ge I: observed wavelengths (in nm), experimental branching ratios, experimental and HFR transition probabilities (*A*) and oscillator strengths obtained in the present work for 4p²–4p5s transitions.

Transition	λ (exp) ^a (nm)	BR	<i>A</i> (10 ⁸ s ⁻¹)		log <i>gf</i>	
			EXP	HFR	EXP	HFR
³ P ₀ – ¹ P ₁ ^o	249.79625	0.0464(46)	0.110(11)	0.0900	–1.51	–1.60
³ P ₁ – ¹ P ₁ ^o	253.32305	0.0362(36)	0.0856(89)	0.0819	–1.61	–1.63
³ P ₂ – ¹ P ₁ ^o	258.91878	0.0168(17)	0.0397(41)	0.0381	–1.92	–1.94
³ P ₁ – ³ P ₂ ^o	259.25340	0.272(14)	0.604(39)	0.698	–0.52	–0.45
³ P ₂ – ³ P ₂ ^o	265.11720	0.721(14)	1.60(7)	1.932	–0.07	0.01
³ P ₀ – ³ P ₁ ^o	265.15683	0.325(16)	0.694(46)	0.791	–0.66	–0.60
³ P ₁ – ³ P ₁ ^o	269.13411	0.221(11)	0.473(31)	0.548	–0.81	–0.75
³ P ₁ – ³ P ₀ ^o	270.96237	1.000	2.08(6)	2.428	–0.64	–0.57
³ P ₂ – ³ P ₁ ^o	275.45878	0.371(19)	0.792(52)	0.963	–0.57	–0.48
¹ D ₂ – ¹ P ₁ ^o	303.90671	0.861(14)	2.04(5)	2.349	–0.07	–0.01
¹ D ₂ – ³ P ₂ ^o	312.48164	0.00715(72)	0.0159(17)	0.0082	–1.93	–2.22
¹ D ₂ – ³ P ₁ ^o	326.94889	0.0806(81)	0.172(19)	0.194	–1.08	–1.03
¹ S ₀ – ¹ P ₁ ^o	422.65625	0.0399(40)	0.0943(98)	0.171	–1.12	–0.86
¹ S ₀ – ³ P ₀ ^o	468.58286	0.00233(23)	0.00498(54)	0.0105	–2.31	–1.98

^aFrom Andrew & Meissner (1959). The wavelengths are given in air above 2000 Å and in vacuum below that limit.

could be performed. A 1/8-m monochromator (ORIEL³ Model 77250), with a resolution of about 6.4 nm mm⁻¹, placed perpendicularly to both the laser beams, was used to single out the desired transitions. The detector was a Hamamatsu⁴ 1564 U microchannel plate (MCP) photomultiplier, which was connected to a Tektronix⁵ DSA 620 digital oscilloscope with an analogue bandwidth of 1 GHz and a sampling rate of 2 Gsamples⁻¹. The oscilloscope was optically triggered with a jitter below 100 ps. The temporal response of the system is mainly limited by the input amplifier of the oscilloscope. Some influence from the limited rise-time of the photomultiplier tube (PMT) (200 ps) and the signal cables is also expected. The measured FWHM of the stray light from the short-pulse laser as observed with this detection system was around 1 ns (see Fig. 2).

The 4p5s ³P_{0,1,2} levels were excited from 4p² ³P₁ and the 4p5s ¹P₁^o level from 4p² ³P₀. The strongest transitions back to low-lying states were selected to monitor the fluorescence exponential decays. The lifetimes were evaluated by fitting the experimental curves with a convolution of an exponential and the laser pulse recorded by the same detection system. It is important to keep the laser intensity low enough to avoid transition saturation. A decay curve with the

excitation laser pulse and the fit is shown in Fig. 2. To make sure that the lifetime values are not affected by radiation trapping or collisions in the laser-produced plasma, measurements with different time delays between the atomization laser pulse and the excitation laser pulse were performed. We found that the lifetime values became constant after a 20-μs delay time. 30–40 curves have been recorded for each level, and only the measurements that have a delay time longer than 20 μs have been used for forming the average to obtain the final lifetime values. Two standard deviations have been taken as the error bar. In addition, we have an uncertainty of 0.08 ns to account for possible residual systematic effects. The results are shown in Table 1.

