

OSCILLATOR STRENGTHS FOR Y I AND Y II AND THE SOLAR ABUNDANCE OF YTTRIUM

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ABSTRACT

Oscillator strengths have been determined from measurements of radiative lifetimes and branching ratios for 154 lines of Y I and 66 lines of Y II. These data are used, together with equivalent widths measured on the Jungfraujoch solar atlas, to perform a new determination of the solar abundance of yttrium: $A_Y = 2.24 \pm 0.03$.

Subject headings: laboratory spectra — Sun: abundances — transition probabilities

I. INTRODUCTION

One of the first determinations of the solar abundance of yttrium was made by Goldberg, Müller, and Aller (1960). Using Coulomb-approximation and f -sum rule oscillator strengths, they found $A_Y = 1.4$ for Y I lines originating from the ground term ($E_{\text{low}} \approx 0.0$ eV) and $A_Y = 3.1$ for Y I lines with $E_{\text{low}} \approx 1.4$ eV [where A_Y means $\log(N_Y/N_H) + 12.0$ in the usual scale].

More recently, the experimental transition probabilities of Corliss and Bozman (1962; hereafter CB) have been used by various authors to derive new solar abundances of yttrium. Aller (1965), from a study of 14 Y I lines, found $A_Y = 3.2$; whereas Wallerstein (1966), using nine Y II lines, found $A_Y = 2.1$. Grevesse, Blanquet, and Boursy (1968) analyzed both Y I and Y II lines and found a discrepancy similar to that reported by Goldberg, Müller, and Aller—i.e., $A_Y = 2.33$ for Y I lines with $E_{\text{low}} \approx 0$ eV, $A_Y = 4.19$ for Y I lines with $E_{\text{low}} \approx 1.4$ eV, and $A_Y = 2.42$ for Y II lines.

Krueger *et al.* (1968) computed transition probabilities for Y II using the Hartree-Fock self-consistent field method and derived $A_Y = 1.43 \pm 0.35$ from a large number of lines. Allen and Cowley (1974) and Allen (1976) used the same set of f -values to obtain A_Y from a smaller number of lines and obtained $A_Y = 2.0$ and $A_Y = 2.18$, respectively.

Recently, Andersen, Ramanujam, and Bahr (1978) measured lifetimes of excited states in Y I and Y II by the beam-foil and beam-sputtering techniques. They normalized older sets of f -values to their lifetimes and revised the solar abundance of yttrium to $A_Y = 2.35$.

Since their publication in 1962, the transition probabilities of CB have been shown to contain significant excitation-dependent, wavelength-dependent, and intensity-dependent errors (see, e.g., Biémont *et al.* 1981). In addition, Allen (1977) has reported a large scatter in abundance values derived using the theoretical f -values of Krueger *et al.* (1968), while Hannaford and Lowe (1981, 1982) and Poulsen *et al.* (1981) have shown that many of the beam-sputtering lifetimes of Andersen, Ramanujam, and Bahr (1978) are too large by significant amounts. For these reasons, and because of the rather large discrepancies which exist between the different sets of f -values available, we have determined a new set of oscillator strengths for a large number of Y I and Y II lines by combining lifetime and branching-ratio measurements. The new f -values are used with equivalent widths measured on the Jungfraujoch solar atlas (Delbouille, Neven, and Roland 1973) to derive the solar abundance of yttrium. Implications of the new f -values for stellar abundance studies are briefly discussed.

II. YTTRIUM TRANSITION PROBABILITIES

a) Lifetime Measurements

The method used to determine lifetimes is the same as that described previously (Hannaford and Lowe 1981, 1982). With this method, an atomic vapor of yttrium is produced by cathodic sputtering in a low-pressure neon discharge and selectively excited by short optical pulses from a nitrogen-laser pumped dye laser. The time decay of the emitted atomic fluorescence is then recorded and the radiative lifetime determined from the decay curve. The system was tested by measuring the lifetimes of eight well-established levels of Ca,

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Al, Na, Cr, Fe, and U which span the range 4–200 ns (Hannaford and Lowe 1981). This includes the range of lifetimes for nearly all the Y I and Y II levels under investigation. Also, lifetimes obtained for a large number of Zr I and Zr II levels with this system have been found to yield consistent Zr abundance values with a low dispersion (Biémont *et al.* 1981). In all cases, checks were made for the presence of radiation trapping and effects due to collisional depopulation by the rare gas.

Our measured lifetimes for 34 levels of Y I and 14 levels of Y II are presented in Tables 1 and 2. For five of the quartet Y I levels below $28,000\text{ cm}^{-1}$, experimental difficulties precluded accurate measurement of the required lifetimes, and in these cases, the lifetimes quoted in Table 1 were measured for a different level of the same term. Measurements of the lifetimes of a number of levels for these terms indicated that within each term the lifetimes of the various levels are essentially constant within the quoted uncertainties.

For Y I, lifetime measurements have previously been reported for only the nine lowest levels in Table 1. Our values (Hannaford and Lowe 1982) are found to be shorter, by factors of between 1.5 and 1.9, than the five beam-foil and beam-sputtering results of Andersen, Ramanujam, and Bahr (1978). They also differ appreciably, by factors ranging from 0.7 to 2.7, from the Hanle and level-crossing results of Beer (1970, 1971) for six levels. However, our data are in excellent agreement with very recent, delayed-coincidence results of Rudolph and Helbig (1982) for all except the $z^2D_{5/2}^{\circ}$ level, for which our value is larger by a factor of 1.4. Our data are also consistent with relative lifetimes derived from recent, relative f -values obtained using the hook method (Cardon, Parkinson, and Tomkins 1980).

For Y II, our lifetimes are systematically lower than the only other direct measurements (Andersen, Ramanujam, and Bahr 1978; beam-foil method), by factors ranging from 0.67 to 0.94.

b) Branching Ratios

Branching ratios were measured on spectra recorded with the 1 m Fourier transform spectrometer (FTS) (Brault 1976) at the Kitt Peak National Observatory. The source of the spectra was a water-cooled hollow-cathode discharge lamp in which the cathode cavity (3 mm diameter, 18 mm long) was fashioned from sintered yttrium powder (99.9% purity). High-purity argon at 0.6 torr flowed continuously through the cathode cavity. The only impurity lines were YO bands.

The FTS mirrors scanned through 13.9 cm to provide a theoretical resolution of 0.043 cm^{-1} . The width of the observed line profiles was 0.10 cm^{-1} (FWHM). Although the high resolution offers good protection from blends, we also examined a Fe/Ar hollow-cathode spectrum to ensure that there were no argon lines coincident with the yttrium lines of interest.

As a test for self-absorption in the source, three spectra were recorded at different power levels that varied the excitation of the Y I quartet odd levels around $17,000\text{ cm}^{-1}$ by a factor of 40, and all branching ratios were measured on each of the three spectra. No significant absorption was observed for any Y II transitions. However, strong Y I transitions to the ground state showed some absorption in the brightest spectrum, and this spectrum was used to measure only the weakest transitions.

The area under the line profile on the transformed spectrum was integrated over ± 10 FWHM on either side of line center to obtain the observed line intensity $A(\lambda)$ in units of photons s^{-1} . The relative line intensity is then given by $I(\lambda) = A(\lambda)/E(\lambda)$, where $E(\lambda)$ is the relative detection efficiency of the spectrometer system. The detection efficiency, $E(\lambda)$, was measured using argon branching ratios as an internal calibration standard. The observed intensities of families of argon lines emitted from common upper levels were measured on the same Y/Ar spectra used for the yttrium measurements and compared with the known relative intensity of these argon lines (Adams and Whaling 1981). Sixty-five argon lines, covering the range 2900–8900 Å, were used in this calibration. We also recorded the FTS response to an incandescent, spectral-continuum source to ensure that smooth interpolation between the 65 individual measurements is justified.

