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TRANSITION PROBABILITIES IN Pr(II) AND THE SOLAR PRASEODYMIUM ABUNDANCE†

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Abstract—We have measured branching ratios for all of the known transitions from five levels in Pr^+. We use the known mean lifetime of four of these levels to compute transition probabilities for 40 transitions. Five of our stronger lines are seen in the sun. We use the equivalent widths of Moore *et al.* and the solar model parameters of Righini and Rigutti to compute the photospheric Pr abundance: $\log(N_{Pr}/N_H)+12 = 0.66 \pm 0.15$. This value is a factor of ten lower than the most recent photospheric abundance measurement of Grevesse and Blanquet. The difference arises in part from the new transition probabilities, in part from the equivalent widths. We justify our use of widths from Moore *et al.* by comparing them with widths measured on the Preliminary Kitt Peak Solar Atlas.

1. INTRODUCTION

ANDERSEN and SØRENSEN(1) have recently measured by the beam-foil time-of-flight method the mean lifetime of four levels in Pr(II): z^5K_7, z^5K_8, z^5K_9, and z^3K_7. To extract individual transition probabilities A_{ij} from their lifetime values $\tau_i = 1/\sum_j A_{ij}$, we have measured the decay branching ratio, $BR_{ik} = A_{ik}/\sum_j A_{ij} = A_{ik}\tau_i$, for each of the classified transitions from each of these levels and for the level z^5K_6, for which we estimate the lifetime by comparing the total intensity radiated by the z^5K_6 and z^5K_7 levels. Five of our strongest lines have been observed in the solar spectrum, and MOORE *et al.*(2) have measured the equivalent widths of these lines in the Utrecht Solar Atlas. We have remeasured the equivalent width of two of these lines as they appear in the Preliminary Edition of the Kitt Peak Solar Atlas. From the equivalent widths and transition probabilities we compute a photospheric Pr abundance.

2. EXPERIMENTAL METHOD AND RESULTS

The Pr(II) levels were excited in a hollow-cathode discharge in helium. The cavity in an aluminum cathode was lined with a rolled cylinder of 0.999 purity praseodymium foil. The source geometry and the two-channel Paschen Runge spectrometer used for the relative line intensity measurements have been described by LENNARD *et al.*(3) For the measurements reported in this paper, an EMI 9783 photomultiplier was used in the measuring channel. The overall detection efficiency of the spectrometer system was calibrated against a tungsten ribbon-filament standard lamp over the 4000–6400 Å wavelength range of the Pr(II) decay branches. This calibrated detection channel was then used to measure the relative photon intensity of each decay branch from an upper level while the monitor channel, set to detect the strongest branch from the upper level, monitored the intensity of the source. The source intensity was found to vary during the period of several hours required to measure all of the decay branches, but the monitor signal, recorded continuously alongside the measuring channel signal on a two-channel chart recorder, enabled us to correct our observations for source variations.

The observed photon intensity I'_{ik} is corrected for the spectrometer detection efficiency $\epsilon(\lambda_{ik})$ to give the true photon intensity $I_{ik} = I'_{ik}/\epsilon(\lambda_{ik})$ and the branching ratio BR_{ik} is computed from the relation $BR_{ik} = I_{ik}/\sum_j I_{ij}$. The sum includes all transitions classified by ROSEN *et al.*(4) from the upper level. These are listed in Table 1. A basic assumption of this experiment is that we have included all the strong transitions from the upper level. We assume that unclassified lines are weak and their neglect introduces negligible error in the sum. The upper levels that we consider are at most 28 kK above the ground state, so there are no energetic transitions beyond the range

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Table 1. The branching ratios and transition probabilities for five levels in Pr(II). The wavelengths are from MOORE *et al.*(2) The log gf_{CB} in the last column are from Corliss and Bozman.(8) The uncertainty in the transition probability varies from ±15% for the strongest lines to ±35% for the weakest lines