3 THE BRANCHING RATIO DETERMINATION

A diffraction grating based inductively coupled argon plasma emission spectrometer of medium resolution (spectral bandpass 4–18 pm, depending on wavelength and diffraction order) has been used to measure branching ratios (BRs) in Ge I. Calibration of the relative response of the spectrometer was made by means of known branching ratios of lines of Ar I, Ar II and Ni I. The Ar lines were emitted by an argon-filled hollow-cathode lamp mounted in the spectrometer in place of the inductively coupled plasma (ICP) torch, while Ni I lines were emitted by the ICP seeded with Ni. The Ar BRs were used to calibrate the region from ≈ 187 to

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⁵Tektronix Inc., 26600 SW Parkway, Wilsonville, OR 97070, USA.

≈ 900 nm, while Ni I was used to obtain more accurate calibration over a narrower range (295–385 nm). Further details of the BR calibration will be given elsewhere (Doidge, in preparation).

Two approaches to the measurement of the BRs of Ge I were tested. A neon-filled Ge hollow-cathode lamp operated at low current was used, and relative intensities of the 4p–5s lines were measured as a function of lamp current. It was found that, over the range of lamp currents studied (3–12 mA), the ratios of the intensities of lines belonging to a given upper level were not constant, and it was concluded that many of the Ge I lines studied were self-absorbed in the hollow-cathode lamp, under the conditions used. The self-absorption leads to underestimation of the BRs of emission lines ending in the lower levels, and overestimation of the lines ending on higher levels. With the ICP, by contrast, the intensity ratios of lines from common upper levels are practically constant (within 1 per cent) over several orders of magnitude of concentration of seeded elements in the plasma. This behaviour is a consequence of the well-known optical thinness of this discharge. The ICP was therefore used to measure the Ge I branching ratios reported here, and the intensity ratios were measured over a hundred-fold range of concentration of Ge.

The branching ratios measured with the Ge-seeded ICP are listed in column (3) of Table 2. By combining the BRs listed there with the lifetimes shown in Table 1 for the corresponding levels, the transition probabilities listed in column (4) of Table 2 were derived. The quoted errors are the sums, in quadrature, of the quoted uncertainties in the lifetimes (Table 1) and the estimated maximum uncertainties of the BR measurements; the latter were typically 5–10 per cent.

4 THE HFR CALCULATIONS

Some calculations of transition probabilities have also been carried out in the present work using the computer code written by Cowan (1981) within the framework of the relativistic Hartree–Fock (HFR) method. As we were interested in transitions involving low-excitation levels, the configuration sets have been limited to the Layzer complexes $n=4$ and $n=5$. The HFR technique was first used in combination with a least-squares optimization process of the Slater integrals. The experimental levels have been taken from the compilation of Sugar & Musgrove (1993). All the known energy levels belonging to the configurations $4s^2 4p^2$, $4p^5 p$, $4p^4 f$, $4p^5 f$ and $4p^5 s$, $4p^4 d$, $4p^5 d$ and $4s^4 p^3$ have been considered for the fitting procedure, with the exception of the two levels at 58 551.407 and 58 943.436 cm^{-1} ($4p^5 d$ configuration), the designations of which are uncertain in the compilation of Sugar & Musgrove (1993). It appears, however, that the fitting procedure was unsatisfying for some levels, particularly those belonging to the $4p^5 p$ and $4p^5 d$ configurations, the convergence being reached only with unrealistically low values of the Slater parameters. Consequently, in order to avoid distortion of the oscillator set values and loss of their accuracy, we have preferred to extend the set of configurations within the limits imposed by our computer code, and to adopt as final results those obtained through *ab initio* calculations (thus without any fitting). Configuration interaction has been finally considered using the following final set of 59 configurations: $4s^2 4p^2 + 4s^2 4pnp$ ($5 \leq n \leq 8$) + $4s^2 4pnf$ ($4 \leq n \leq 8$) + $4s^2 4d^2 + 4s^2 5s^2 + 4s^2 5p^2 + 4s^2 5d^2 + 4p^4 + 4s^4 p^2 5s + 4s^4 p^2 4d + 4s^4 p^2 5d + 4s^2 4d5s + 4s^2 4d5d + 4s^2 5s5d + 4s^2 4f5p + 4s^2 5p5f + 4p^3 5p + 4p^3 4f + 4p^3 5f + 4p^2 4d^2 + 4s^2 4d5g + 4s^2 5s5g + 4s^4 p^2 5g$ (even parity) and $4s^2 4pns$ ($5 \leq n \leq 8$) + $4s^2 4pnd$ ($4 \leq n \leq 8$) + $4s^2 4png$ ($5 \leq n \leq 8$) + $4s^4 p^3 + 4s^4 p^2 5p + 4s^4 p^2 4f + 4s^4 p^2 5f + 4s^2 4d5p + 4s^2 4d4f +$

$4s^2 4d5f + 4s^2 5s5p + 4s^2 4f5s + 4s^2 4f5d + 4s^2 5s5f + 4s^2 5p5d + 4p^3 5s + 4p^3 4d + 4p^3 5d + 4p^3 5g$ (odd parity).