The branching ratio $R(\lambda_1)$ for the transition λ_1 is then $R(\lambda_1) = I(\lambda_1)/\sum I(\lambda_i)$, where the sum in the denominator includes all transitions by which the upper level decays. We have used the Y I and Y II energy levels of Palmer (1977) to compute all transitions with parity change and $\Delta J = \pm 1, 0$ and have examined our recorded spectra for the predicted wavelengths between 2900 Å and 9000 Å. By this means, we have set an upper limit, based on the noise level, for any transitions not observed in this wavelength range. This limit does not exceed 1%. Two transitions, 2667.59 Å and 2705.88 Å from the Y I $y^4P_{5/2}^{\circ}$ level, are below the blue cutoff of our spectra, but of these, Palmer (1977) detected only the 2705.88 Å line and found it to be only about 1% as strong as the 4513.58 Å line from the same upper level, a transition that we find to be a 12% branch. Palmer has also observed many transitions from Y I levels in the 9000–33000 Å range and, in particular, strong infrared transitions from the low-excitation doublet levels $z^2D_{3/2,5/2}^{\circ}$, $z^2F_{5/2,7/2}^{\circ}$, $y^2P_{3/2}^{\circ}$, and $y^2F_{5/2,7/2}^{\circ}$. The effect of unseen infrared branches on our measured branching ratios has been estimated from a comparison of the f -values derived from our measured branching ratios with relative f -values obtained by the hook method (Cardon, Parkinson, and Tomkins 1980). The method of correction is outlined in the Appendix. The corrections to the branching ratios amount to approximately 15% for the 14 transitions originating from the above low-excitation doublet levels. The branching ratios (and f -values) given in Table

TABLE 1
LIFETIMES, BRANCHING RATIOS, AND OSCILLATOR STRENGTHS FOR Y I LINES

UPPER LEVEL		LOWER LEVEL	λ (Å) ^a	BRANCHING RATIO (%)	f	
Level, E (cm ⁻¹)	τ (ns)				This Work	Others ^b
$z^2D_{3/2}^o$, 16,066	185 (10) ^c	$a^2D_{3/2}$	6222.579	10.8 (1.8) ^d	0.0051 (9) ^d	0.0017
		$a^2D_{5/2}$	6435.022	75 (13) ^d	0.025 (4) ^d	0.0043
$z^2D_{3/2}^o$, 16,146	175 (10) ^c	$a^2D_{3/2}$	6191.720	81 (14) ^d	0.027 (5) ^d	0.0068
		$a^2D_{5/2}$	6402.007	4.7 (8) ^d	0.0011 (2) ^d	0.0032
$z^2F_{5/2}^o$, 21,529	40 (1)	$a^2D_{3/2}$	4643.698	72 (12) ^d	0.088 (15) ^d	0.030, 0.048 ^e
		$a^2D_{5/2}$	{4760.978}	14 (2) ^d	0.0117 (20) ^d	0.0045, 0.0061 ^e
$z^2F_{7/2}^o$, 21,915	64 (1) ^c	$a^2D_{5/2}$	4674.848	85 (15) ^d	0.058 (10) ^d	0.023, 0.031 ^e
$y^2D_{3/2}^o$, 24,131 ...	5.3 (2) ^c	$a^2D_{3/2}$	4142.841	84.1 (3)	0.41 (1)	0.20, 0.20 ^e
$y^2P_{3/2}^o$, 24,481	15.4 (3) ^c	$a^2D_{5/2}$	4235.929	15.9 (2)	0.054 (2)	0.042, 0.022 ^e
		$a^2D_{3/2}$	4083.705	39 (7) ^d	0.063 (10) ^d	0.058, 0.029 ^e
$y^2F_{5/2}^o$, 24,519	6.3 (2) ^c	$a^2D_{5/2}$	{4174.133}	47 (8) ^d	0.053 (9) ^d	0.040, 0.029 ^e
		$a^2D_{3/2}$	4077.359	70 (12) ^d	0.42 (7) ^d	0.28, 0.26 ^e
$y^2D_{5/2}^o$, 24,747	6.0 (2) ^c	$a^2D_{5/2}$	4167.513	15 (3) ^d	0.062 (11) ^d	0.048, 0.034 ^e
		$a^2D_{3/2}$	{4039.826}	6.7 (1)	0.0411 (15)	0.028, 0.017 ^e
$y^2F_{7/2}^o$, 24,899	6.7 (2) ^c	$a^2D_{5/2}$	4128.304 ^f	93.3 (4)	0.40 (1)	0.18, 0.17 ^e
		$a^2D_{3/2}$	4102.364	85 (15)	0.43 (7)	0.22, 0.24 ^e
$x^2P_{3/2}^o$, 28,140	3.9 (2)	$a^2D_{5/2}$	3552.691	8.9 (2)	0.043 (1)	0.038, 0.017 ^e
		$a^2D_{3/2}$	{3620.940}	91.1 (1)	0.307 (15)	0.20, 0.15 ^e
$z^4G_{5/2}^o$, 28,694	16.6 (1.0), ($J=9/2$) ^g	$a^2D_{3/2}$	3484.048	2.0 (2)	0.0033 (3)	
		$a^2D_{5/2}$	3549.659	0.17 (2)	0.00019 (2)	
		$a^4F_{3/2}$	5630.138	81.9 (3)	0.35 (2)	0.093
		$a^4F_{5/2}$	5675.267	15.3 (2)	0.045 (3)	0.010
$z^4G_{9/2}^o$, 29,364	16.6 (1.0)	$a^4F_{7/2}$	5740.218	0.66 (3)	0.015 (1)	
		$a^4F_{7/2}$	5527.561	90.3 (1)	0.31 (2)	0.070
		$a^4F_{9/2}$	5606.335	9.7 (2)	0.0275 (15)	0.0093
		$a^4F_{9/2}$	5466.467	100	0.34 (2)	0.059
$z^4G_{11/2}^o$, 29,820 ...	15.7 (1.0)	$a^4F_{9/2}$	5466.467	100	0.34 (2)	0.059
$y^4F_{3/2}^o$, 31,508	10.1 (1.0), ($J=5/2$) ^g	$a^2D_{3/2}$	3172.835	1.02 (7)	0.0015 (2)	
		$a^2D_{5/2}$	3227.156 ^h	0.11 (1)	0.000115 (15)	
		$a^4F_{3/2}$	4859.841	73.3 (1)	0.257 (25)	0.098
		$a^4F_{5/2}$	4893.436	22.4 (1.0)	0.053 (6)	0.018
$y^4F_{5/2}^o$, 31,680	10.1 (1.0)	$b^2D_{3/2}$	6443.845 ^h	3.2 (1.5)	0.02 (1)	
		$a^2D_{3/2}$	3155.647	0.27 (2)	0.00060 (7)	
		$a^2D_{5/2}$	3209.377	0.30 (2)	0.00046 (5)	
		$a^4F_{3/2}$	{4819.639}	16.0 (4)	0.083 (9)	0.043
$y^4F_{7/2}^o$, 31,909	10.5 (1.0)	$a^4F_{5/2}$	4852.682	63.4 (6)	0.22 (2)	0.082
		$a^4F_{7/2}$	4900.084 ^h	20.0 (4)	0.054 (5)	
		$a^2D_{5/2}$	3185.956 ^f	0.13 (1)	0.00025 (3)	
		$a^4F_{5/2}$	4799.301	16.5 (3)	0.072 (7)	0.037
$y^4F_{9/2}^o$, 32,188	10.4 (1.0)	$a^4F_{7/2}$	4845.668	70.3 (7)	0.24 (2)	0.089
		$a^4F_{9/2}$	4906.108	13.1 (3)	0.036 (4)	0.011
		$a^4F_{7/2}$	4781.033	10.5 (2)	0.043 (4)	0.020
		$a^4F_{9/2}$	{4839.866}	89.5 (3)	0.30 (3)	0.11
$e^4D_{1/2}$, 33,148	15 (3)	$z^4F_{3/2}^o$	5493.148	53.6 (4)	0.08 (2)	0.033
		$z^2D_{3/2}^o$	5879.929	12.8 (1.5)	0.022 (6)	0.016
		$z^4D_{1/2}^o$	{5981.881}	21.4 (4.5)	0.08 (2)	0.070
		$z^4P_{1/2}^o$	{7054.189}	12.2 (5.5)	0.06 (3)	0.047
$y^4D_{1/2}^o$, 33,215 ...	6.7 (3), ($J=3/2$) ^g	$a^4F_{3/2}$	{4487.460}	100	0.23 (1)	0.13
$e^4D_{3/2}$, 33,238	15 (3), ($J=1/2$) ^g	$z^4F_{3/2}^o$	5466.242	15.8 (1.5)	0.047 (15)	0.15
		$z^4F_{5/2}^o$	5556.417	33.6 (1.5)	0.07 (2)	0.028
		$z^2D_{5/2}^o$	{5821.838}	9.7 (7)	0.022 (7)	0.013
		$z^4D_{1/2}^o$	5949.987	8.6 (1.0)	0.06 (2)	
		$z^4D_{3/2}^o$	6087.934	16.4 (1.0)	0.041 (15)	0.027
		$z^4P_{1/2}^o$	7009.883	6.6 (1.0)	0.065 (25)	0.034
		$z^4P_{3/2}^o$	7035.150	9.4 (1.5)	0.047 (15)	0.035

TABLE 1—Continued

UPPER LEVEL		LOWER LEVEL	λ (Å) ^a	BRANCHING RATIO (%)	<i>f</i>	
Level, <i>E</i> (cm ⁻¹)	τ (ns)				This Work	Others ^b
$y^4D_{3/2}^o$, 33,265 ...	6.7 (3)	$a^2D_{3/2}$	3005.262	3.2 (2)	0.0065 (4)	0.011, 0.0037 ^c
		$a^2D_{5/2}$	3053.951 ^h	0.13 (4)	0.00018 (6)	
		$a^4F_{3/2}$	{4477.442}	21.4 (8)	0.096 (5)	0.070
		$a^4F_{5/2}$	{4505.948}	71.8 (6)	0.218 (10)	0.15
		$a^2F_{5/2}$	5573.033	1.2 (1)	0.0056 (6)	
		$a^4P_{3/2}$	5619.962	1.33 (10)	0.0063 (6)	
		$b^2D_{3/2}$	5788.361	0.63 (15)	0.0047 (10)	
		$b^2D_{5/2}$	5844.131	0.38 (20)	0.0019 (9)	
$y^4D_{5/2}^o$, 33,358	6.9 (3)	$a^2D_{3/2}$	2996.939	5.8 (2)	0.017 (1)	0.022, 0.0085 ^c
		$a^2D_{5/2}$	3045.363	7.4 (3)	0.0149 (9)	0.022, 0.0078 ^c
		$a^4F_{3/2}$	4459.010	1.22 (7)	0.0079 (6)	
		$a^4F_{5/2}$	{4487.279}	13.9 (3)	0.061 (3)	0.033
		$a^4F_{7/2}$	4527.783	57.5 (6)	0.192 (10)	0.104
		$a^2F_{5/2}$	{5544.504}	8.9 (3)	0.060 (3)	0.047
		$a^2F_{7/2}$	5714.944	1.41 (7)	0.0075 (5)	
		$a^4P_{5/2}$	{5590.952}	3.36 (15)	0.0229 (15)	0.0083
		$b^2D_{3/2}$	5757.589	0.53 (5)	0.0057 (6)	
		$a^2D_{3/2}$	2974.588	24.3 (5)	0.070 (4)	0.080, 0.038 ^c
		$a^2D_{5/2}$	3022.281	4.54 (15)	0.0090 (6)	0.010, 0.0043 ^c
		$a^4F_{3/2}$	4409.700	0.19 (6)	0.0012 (4)	
$x^2F_{5/2}^o$, 33,608	6.9 (4)	$a^4F_{5/2}$	4437.340	5.94 (10)	0.0255 (15)	0.025
		$a^4F_{7/2}$	4476.952	18.8 (4)	0.062 (4)	0.044
		$a^2F_{5/2}$	{5468.470}	26.1 (5)	0.17 (1)	0.042
		$a^2F_{7/2}$	5634.198	0.15 (7)	0.0008 (4)	
		$a^4P_{3/2}$	5469.104	0.25 (9)	0.0024 (7)	
		$a^4P_{5/2}$	5513.648	16.4 (3)	0.109 (7)	0.025
		$b^2D_{3/2}$	5675.641	2.9 (1)	0.031 (2)	
		$b^2D_{5/2}$	5729.253	0.16 (8)	0.0011 (5)	
		$a^2G_{7/2}$	6622.481	0.31 (8)	0.0022 (5)	0.0095
		$z^4F_{5/2}^o$	5401.877	0.9 (4)	0.0035 (20)	
		$z^4F_{7/2}^o$	5541.629	7.8 (4)	0.024 (8)	0.012
		$z^4F_{9/2}^o$	{5706.714}	44.7 (8)	0.12 (4)	0.047
		$z^4D_{5/2}^o$	5902.912	6.1 (4)	0.028 (10)	0.020
		$z^4D_{7/2}^o$	{6009.183}	29.2 (10)	0.11 (3)	0.049
$z^2G_{9/2}^o$, 33,789	20.5 (2.0)	$z^4P_{5/2}^o$	6845.195	11.3 (6)	0.07 (2)	0.048
		$a^4F_{9/2}$	4491.740	4.7 (3)	0.0069 (8)	0.0062
		$a^2F_{7/2}$	{5577.416}	64.8 (7)	0.18 (2)	0.060
		$a^2G_{9/2}$	6538.568	30.5 (9)	0.096 (9)	0.039
$x^2D_{3/2}^o$, 33,907	7.0 (3)	$a^2D_{3/2}$	2948.406	24.9 (5)	0.046 (2)	0.068, 0.028 ^c
		$a^2D_{5/2}$	2995.257	3.6 (1)	0.0046 (2)	0.0085, 0.0029 ^c
		$a^4F_{3/2}$	4352.404	0.46 (5)	0.0019 (2)	0.033
		$a^4F_{5/2}$	4379.327	5.5 (1)	0.150 (8)	0.027
		$a^2F_{5/2}$	5380.629	22.4 (5)	0.093 (5)	0.032
		$a^4P_{3/2}$	5381.244	0.68 (14)	0.0043 (9)	
		$a^4P_{5/2}$	5424.362	24.4 (5)	0.102 (6)	0.038
		$b^2D_{3/2}$	{5581.077}	7.8 (2)	0.052 (3)	0.017
		$b^2D_{5/2}$	{5632.907}	5.2 (2)	0.024 (1)	0.0098
		$a^2P_{1/2}$	6815.146	5.0 (1.2)	0.100 (24)	0.070
		$a^2D_{5/2}$	2984.254	35.4 (1.0)	0.085 (3)	0.093, 0.045 ^c
		$a^4F_{7/2}$	4394.007	1.44 (10)	0.0056 (4)	0.0079
$x^2F_{7/2}^o$, 34,030	7.4 (2)	$a^4F_{9/2}$	4443.652	7.7 (4)	0.025 (1)	0.022
		$a^2F_{5/2}$	{5503.464}	47.3 (10)	0.39 (2)	0.14
		$a^4P_{5/2}$	5388.388	0.83 (10)	0.0065 (9)	
		$b^2D_{5/2}$	5594.124	3.7 (2)	0.031 (2)	0.010
		$a^2G_{9/2}$	6437.170	3.6 (5)	0.024 (4)	0.010