According to a procedure described by Migdalek & Baylis (1978), core–valence correlation has been represented by a core polarization potential 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. The Cowan HFR code has been corrected accordingly and the procedure appears successful for providing accurate f -values in heavy ions like Yb II and Tm II (Biémont et al. 1998a,b; Quinet, Palmeri & Biémont 1998). The dipole polarizability of the ionic core, α_d , has been chosen to be equal to $4.05a_0^3$ for the $3d^{10}4s$ configuration, which corresponds to the value reported by Fraga, Karwowski & Saxena (1976). For the cut-off radius, r_c , we used the average value $\langle r \rangle$ for the outermost core orbital as calculated by the Cowan code, i.e. $\langle r \rangle = 1.897a_0$.

All the F^k , G^k and R^k integrals were scaled down by a factor of 0.85, while the spin–orbit integrals, ζ_{nl} , characterized by small numerical values, were used without scaling. It was found that the absolute values of the experimental levels and also the fine structure of the multiplets are generally nicely reproduced.

The HFR lifetime values are given in column (7) of Table 1, while the corresponding transition probabilities (A_{ki} , in units of 10^8 s^{-1}) are reported in column (5) of Table 2.

5 COMPARISON WITH PREVIOUS RESULTS

5.1 Radiative lifetimes

The laser lifetimes obtained in the present work and the HFR lifetimes, calculated according to the procedure described in Section 4, are compared, in Table 1, with previously published results. For the $5p^{1,3}P^o$ levels, the laser measurements are in nice agreement with the delayed-coincidence results of Tint, Kono & Goto (1990) while, for the same levels, the HFR results appear systematically and consistently smaller than the experimental ones, the mean ratio being remarkably constant: 1.171 ± 0.013 where the error represents the standard deviation. Similar findings have been reported previously in different ions when comparing HFR lifetimes with accurate beam-laser measurements [see e.g. the cases of Fe II (Biémont et al. 1991), Cr II (Pinnington et al. 1993) and Ag II (Biémont et al. 1997)]. The beam-foil results of Andersen, Petkov & Sorensen (1975) are systematically lower than the laser measurements but should be less accurate. The delayed-coincidence results of Komarovskii & Verolainen (1989), on the other hand, are considerably larger than all the other experimental results. This finding seems to indicate systematic errors in their measurements.

5.2 Oscillator strengths

The HFR oscillator strengths calculated in the present work are reported in Table 3, where they are compared with previous results published after 1974. We report also in the same table, under the label ‘EXP’, the f -values deduced from the laser lifetime and branching fraction measurements of the present work.

Holmgren & Garpman (1974) have calculated transition probabilities for the $np(n+1)s$ – np^2 transition array in the Group IV elements using relativistic self-consistent-field wavefunctions. As it appears from Table 3 (label ‘HG’), the HFR results (also calculated in the length formation) and the EXP data are systematically lower than the length form data of Holmgren & Garpman (1974) (the

Table 3. Ge I: comparison of the oscillator strengths ($\log gf$) obtained in this work for the $4p^2-4p5s$ transitions with previous results.