TABLE 1—Continued

UPPER LEVEL		LOWER LEVEL	λ (Å) ^a	BRANCHING RATIO (%)	<i>f</i>	
Level, <i>E</i> (cm ⁻¹)	τ (ns)				This Work	Others ^b
<i>e</i> ⁴ <i>P</i> _{3/2} , 34,156	15 (4)	<i>z</i> ² <i>P</i> _{1/2} ^o	4231.302	1.80 (10)	0.006 (2)	
		<i>z</i> ² <i>P</i> _{3/2} ^o	4385.474	10.4 (3)	0.020 (5)	0.016
		<i>z</i> ⁴ <i>F</i> _{3/2} ^o	5205.011	1.25 (25)	0.0034 (10)	
		<i>z</i> ² <i>D</i> _{5/2} ^o	5526.427 ^h	0.60 (2)	0.0012 (5)	
		<i>z</i> ² <i>D</i> _{3/2} ^o	5550.998	10.4 (3)	0.032 (6)	
		<i>z</i> ⁴ <i>D</i> _{1/2} ^o	5641.774	2.75 (10)	0.018 (5)	
		<i>z</i> ⁴ <i>D</i> _{3/2} ^o	5693.633	16.8 (4)	0.055 (15)	
		<i>z</i> ⁴ <i>D</i> _{5/2} ^o	{5765.656}	56.0 (4)	0.12 (3)	0.040
<i>e</i> ² <i>D</i> _{5/2} , 34,257	23 (4)	<i>z</i> ² <i>P</i> _{3/2} ^o	4366.024	31.4 (6)	0.06 (2)	0.065
		<i>z</i> ⁴ <i>F</i> _{5/2} ^o	5258.474	0.65 (20)	0.0012 (4)	
		<i>z</i> ⁴ <i>F</i> _{7/2} ^o	5390.813	6.7 (3)	0.0095 (30)	
		<i>z</i> ² <i>D</i> _{3/2} ^o	5519.880	2.7 (2)	0.0081 (25)	
		<i>z</i> ² <i>D</i> _{5/2} ^o	{5495.580}	31.4 (3)	0.06 (2)	0.018
		<i>z</i> ⁴ <i>D</i> _{5/2} ^o	5732.090	17.4 (3)	0.037 (10)	0.012
		<i>z</i> ⁴ <i>D</i> _{7/2} ^o	{5832.250}	9.75 (20)	0.016 (5)	0.0091
		<i>a</i> ² <i>F</i> _{5/2}	4821.628	12.3 (2)	0.035 (2)	
<i>x</i> ⁴ <i>D</i> _{5/2} ^o , 36,061	12.0 (5)	<i>a</i> ² <i>F</i> _{7/2}	4950.005	2.37 (10)	0.0055 (3)	
		<i>a</i> ⁴ <i>P</i> _{3/2}	{4822.121}	60.7 (3)	0.265 (10)	0.12
		<i>a</i> ⁴ <i>P</i> _{5/2}	4856.714	24.1 (2)	0.071 (3)	0.033
		<i>b</i> ² <i>D</i> _{3/2}	4981.965	0.55 (8)	0.0026 (4)	
		<i>a</i> ² <i>F</i> _{5/2}	4804.313	24.2 (2)	0.060 (2)	0.033
<i>z</i> ⁴ <i>S</i> _{3/2} ^o , 36,136 ⁱ	9.3 (3)	<i>a</i> ⁴ <i>P</i> _{1/2}	4780.163	8.33 (9)	0.061 (2)	0.034
		<i>a</i> ⁴ <i>P</i> _{3/2}	4804.803	35.6 (3)	0.133 (4)	0.075
		<i>a</i> ⁴ <i>P</i> _{5/2}	{4839.147}	29.4 (3)	0.074 (2)	0.042
		<i>a</i> ² <i>D</i> _{3/2}	4963.489	1.29 (9)	0.0051 (4)	
		<i>a</i> ² <i>D</i> _{5/2}	5004.435	1.15 (15)	0.0031 (4)	
		<i>a</i> ² <i>F</i> _{5/2}	4581.325	15.1 (3)	0.032 (1)	0.033
<i>y</i> ⁴ <i>P</i> _{3/2} ^o , 37,148	9.8 (4)	<i>a</i> ⁴ <i>P</i> _{1/2}	4559.362	40.0 (4)	0.25 (1)	0.28
		<i>a</i> ⁴ <i>P</i> _{3/2}	{4581.771}	8.96 (9)	0.029 (1)	0.43
		<i>a</i> ⁴ <i>P</i> _{5/2}	4612.991	17.6 (2)	0.038 (2)	0.033
		<i>b</i> ² <i>D</i> _{3/2}	4725.842	14.2 (4)	0.049 (2)	0.078
		<i>b</i> ² <i>D</i> _{5/2}	4762.955	4.1 (2)	0.0095 (6)	
<i>y</i> ⁴ <i>P</i> _{5/2} ^o , 37,476	7.0 (2)	<i>a</i> ² <i>F</i> _{5/2}	{4513.575}	11.6 (1)	0.051 (2)	0.050
		<i>a</i> ⁴ <i>P</i> _{3/2}	4514.007	23.4 (2)	0.153 (5)	0.12
		<i>a</i> ⁴ <i>P</i> _{5/2}	4544.306	28.7 (2)	0.127 (4)	0.10
		<i>b</i> ² <i>D</i> _{3/2}	4653.784	10.9 (2)	0.076 (2)	
		<i>b</i> ² <i>D</i> _{5/2}	{4689.767}	23.7 (2)	0.112 (3)	0.078
		<i>a</i> ² <i>G</i> _{7/2}	5271.815 ^h	0.75 (20)	0.0034 (8)	
		<i>a</i> ² <i>P</i> _{3/2}	5532.566 ^h	0.95 (20)	0.009 (2)	
<i>f</i> ⁴ <i>D</i> _{7/2} , 38,866	23 (7)	<i>z</i> ⁴ <i>F</i> _{5/2} ^o	4232.541	4.50 (15)	0.007 (2)	
		<i>z</i> ⁴ <i>F</i> _{7/2} ^o	4317.863	3.35 (25)	0.004 (1)	
		<i>z</i> ⁴ <i>F</i> _{9/2} ^o	4417.431	7.35 (30)	0.0075 (20)	
		<i>z</i> ⁴ <i>D</i> _{5/2} ^o	4534.087	10.1 (3)	0.018 (6)	
		<i>z</i> ⁴ <i>D</i> _{7/2} ^o	{4596.528}	43.9 (4)	0.06 (2)	0.13
		<i>z</i> ⁴ <i>P</i> _{5/2} ^o	5070.187	30.8 (6)	0.07 (2)	0.11

NOTE.—Figures in parentheses represent uncertainty in last figure(s).
^aWavelengths are from Palmer 1977 unless otherwise noted. Underlined wavelengths are those used in the final solar abundance analysis.
Wavelengths within braces are lines examined in the solar spectrum but rejected from the final analysis for reasons outlined in the text.
^bValues are from CB unless otherwise noted.
^cFrom Hannaford and Lowe 1982.
^dValues corrected for unmeasured infrared branches.
^eCardon, Parkinson, and Tomkins 1980.
^fFrom MIT tables, Harrison 1939.
^gLifetime measured for different level (as indicated) of the same term.
^hCalculated from Palmer's term values.
ⁱThis level reclassified from *x*⁴*D*_{3/2}^o, according to Palmer 1977.

TABLE 2
LIFETIMES, BRANCHING RATIOS, AND OSCILLATOR STRENGTHS FOR Y II LINES

UPPER LEVEL		LOWER LEVEL	λ (Å) ^a	BRANCHING RATIO (%)	f	
Level, E (cm ⁻¹)	τ (ns)				This Work	Others ^b
$z^3P_0^o$, 23,445	54.7 (1.0)	a^3D_1	4422.588	100	0.0179 (4)	0.0087
$z^3P_1^o$, 23,776	51.5 (1.0)	a^1S_0	4204.694	11.3 (1)	0.0175 (4)	0.010, 0.019 ^c
		a^3D_1	4358.727	28.6 (3)	0.0158 (3)	0.0080, 0.098 ^c
		a^3D_2	4398.010	59.3 (3)	0.0201 (4)	0.011, 0.14 ^c , 0.074 ^d
		a^1D_2	4881.436	0.77 (6)	0.00032 (3)	0.022 ^c
$z^3P_2^o$, 24,647	56.8 (1.0)	a^3D_1	4199.274	3.04 (9)	0.00236 (9)	0.0014, 0.0088 ^c
		a^3D_2	4235.731	13.2 (2)	0.0063 (1)	0.0044, 0.049 ^c
		a^3D_3	4309.622	73.0 (3)	0.0256 (5)	0.016, 0.19 ^c
		a^1D_2	4682.325	10.7 (2)	0.0062 (2)	0.0022, 0.0041 ^c
$z^1D_2^o$, 26,147	6.3 (2)	a^3D_1	3950.356	17.5 (4)	0.109 (4)	0.067, 0.12 ^c
		a^3D_2	3982.600	17.1 (3)	0.065 (3)	0.032, 0.066 ^c
		a^1D_2	4374.946	62.7 (6)	0.286 (9)	0.14, 0.11 ^c
		a^3F_2	5509.896	2.67 (7)	0.0193 (8)	0.0042, 0.030 ^c
$z^3F_2^o$, 27,227	6.3 (3)	a^3D_1	3788.697 ^e	50.3 (1.0)	0.29 (1)	0.15, 0.42 ^c
		a^3D_2	3818.344	6.10 (15)	0.0212 (10)	0.016, 0.038 ^c , 0.056 ^d
		a^3D_3	3878.288	1.78 (5)	0.0046 (3)	0.0039, 0.0011 ^c
		a^1D_2	4177.536	33.1 (7)	0.138 (7)	0.11, 0.064 ^c
		a^3F_2	5200.413	8.30 (25)	0.054 (3)	0.018, 0.048 ^c , 0.058 ^d
		a^3F_3	5289.817	0.42 (4)	0.0020 (2)	0.00083, 0.0019 ^c
$z^1P_1^o$, 27,517	5.0 (2.0) ^f	a^1S_0	3633.123	66.3 (1.0)	0.8 (3)	0.51, 0.73 ^c
		a^3D_1	3747.554	9.8 (2)	0.041 (15)	0.026, 0.045 ^c
		a^3D_2	3776.558	12.0 (2)	0.031 (10)	0.018, 0.10 ^c
		a^3F_2	5123.210	6.3 (3)	0.03 (1)	0.0086, 0.027 ^c
		b^1D_2	7881.881	4.8 (4)	0.05 (2)	0.011, 0.00034 ^c
$z^3F_3^o$, 27,532	6.3 (3)	a^3D_2	3774.339	69.0 (5)	0.33 (2)	0.14, 0.46 ^c
		a^3D_3	3832.895	18.6 (2)	0.065 (3)	0.040, 0.088 ^c
		a^1D_2	4124.907	1.11 (4)	0.0063 (3)	0.0048, 0.010 ^c
		a^3F_2	5119.111	0.99 (8)	0.0087 (8)	0.0040, 0.0098 ^c
		a^3F_3	5205.731	10.0 (4)	0.065 (5)	0.021, 0.075 ^c , 0.054 ^d
		a^3F_4	5320.782	0.24 (5)	0.0013 (3)	0.00053, 0.00031 ^c
$z^3F_4^o$, 28,394	5.7 (3)	a^3D_3	3710.286	88.0 (6)	0.41 (2)	0.14, 0.56 ^c
		a^3F_3	4982.128	0.87 (7)	0.0073 (3)	0.0019, 0.0067 ^c , 0.0054 ^d
		a^3F_4	5087.420	11.1 (7)	0.076 (6)	0.014, 0.076 ^c
$z^3D_1^o$, 28,595	4.5 (3)	a^1S_0	3496.082	15.7 (3)	0.192 (15)	0.14, 0.29 ^c
		a^3D_1	3601.913	50.6 (5)	0.219 (15)	0.18, 0.26 ^c
		a^3D_2	3628.704	14.8 (3)	0.039 (3)	0.034, 0.022 ^c
		a^1D_2	3951.589	0.66 (5)	0.0021 (2)	0.0026, 0.22 ^c
		a^3F_2	4854.867	17.6 (7)	0.083 (7)	0.024, 0.11 ^c
		b^1D_2	7264.164	0.6 (2)	0.0063 (15)	0.0038, 0.00031 ^c
$z^3D_2^o$, 28,730	4.3 (3)	a^3D_1	3584.517	17.3 (3)	0.129 (9)	0.097, 0.16 ^c
		a^3D_2	3611.043	44.7 (9)	0.204 (15)	0.14, 0.24 ^c
		a^3D_3	3664.615	15.7 (3)	0.053 (4)	0.037, 0.083 ^c
		a^1D_2	3930.658	0.91 (4)	0.0049 (4)	0.0044, 0.0053 ^c
		a^3F_2	4823.305	1.90 (8)	0.015 (1)	0.0054, 0.017 ^c , 0.025 ^d
		a^3F_3	4900.110	19.4 (8)	0.116 (9)	0.024, 0.15 ^c , 0.12 ^d
		a^3P_2	6832.482	0.14 (3)	0.0023 (6)	0.0011, 0.0026 ^c
$z^3D_3^o$, 29,214	4.4 (3)	a^3D_2	3549.005	17.4 (3)	0.105 (7)	0.076, 0.14 ^c
		a^3D_3	3600.739	60.5 (1.0)	0.27 (2)	0.14, 0.35 ^c
		a^3F_3	4786.578	0.93 (9)	0.0073 (7)	0.0034, 0.0094 ^c

TABLE 2—*Continued*

UPPER LEVEL				<i>f</i>			
n.	Level, <i>E</i> (cm ⁻¹)	<i>τ</i> (ns)	LOWER LEVEL	<i>λ</i> (Å) ^a	BRANCHING RATIO (%)	This Work	Others
<i>y</i> ³ <i>P</i> ₀ ^o , 32,049	3.4 (2)		<i>a</i> ³ <i>F</i> ₄	<u>4883.685</u>	20.5 (1.0)	0.13 (1)	0.036, 0.17 ^c , 0.14 ^d
			<i>a</i> ³ <i>P</i> ₂	<u>6613.735</u>	0.74 (20)	0.016 (4)	0.0080, 0.032 ^c
			<i>a</i> ³ <i>D</i> ₁	<u>3203.322</u>	94.0 (6)	0.142 (9)	0.12, 0.32 ^c
			<i>a</i> ³ <i>P</i> ₁	<u>5544.610</u>	6.0 (6)	0.027 (3)	0.056 ^c
<i>y</i> ³ <i>P</i> ₁ ^o , 32,124	3.3 (2)		<i>a</i> ¹ <i>S</i> ₀	3112.027	0.43 (4)	0.0057 (6)	0.0070, 0.010 ^c
			<i>a</i> ³ <i>D</i> ₁	3195.616	27.2 (3)	0.126 (7)	0.13, 0.27 ^c
			<i>a</i> ³ <i>D</i> ₂	3216.688	67.1 (3.0)	0.19 (1)	0.13, 0.41 ^c
			<i>a</i> ¹ <i>D</i> ₂	<u>3467.877</u>	0.89 (4)	0.0029 (2)	0.0046, 0.022 ^c
<i>y</i> ³ <i>P</i> ₂ ^o , 32,283	3.6 (2)		<i>a</i> ³ <i>P</i> ₀	5480.732	2.5 (2)	0.103 (9)	0.038, 0.16 ^c
			<i>a</i> ³ <i>P</i> ₂	<u>5546.008</u>	1.9 (2)	0.016 (2)	0.0080, 0.031 ^c
			<i>a</i> ³ <i>D</i> ₁	3179.416	1.36 (3)	0.0096 (6)	0.012, 0.023 ^c
			<i>a</i> ³ <i>D</i> ₂	3200.273	17.4 (2)	0.074 (4)	0.074, 0.18 ^c
			<i>a</i> ³ <i>D</i> ₃	3242.282	73.0 (4)	0.23 (1)	0.16, 0.59 ^c
			<i>a</i> ¹ <i>D</i> ₂	3448.811	1.48 (6)	0.0073 (5)	0.0086, 0.0085 ^c
			<i>a</i> ³ <i>P</i> ₁	<u>5473.388</u>	1.54 (10)	0.032 (3)	0.013, 0.060 ^c
			<i>a</i> ³ <i>P</i> ₂	5497.406	4.15 (25)	0.053 (4)	0.022, 0.090 ^c
			<i>b</i> ¹ <i>D</i> ₂	<u>5728.888</u>	1.11 (10)	0.015 (2)	0.0076, 0.036 ^c

NOTE.—Figures in parentheses represent uncertainty in last figure(s).