Transition	λ (nm)	This work		PREVIOUS RESULTS									
		HFR	EXP	LCGJ	PMSL	HG	MPPR	L	G	BMM		WM	
						V				L	L		V
$^3P_0-^1P^o_1$	249.79625	-1.60	-1.51	-1.42	-1.38	-1.95	-1.51	-1.44	-1.79	-1.80	-1.39	-1.33	-1.44
$^3P_1-^1P^o_1$	253.32305	-1.63	-1.61	-1.51	-1.50	-1.87	-1.56	-1.55	-1.72	-1.74	-1.72	-1.99	-1.54
$^3P_2-^1P^o_1$	258.91878	-1.94	-1.92	-1.82	-1.77	-2.42	-1.85	-1.82	-2.29	-2.26	-2.22	-1.94	-1.81
$^3P_1-^3P^o_2$	259.25340	-0.45	-0.52	-0.41	-0.48	-0.76	-0.44	-0.51	-0.63	-0.64	-0.44	-0.70	-0.45
$^3P_2-^3P^o_2$	265.11720	0.01	-0.07	-0.06	0.00	-0.27	0.05	-0.06	-0.17	-0.19	0.00	-0.19	0.02
$^3P_0-^3P^o_1$	265.15683	-0.60	-0.66	-0.59	-0.63	-0.88	-0.58	-0.65	-0.77	-0.80	-0.60	-0.85	-0.57
$^3P_1-^3P^o_1$	269.13411	-0.75	-0.81	-0.77	-0.76	-1.02	-0.69	-0.82	-0.93	-0.94	-0.73	-0.91	-0.70
$^3P_1-^3P^o_0$	270.96237	-0.57	-0.64	-0.52	-0.60	-0.83	-0.50	-0.65	-0.75	-0.76	-0.57	-0.74	-0.51
$^3P_2-^3P^o_1$	275.45878	-0.48	-0.57	-0.51	-0.48	-0.72	-0.40	-0.55	-0.65	-0.67	-0.48	-0.67	-0.43
$^1D_2-^1P^o_1$	303.90671	-0.01	-0.07	0.02	0.02	-0.13	0.08	-0.04	-0.15	-0.15	0.04	-0.19	0.07
$^1D_2-^3P^o_2$	312.48164	-2.22	-1.93	-1.64	-1.62	-2.08	-1.70	-1.77	-2.12	-2.12	-2.10	-2.10	-1.64
$^1D_2-^3P^o_1$	326.94899	-1.03	-1.08	-0.92	-0.75	-1.08	-0.90	-0.92	-1.15	-1.19	-1.07	-1.32	-0.86
$^1S_0-^1P^o_1$	422.65625	-0.86	-1.12	-0.77	-0.77	-0.68	-0.74	-0.86	-0.98	-1.00	-0.80	-1.31	-0.77
$^1S_0-^3P^o_1$	468.58286	-1.98	-2.31	-2.01	-1.49	-1.68	-1.92	-2.01	-2.07	-2.10	-2.00	-2.55	-1.03

HFR, EXP: this work (see the text); LCGJ: Lotrian et al. (1978); PMSL: Pokrzywska et al. (1985); HG: Holmgren & Garpman (1974); MPPR: Musiol et al. (1996); G: Ganas (1989); BMM: Bieron et al. (1991); WM: Wiese & Martin (1980). 'L' denotes length and 'V' velocity.

mean deviation for 14 lines being $\bar{\Delta} = 0.104$ and 0.154 dex, respectively). Larger discrepancies are observed when the velocity form results are considered. However, the fact that the length-velocity agreement is not good in HG calculations indicates that the quality of the self-consistent field (SCF) wavefunctions could be substantially improved.

Emission measurements have been reported by Lotrian et al. (1978) (heading 'LCGJ' in Table 3) for 27 transitions of Ge I. Branching ratios have been measured in the spectral range 190.0–470.0 nm, and the absolute scale for the transition probabilities has been established on the basis of the lifetime measurements of Andersen et al. (1975). The agreement with the HFR calculations is satisfying for the $4p^2-4p5s$ transitions, with the exception of the intercombination line situated at 312.4816 nm. When comparing with the experimental results of the present work, large discrepancies are observed for the lines of astrophysical interest appearing at 312.48, 326.95, 422.66 and 468.58 nm.

Ganas (1989) has considered a semi-empirical, analytical, atomic independent particle model potential adjusted to experimental single-particle energy levels to calculate optical oscillator strengths for $4p^2-5s^2$ $^3P_0-^3P^o_1$ and $4p^2-5s^2$ $^3P_1-^3P^o_1$ transitions. His result for the $4p-5s$ transition ($f = 0.2225$) agrees well with the HFR value ($f = 0.2512$).

Relative transition probabilities of the $4p^2-4p5s$ and $4p^2-4p4d$ transitions have been measured in emission by Pokrzywska et al. (1985) with a wall-stabilized arc. The results have been put on an absolute scale using the beam-foil lifetimes measured by Andersen et al. (1975). More recently, the results of Pokrzywska et al. (1985) have been revised by Musiol et al. (1996), who used a similar technique (wall-stabilized arc) and normalized their results with the delayed-coincidence measurements of Tint et al. (1990). The set of results of Musiol et al. for the 14 $4p-5s$ transitions differs by $\bar{\Delta} = 0.136$ dex from the HFR results.

The excitation energies and oscillator strengths of the $np^2-np(n+1)s$ transitions of Ge I have been calculated by Bieron, Marcinek & Migdalek (1991) using the relativistic configuration interaction (CI) approach. The Multiconfiguration Dirac-Fock (MCDHF) results obtained with the extended average level (EAL) option using the longest basis (multiconfiguration + CI approach)

agree reasonably well in the Babushkin gauge with the HFR results for the $\Delta S = 0$ transitions ($\bar{\Delta} = 0.10$ dex for eight $4p^2-4p5s$ transitions). For the weaker intercombination lines, for which length and velocity form results differ substantially, the differences are somewhat larger ($\bar{\Delta} = 0.15$ dex for six transitions).