^aWavelengths are from Palmer 1977 unless otherwise noted. Underlined wavelengths are those used in the final solar abundance analysis.

^bValues are from CB unless otherwise noted.

^cKrueger *et al.* 1968.

^dPirronello and Strazzulla 1980.

^eCalculated from Palmer's term values.

^fThis lifetime has an uncharacteristically large uncertainty as a result of nonexponential features in the decay curve—possibly due to collisional mixing of the excited level with other levels of similar energy.

1 for these transitions include this correction, and the uncertainties assigned to the corrected branching ratios are taken as being equal to the correction factors.

For all other lines, the uncertainties assigned to the branching ratios have been computed from the uncertainties in the observed line intensities $A(\lambda)$ and in the spectrometer efficiency ratios $E(\lambda_1)/E(\lambda_2)$ that appear in the branching ratio. The uncertainty in the efficiency ratio $E(\lambda_1)/E(\lambda_2)$ amounted to 11% for the full 6000 Å range of our spectrum; this is much larger than the uncertainty in the observed line intensity for all except the weakest branches.

Our branching ratios are in very good agreement with the values of Cardon, Parkinson, and Tomkins (1980). A comparison of our results with branching ratios deduced from the transition probabilities of CB shows that the CB values generally agree with ours to within 20–40% for branching ratios larger than 10%, but for fainter lines the CB results are lower by factors ranging from 1.5 to 3.

c) Oscillator Strengths

The *f*-values derived from our lifetimes and branching ratios are given in Tables 1 and 2, along with previously reported values. The values for transitions from the low-lying doublet levels of Y I include the correction for

the effect of unmeasured infrared branches (see § IIb and Appendix). In most cases, our *f*-values are found to be larger, by factors of up to 7, than the data of CB.

For Y I, our *f*-values are a factor of ~2 higher than the normalized hook data of Cardon, Parkinson, and Tomkins (1980). This difference has been discussed previously (Hannaford and Lowe 1982) and is attributed mainly to variations between our measured lifetime values and those used by Cardon *et al.* to normalize their hook data.

For Y II, Pirronello and Strazzulla (1980) have computed *f*-values for eight lines using the scaled Thomas-Fermi method. Our values agree with their results for five lines but are significantly smaller for the other three lines (see Table 2). The theoretical Y II *f*-values of Krueger *et al.* (1968) are on the average ~40% higher than ours, but, on an individual basis, variations of greater than an order of magnitude are found. This is comparable with the dispersion previously found by Allen (1977), on the basis of solar and stellar abundance studies.

III. SOLAR ANALYSIS

a) Selection of Solar Lines

The problem of the identification of Y I and Y II lines in the solar photospheric spectrum has been carefully

reexamined on the following basis. The laboratory wavelengths (λ_{lab}) of the Y I and Y II lines have been taken from the analysis of Palmer (1977), and the solar wavelengths ($\lambda_{\odot}$), from the tables of Pierce and Breckinridge (1973) or from interpolations between neighboring lines given by these authors. All lines which could be due to Y I or Y II have been carefully examined on the very high resolution (resolving power $\approx 10^6$) and low noise ($S/N \approx 2000$) tracings of the solar photospheric spectrum of Delbouille, Neven, and Roland (1973). Effects due to isotopic splitting and hyperfine structure are insignificant for yttrium, since there is only one stable isotope, and the hyperfine splitting factors are very small, typically less than 1 mÅ (Kuhn and Woodgate 1950; Fricke, Kopfermann, and Penselin 1959; Beer 1970, 1971).

Equivalent widths for these solar lines have been measured independently by four people. Uncertainties have been assigned to each line on the basis of the differences between the four sets of measurements and of the shapes of the lines in the solar spectrum.

On the basis of the small uncertainties in the solar and laboratory wavelengths (typically 2–3 mÅ), we estimate that a reasonable criterion for rejecting an identification is when $\Delta\lambda > 25$ mÅ, where $\Delta\lambda = |\lambda_{\odot} - \lambda_{\text{lab}}|$. For Y II, we have studied in detail 42 of the 55 lines previously identified by Moore, Minnaert, and Houtgast (1966) as unblended Y II lines, and all but one of these 42 lines fall within the above wavelength range. However, for Y I, 18 of the 40 lines we have examined, which include many of the Y I identifications proposed by Moore, Minnaert, and Houtgast (1966), fall outside this range, and these lines have been rejected. In all cases where $\Delta\lambda$ is larger than 25 mÅ, the derived abundance is also much too large (often by factors of 10–100) for the line to be due solely to Y I, and it is concluded that for these lines, Y I must be a small or negligible contributor, falling in the wings of the measured line.

It is also important in the final analysis to exclude all lines which are significantly influenced by blending since these lead to systematically high abundance values. Particular care must be taken in the case of Y I since these lines are often very faint. The transition probabilities and equivalent widths of most of the Y I and Y II lines have been determined to an accuracy of about 15% or better, and so, in the absence of blends, the distribution of solar abundances should be sharply peaked. A histogram of our experimental abundance results for Y II is shown in Figure 1. It can be seen that the distribution is indeed quite sharp, and hence we conclude that the atomic data are of sufficient accuracy for the abundance results to be used as an aid in the identification of solar lines, particularly in the case of the weaker Y I lines. The corresponding distribution for Y I lines, although peaked in a position similar to that of Y II, was found to be broad and asymmetric with a long tail on the high-abun-

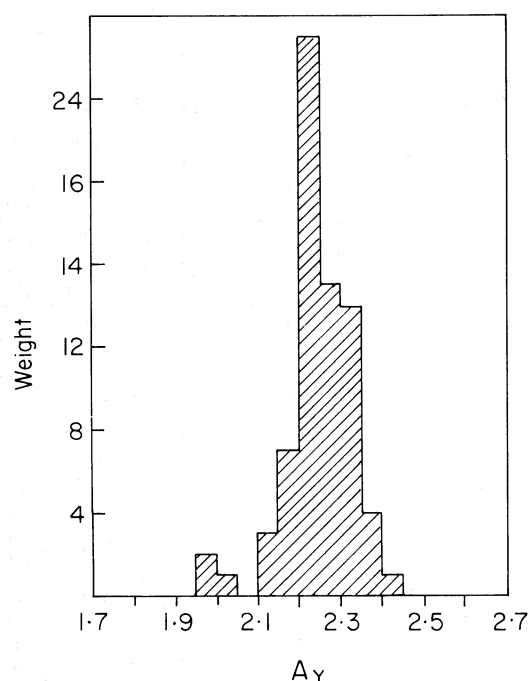


FIG. 1.—Distribution of Y II solar abundance results.

dance side. This tail is attributed to lines which are seriously influenced by blending. After removing the 18 lines for which $\Delta\lambda > 25$ mÅ, we find that for several of the remaining Y I lines, the derived abundances are very large, and these lines are assumed to be blends in which the Y I line is very close to an unknown contributor. Consequently, in the final analysis we have rejected a further 14 lines for which the abundance value exceeds the most probable value by more than 0.35 dex, which is the maximum deviation on the low-abundance side of the Y I distribution.

The eight Y I lines and 41 Y II lines we have retained for the final analysis are listed in Tables 3 and 4. The various lines that were examined and rejected for the reasons detailed above are indicated in Tables 1 and 2.

b) Solar Abundance Analysis

The solar abundance of yttrium has been derived for each line from the data given in Tables 3 and 4 using direct integration of the line profiles, assuming local thermodynamic equilibrium. We adopted the photospheric model of Holweger and Müller (1974). Arguments in favor of this model have been presented by Lambert (1978), Lambert and Luck (1978), Blackwell, Shallis, and Simmons (1980), and Biémont *et al.* (1981).