6 SOLAR IMPLICATIONS OF THE RESULTS

Ge I has been observed in the solar photospheric spectrum, and five Fraunhofer lines attributed to Ge I are quoted by Moore et al. (1966) in their 'Preliminary Table of Solar Wavelengths': three lines appear in the UV region ($\lambda = 303.9067$, 312.4816 and 326.9489 nm), the two additional ones being observed at 422.6563 and 468.5829 nm. Ge I has been the subject of different abundance determinations. Among the most recent attempts, let us mention the work of Lambert, Mallia & Warner (1969), who deduced $A_{\text{Ge}} = 3.32$ on the standard logarithmic scale, where $\log N(\text{H}) = 12.00$, and Ross & Aller (1974, 1976), who obtained $A_{\text{Ge}} = 3.50 \pm 0.08$. These results were discussed by Biémont & Grevesse (1977), who showed that using the beam-foil lifetime values measured by Andersen et al. (1975) to renormalize the f -values would lead to an increase of Lambert et al.'s result to 3.48 and a decrease of Ross & Aller's (1974, 1976) abundance to 3.34! The abundance quoted by Anders & Grevesse (1989) in their recent compilation is 3.41 ± 0.14 , which is lower by 0.22 dex than the meteoritic abundance ($A_{\text{Ge}} = 3.63 \pm 0.04$) proposed in the same compilation. Grevesse & Meyer (1985) have suggested that the discrepancy photosphere-meteorites for this element could be real and would imply chemical enrichment in CI chondrites. This conclusion has been reconsidered, however, by Anders & Grevesse (1989), who noticed that germanium is indeed depleted in all other chondrite classes, like other elements of similar volatility. This fact apparently reflects volatile loss during chondrule formation, in agreement with the conclusions of Larimer & Anders (1967), but there is no specific reason why germanium behaviour should appear different from that of other elements of similar volatility. On the basis of the new atomic data obtained in the present work, it is interesting to consider again the observed discrepancy between the Solar and meteoritic abundances.

For that purpose, we have reconsidered carefully the five absorption features observed in the photospheric spectrum and attributed at least in part to germanium. The two absorption lines at 312.4816 and 422.6563 nm are strongly perturbed and consequently cannot be used for an abundance determination.

The line at 303.9067 nm has been considered by Ross & Aller (1974). The abundance obtained by these authors is 3.45 (in the usual logarithmic scale) using $\log gf = -0.15$. The experimental oscillator strength obtained in the present work would lower this value to 3.37. As this line is strongly blended and appears in a spectral region where the continuum is badly located, we consider it as a poor abundance indicator and we have preferred not to retain it for the final analysis.

The weak line at 468.5829 nm can be easily measured on the photospheric spectrum and has been used by Lambert et al. (1969) in their abundance determination. Unfortunately, this line is blended with a Co I transition appearing at 468.5856 nm. An additional blend of unknown origin has been mentioned by Grevesse & Meyer (1985) as affecting the red wing of the profile. Consequently, we do not feel that this line is suitable for an accurate abundance determination.

We are left with the only transition at 326.9489 nm. Using an oscillator strength ($\log gf = -1.15$) derived by Lawrence (1967), Ross & Aller (1974) deduced $A_{\text{Ge}} = 3.53$ from a detailed spectral synthesis. Grevesse & Meyer (1985) obtained an abundance value of 3.46 [using $\log gf = -0.92$ as derived from the lifetime measurements of Andersen et al. (1975) and branching fractions from Lotrian et al. (1978)]. We have remeasured the equivalent width of this line on enlargements of the high-resolution *Jungfraujoch* spectra (Delbouille, Neven & Rowland 1973), and we obtain an equivalent width $W_\lambda = 42.6 \text{ mÅ}$ which is very close to the value measured by Grevesse & Meyer (1985) ($W_\lambda = 43.3 \text{ mÅ}$). Using a method of direct integration of the line profiles with the Holweger & Müller (1974) model atmosphere, a microturbulence of 0.85 km s^{-1} and partition functions for Ge I and Ge II recalculated on the basis of the energy levels presently available, we obtain $A_{\text{Ge}} = 3.58 \pm 0.05$ where the uncertainty represents an estimate of the error affecting the oscillator strengths and the equivalent width. This result, which represents the best estimate of the solar abundance of germanium, is now very close to the meteoritic result as adopted by Anders & Grevesse (1989): $A_{\text{Ge}} = 3.63 \pm 0.04$.

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