Each A_Y value is assigned a weighting factor from 3 to 1 on the basis of its uncertainty (ΔA_Y), which has been estimated from the combined effect of the uncer-

TABLE 3
SOLAR DATA AND RESULTS FOR Y I

λ_{lab} (Å)	$\lambda_{\odot}$ (Å)	E_{low} (eV)	W_{λ} (mÅ)	$\log gf$	A_Y	Weight
4128.304 ...	.302	0.07	8.3	0.38	1.89	1
4142.841 ...	.836	0.00	14.0	0.21	2.26	1
4643.698 ...	.720	0.00	3.8	-0.45	2.22	1
4674.848 ...	.848	0.07	2.4	-0.46	2.09	1
5527.561 ...	.542	1.40	2.1	0.40	2.37	1
5606.335 ...	.335	1.43	0.19	-0.56	2.31	1
6222.579 ...	.570	0.00	0.31	-1.70	2.24	1
6435.022 ...	.015	0.07	1.25	-0.82	2.03	1

TABLE 4
SOLAR DATA AND RESULTS FOR Y II

λ_{lab} (Å)	$\lambda_{\odot}$ (Å)	E_{low} (eV)	W_{λ} (mÅ)	$\log gf$	A_Y	Weight
3203.322	.325	0.10	50.0	-0.37	2.16	1
2467.877	.874	0.41	8.2	-1.84	2.22	2
3496.082	.085	0.00	46.1	-0.72	2.11	1
3549.005	.007	0.13	59.4	-0.28	2.27	2
3584.517	.521	0.10	60.0	-0.41	2.37	1
3600.739	.738	0.18	75.0	0.28	2.25	3
3601.913	.921	0.10	62.0	-0.18	2.24	1
3611.043	.048	0.13	63.9	0.01	2.16	2
3628.704	.707	0.13	50.8	-0.71	2.33	1
3710.286	.292	0.18	76.0	0.46	2.00	2
3747.554	.556	0.10	46.5	-0.91	2.21	1
3774.339	.335	0.13	80.7	0.21	2.22	3
3776.558	.560	0.13	54.0	-0.81	2.38	1
3788.697 ^a ...	.700	0.10	76.0	-0.07	2.34	1
3818.344	.345	0.13	48.6	-0.98	2.36	1
3950.356	.354	0.10	59.6	-0.49	2.21	1
4124.907	.909	0.41	20.1	-1.50	2.22	3
4374.946	.939	0.41	78.1	0.16	2.25	1
4398.010	.015	0.13	49.7	-1.00	2.27	3
4823.305	.310	0.99	19.2	-1.11	2.28	1
4854.867	.870	0.99	46.2	-0.38	2.29	3
4881.436	.440	0.41	1.1	-2.79	2.03	1
4883.685	.689	1.08	58.9	0.07	2.28	3
4900.110	.124	1.03	55.3	-0.09	2.29	3
4982.128	.133	1.03	12.0	-1.29	2.22	2
5087.420	.425	1.08	48.7	-0.17	2.21	3
5119.111	.119	0.99	14.0	-1.36	2.32	3
5123.210	.215	0.99	31.3	-0.83	2.31	1
5200.413	.414	0.99	37.6	-0.57	2.21	3
5205.731	.729	1.03	48.8	-0.34	2.31	2
5289.817	.821	1.03	4.2	-1.85	2.25	3
5320.782	.803	1.08	4.1	-1.95	2.38	1
5473.388	.385	1.74	7.3	-1.02	2.34	3
5509.896	.905	0.99	20.0	-1.01	2.15	1
5544.610	.613 ^a	1.74	6.3	-1.09	2.33	2
5546.008	.008	1.75	6.4	-1.10	2.36	1
5728.888	.876	1.84	3.4	-1.12	2.16	3
6613.735	.745	1.75	4.5	-1.11	2.15	1
6832.481	.478	1.75	0.8	-1.94	2.21	1
7264.164	.185	1.84	3.3	-1.50	2.45	1
7881.881	.906	1.84	14.5	-0.57	2.20	1

^a Moore, Minnaert, and Houtgast 1966 identified this line as due to Y II and Y I, with Y II being the main contributor. We have found the Y I contribution to be completely negligible.

tainties in the f -values and equivalent width measurements. Weight 3 corresponds to lines with $\Delta A_Y \leq 0.08$ dex, weight 2 to lines with $0.08 < \Delta A_Y \leq 0.12$ dex, and weight 1 to lines with $0.12 < \Delta A_Y < 0.20$ dex.

A microturbulent velocity of $\xi = 0.85 \text{ km s}^{-1}$ (isotropic and independent of the optical depth) has been deduced in the following way. The Y II line sample has been divided into three subgroups according to the intensity of the lines, $\log W_\lambda/\lambda$, where W_λ is the equivalent width: (1) the 17 faintest lines (with $\log W_\lambda/\lambda < -5.3$), which are independent of damping and microturbulence; (2) the 12 strongest lines (with $\log W_\lambda/\lambda > -4.8$), which depend on both damping and microturbulence; and (3) the remaining 12 lines, which are less dependent on damping than on microturbulence. The 17 faint lines lead to $A_Y = 2.26 \pm 0.04$, where the quoted error represents twice the standard deviation of the mean. The abundances for the two other subgroups of lines have been derived for different values of ξ (in the range $0.6\text{--}1.2 \text{ km s}^{-1}$) and for different values of the damping enhancement factor Δ (in the range $1.0\text{--}2.0$) to be applied to the van der Waals-type broadening parameter. The best agreement of the intermediate and strong line subgroup abundances with the faint line result is obtained for $\xi = 0.85 \text{ km s}^{-1}$ and no enhancement factor for the broadening parameter. This is consistent with the results obtained by Blackwell and Shallis (1979) and Blackwell, Shallis, and Simmons (1980).

Our abundance results are given in Tables 3 and 4. In practice, the mean abundance including all Y II lines is rather insensitive to modifications of the above parameters; for example, an increase of ξ by 0.1 km s^{-1} would result in a mean decrease of A_Y by only 0.02 dex, and an enhancement factor of $\Delta = 1.5$ applied to the damping parameter would likewise decrease the mean abundance by 0.02 dex.

The mean values, $\bar{A}_Y$, of the logarithmic solar abundances deduced from this study are

$$\bar{A}_Y = 2.18 \pm 0.12 \quad \text{for Y I (8 lines),}$$

$$\bar{A}_Y = 2.25 \pm 0.03 \quad \text{for Y II (41 lines),}$$

where the quoted errors represent twice the standard deviation of the mean. (The solar abundances quoted in Table 3 are determined using f -values corrected for

unmeasured infrared branches. If uncorrected f -values were used, the mean solar abundance of Y I would change from 2.18 to 2.15.)

The combined result is

$$A_Y = 2.24 \pm 0.03.$$

The presently accepted meteoritic abundance of yttrium is 4.8 Y atoms per 10^6 silicon atoms (Cameron 1981). Normalized to the solar scale, this leads to $A_Y(\text{meteorites}) = 2.24$, in very good agreement with the above photospheric results.

IV. DISCUSSION

The present determination for yttrium now completes the set of solar abundance values for each member of the important Sr-Y-Zr abundance peak corresponding to a magic number of 50 neutrons. These values are

$$A_{\text{Sr}} = 2.90 \quad (\text{Hauge 1972}),$$

$$A_Y = 2.24 \pm 0.03 \quad (\text{this work}),$$

$$A_{\text{Zr}} = 2.56 \pm 0.05 \quad (\text{Biémont et al. 1981}).$$

The new transition probabilities for Y I and Y II, and also the previously published results for Zr I and Zr II, have important implications concerning the abundances of these elements in both cool stars (mainly Y I lines) and hot stars (mainly Y II lines). The ratios $A_{\text{Sr}}/A_Y/A_{\text{Zr}}$, as well as the absolute abundance values, are known to vary by very large amounts in different types of stars, particularly in CP (chemically peculiar) stars. Thus, in order to be able to test the different theories proposed to explain the Sr-Y-Zr patterns, it is important to have reliable data for the transition probabilities. The impact of the new f -values for Y II and Zr II in the case of CP stars (Si, cool Ap, Hg-Mn, Am, Fm, and δ Delphini stars) has recently been discussed by Grevesse et al. (1981), and the effect of the new Y I and Zr I data in the case of cool stars is presently under investigation.

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APPENDIX

EFFECT OF UNMEASURED INFRARED TRANSITIONS ON THE Y I BRANCHING RATIOS

Some of the low-lying levels of Y I have strongly allowed transitions in the infrared that are above the 9000 Å cutoff of our spectrometer. A comparison of our uncorrected f -values with the relative f -values of Cardon,

Parkinson, and Tomkins (1980) (which were obtained by the hook method and therefore do not depend on a knowledge of the branching ratios) indicates that the ratio $r = f_{\text{this work}}/f_{\text{Cardon et al.}}$ has a mean value of 2.13

(standard deviation 0.16) for the $z^2F_{5/2,7/2}^o$, $y^2P_{3/2}^o$, and $y^2F_{5/2,7/2}^o$ levels, for which Palmer (1977) reports strong infrared transitions, and only 1.82 (standard deviation 0.14) for the $x^2D_{3/2}^o$ and $x^2F_{5/2,7/2}^o$ levels, for which Palmer reports no infrared transitions. If this systematic difference in r is due to the omission of infrared branches in our measurements, then our R and f -values for the first group of levels should be lowered on the average by $\sim 15\%$ to allow for this omission.

An estimate of the relative strength of the infrared branches for some of the levels may be obtained from the reported intensity measurements using the results of Palmer for lines in the infrared and those of this work for lines below 9000 Å. The five low-excitation doublet levels $y^2D_{3/2,5/2}^o$, $y^2F_{5/2,7/2}^o$, and $y^2P_{3/2}^o$ have approximately equal energies (24,131–24,899 cm^{-1}) and therefore should have similar relative populations in the two sets of intensity measurements. They also have strong or fairly strong infrared lines, most of which occur over a fairly narrow range of wavelengths (12000–20000 Å). The ratio $\Sigma_{\text{IR}} I(\text{Palmer}) / \Sigma_{<9000 \text{ Å}} I$ (this work) for each of these levels should therefore be approximately proportional to $\Sigma_{\text{IR}} A / \Sigma_{<9000 \text{ Å}} A$ (where A is the transition probability). A plot of the change in r , i.e., $\Delta r = r - 1.82$, versus $\Sigma_{\text{IR}} I(\text{Palmer}) / \Sigma_{<9000 \text{ Å}} I$ (this work) shows an approximately linear correlation, from which we con-

clude that the observed difference in r does result from the omission of infrared branches.

The actual correction factor to be applied to each level should depend on the relative strength of the infrared branches from that level. However, as the uncertainties in our correction factors are rather large and as we require factors for levels covering a wide range of energies, where the ratio $\Sigma_{\text{IR}} I(\text{Palmer}) / \Sigma_{<9000 \text{ Å}} I$ (this work) is almost certainly not proportional to $\Sigma_{\text{IR}} A / \Sigma_{<9000 \text{ Å}} A$, we have chosen to apply an average correction factor. This factor, which amounts to 15% ($\pm 15\%$), has been applied to the $z^2F_{5/2,7/2}^o$, $y^2P_{3/2}^o$, and $y^2F_{5/2,7/2}^o$ levels, and also to the $z^2D_{3/2,5/2}^o$ levels, for which Palmer reports strong infrared transitions but for which no hook data are available.

The strong infrared transitions observed by Palmer are not seen in the recent infrared solar atlas of Delbouille *et al.* (1981). However, if the infrared branches have branching ratios of not more than 15%, one can estimate an upper limit for their f -values and for the equivalent widths one would expect to see in the solar spectrum. The predicted solar widths, for those lines that are not severely blended or masked, are only a few tenths of a milliangstrom, which is below the limit of reliable detection.

REFERENCES

- Adams, D. L., and Whaling, W. 1981, *J. Opt. Soc. Am.*, **71**, 1036.
 Allen, M. S. 1976, *Pub. A.S.P.*, **88**, 338.
 ———. 1977, *Ap. J.*, **213**, 121.
 Allen, M. S., and Cowley, C. R. 1974, *Astr. Ap.*, **36**, 315.
 Aller, L. H. 1965, *Adv. Astr. Ap.*, **3**, 1.
 Andersen, T., Ramanujam, P. S., and Bahr, K. 1978, *Ap. J.*, **223**, 344.
 Beer, H. 1970, *Zs. Phys.*, **239**, 351.
 ———. 1971, *Ann. Phys. (Leipzig)*, **7**, 110.
 Biémont, E., Grevesse, N., Hannaford, P., and Lowe, R. M. 1981, *Ap. J.*, **248**, 867.
 Blackwell, D. E., and Shallis, M. J. 1979, *M.N.R.A.S.*, **186**, 673.
 Blackwell, D. E., Shallis, M. J., and Simmons, G. J. 1980, *Astr. Ap.*, **81**, 340.
 Brault, J. W. 1976, *J. Opt. Soc. Am.*, **66**, 1081.
 Cameron, A. G. W. 1981, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press), p. 23.
 Cardon, B. L., Parkinson, W. H., and Tomkins, F. S. 1980, *J. Opt. Soc. Am.*, **70**, 1372.
 Corliss, C. H., and Bozman, W. R. 1962, *NBS Monog.*, No. 53 (CB).
 Delbouille, L., Neven, L., and Roland, G. 1973, *Photometric Atlas of the Solar Photospheric Spectrum from λ 3000 to λ 10000* (Liège: Institute of Astrophysics, University of Liège).
 Delbouille, L., Roland, G., Brault, J. W., and Testerman, L. 1981, *Photometric Atlas of the Solar Spectrum from 1850 to 10,000 cm^{-1} , Preliminary Data* (Tucson: Kitt Peak National Observatory).
 Fricke, G., Kopfermann, H., and Penselin, S. 1959, *Zs. Phys.*, **154**, 218.
 Goldberg, L., Müller, E. A., and Aller, L. H. 1960, *Ap. J. Suppl.*, **45**, 1.
 Grevesse, N., Biémont, E., Hannaford, P., and Lowe, R. M. 1981, in *23d Liège Ap. Colloquium, Upper Main Sequence CP Stars* (Liège: University of Liège), p. 211.
 Grevesse, N., Blanquet, G., and Boury, A. 1968, in *Origin and Distribution of the Elements*, ed. L. H. Ahrens (Oxford: Pergamon), p. 177.
 Hannaford, P., and Lowe, R. M. 1981, *J. Phys. B*, **14**, L5.
 ———. 1982, *J. Phys. B*, **15**, 65.
 Harrison, G. R. 1939, *MIT Wavelength Tables* (New York: Wiley).
 Hauge, O. 1972, *Solar Phys.*, **26**, 276.
 Holweger, H., and Müller, E. A. 1974, *Solar Phys.*, **39**, 19.
 Krueger, T. K., Aller, L. H., Ross, J. E., and Czyzak, S. J. 1968, *Ap. J.*, **152**, 765.
 Kuhn, H., and Woodgate, G. K. 1950, *Proc. Phys. Soc. London*, **63**, 830.
 Lambert, D. L. 1978, *M.N.R.A.S.*, **182**, 249.
 Lambert, D. L., and Luck, R. E. 1978, *M.N.R.A.S.*, **183**, 79.
 Moore, C. E., Minnaert, M. G. J., and Houtgast, J. 1966, *NBS Monog.*, No. 61.
 Palmer, B. A. 1977, Ph.D. thesis, Purdue University.
 Pierce, A. K., and Breckinridge, J. B. 1973, *Kitt Peak Obs. Contrib.*, No. 559.
 Pirronello, V., and Strazzulla, G. 1980, *Ap. Space Sci.*, **72**, 55.
 Poulsen, O., Andersen, T., Bentzen, S. M., and Nielsen, U. 1981, *Phys. Rev. A*, **24**, 2523.
 Rudolph, J., and Helbig, V. 1982, *J. Phys. B*, **15**, L1.
 Wallerstein, G. 1966, *Icarus*, **5**, 75.

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