Upper Level (E_u cm^{-1})	RMT No.	Wavelength (Å)	Lower Level	Branching Ratio (%)	Transition Probability (10^6 sec^{-1})	log gf	log gf_{CB}
z^3K_7	—	3792.435	$a^5I^o_6$	< 0.6	< 1.0	< -1.5	—
(28010)	9	3997.054	$a^5I^o_7$	11.2	18.7	-0.17	-0.79
	26	4062.817	$a^3I^o_6$	60.1	100.0	0.57	0.01
	9	4241.019	$a^5I^o_8$	13.8	23.0	-0.03	-0.48
	26	4359.795	$a^3I^o_7$	6.4	10.6	-0.34	-0.82
	—	4365.328	$a^5L^o_7$	0.6	1.0	-1.38	—
	—	4912.629	$a^5K^o_8$	3.4	5.7	-0.51	-1.52
	—	5879.253	$b^5I^o_7$	4.6	7.6	-0.23	-1.14
z^5K_9	4	4100.746	$a^5I^o_8$	66.9	83.6	0.60	0.06
(28816)	37	5034.415	$a^5K^o_9$	9.0	11.3	-0.09	-0.71
	35	5110.768	$a^5L^o_{10}$	22.2	27.8	0.32	-0.37
	—	5810.622	$b^5I^o_8$	1.9	2.3	-0.65	-1.36
z^5K_8	4	4143.136	$a^5I^o_7$	49.0	58.3	0.41	-0.17
(27128)	4	4405.849	$a^5I^o_8$	7.6	9.0	-0.35	-0.89
	20	4534.154	$a^3I^o_7$	4.1	4.9	-0.59	-0.95
	—	4540.151	$a^5L^o_7$	0.3	0.4	-1.68	—
	—	4826.310	$a^5K^o_7$	0.3	0.4	-1.62	—
	37	5135.125	$a^5K^o_8$	10.5	12.5	-0.08	-0.89
	35	5173.898	$a^5L^o_9$	26.7	31.8	0.34	-0.52
	—	5502.20	$a^5K^o_9$	< 0.5	< 0.6	< -1.3	—
	—	6200.79	$b^5I^o_7$	1.6	1.8	-0.74	-1.55
z^5K_7	4	4179.422	$a^5I^o_6$	40.9	52.4	0.31	-0.07
(25569)	4	4429.238	$a^5I^o_7$	17.8	22.8	-0.01	-0.61
	20	4510.161	$a^3I^o_6$	9.0	11.6	-0.28	-0.78
	20	4879.121	$a^3I^o_7$	1.4	1.8	-1.00	-2.33
	—	4886.045	$a^5L^o_7$	1.0	1.3	-1.14	-2.13
	—	4914.418	$a^5K^o_6$	0.6	0.7	-1.42	—
	37	5219.053	$a^5K^o_7$	7.4	9.5	-0.24	-0.93
	35	5220.113	$a^5L^o_8$	18.3	23.5	0.16	-0.74
	—	5258.20	$b^5I^o_7$	0.8	1.0	-1.19	—
	—	5582.11	$a^5K^o_8$	< 0.1	< 0.1	< -2.2	—
	—	6278.675	$b^5I^o_6$	2.1	2.6	-0.63	-1.65
z^5K_6	4	4222.98	$a^5I^o_5$	36.4	39.1	0.13	-0.36
(24118)	4	4449.867	$a^5I^o_6$	11.5	12.4	-0.32	-1.01
	20	4468.712	$a^3I^o_5$	14.3	15.4	-0.22	-0.89
	4	4734.177	$a^5I^o_7$	2.3	2.5	-0.96	-2.14
	20	4826.649	$a^3I^o_6$	0.9	1.0	-1.36	—
	—	4943.735	$a^5L^o_6$	0.6	0.6	-1.52	-2.29
	20	5251.738	$a^3I^o_7$	1.0	1.1	-1.24	-1.83
	35	5259.743	$a^5L^o_7$	20.8	22.4	0.08	-0.83
	37	5292.630	$a^5K^o_6$	8.7	9.3	-0.30	-1.14
	—	5647.64	$a^5K^o_7$	0.6	0.7	-1.37	—
	—	6397.996	$b^5I^o_5$	1.8	1.9	-0.82	-1.75

of earlier searches of the Pr^+ spectrum. We cannot rule out the possibility of longer wavelength transitions to unknown odd terms at higher excitation energy, but one may expect that such low energy transitions would have low probability. A number of allowed transitions between our upper levels and known levels in lower terms are too weak to be observed in our experiment or in the work of MEGGERS *et al.*(5)

Table 1 lists the experimental branching ratios BR_{ik}, and the transition probabilities $A_{ik} = BR_{ik}\tau_i^{-1}$ computed from these branching ratios and the lifetimes measured by ANDERSEN and SØRENSEN.(1) These authors did not measure a lifetime for the z^5K_6 level. We have estimated the lifetime of this level after the method introduced by ROBERTS *et al.*(6) for comparing the lifetime of two levels in the same term on the assumption that the population of two levels within the same term follows statistical equilibrium. For the two levels z^5K_6 and z^5K_7 we have

$$\tau_6/\tau_7 = \sum_i A_{7i}/\sum_k A_{6k} = \frac{\sum_i I_{7i}N_6}{\sum_k I_{6k}N_7} = \frac{\sum_i I_{7i}g_6\,e^{-\alpha E_6}}{\sum_k I_{6k}g_7\,e^{-\alpha E_7}}. \tag{1}$$

The total intensities ΣI_{nk} are measured in this experiment, the g_n are the statistical weights, and the E_n are ithe known excitation energies of the two levels. For the coefficient α we use the value $2.36 \pm 0.50\,\text{eV}^{-1}$ as measured by LENNARD(7) who used our hollow cathode source under similar conditions. This value of α would correspond to a source "temperature" of 4920 ± 1000°K, but we emphasize that we assume a statistical population ratio only for two levels in the same term that differ in excitation energy by less than 6%. Transition probabilities for decay branches from the $J = 6$ level are then given by

$$A_{6k} = \frac{BR_{6k}}{\tau_6} = \frac{I_{6k}g_7\exp[-\alpha(E_6 - E_7)]}{\tau_7 \sum_i I_{7i}g_6}. \tag{2}$$

The small difference in energy $E_7 - E_6$ gives the exponential factor in eqn (2) the value 1.53 ± 0.15 and is responsible for an additional 10% uncertainty in the transition probability for lines originating from the z^5K_6 level.

The uncertainty in our branching ratios varies with the strength of the line. For strong branches ($BR > 50\%$) the uncertainty is negligible ($<1\%$), but for the weakest branches the uncertainty in the branching ratio may be as large as ±25%. The five lines used in the abundance determination (see Table 2) have medium to strong branching ratios of 7–49%. For these lines we assign an uncertainty to the transition probability ±15%, the uncertainty in the measured lifetimes. For λ5259, we estimate an uncertainty of ±25% in the transition probability, with the additional uncertainty stemming from our estimate of the total transition probability of the z^5K_6 level.

Table 2. Equivalent widths of five photospheric Pr(II) lines. The underlined values were used to compute the abundance ratio in the last column. The uncertainty in the mean abundance ratio is the statistical deviation of the five values

	Equivalent Width (mÅ)			
(Å)	MOORE et al. (2)	GREVESSE (9)	K.P.N.O. (10)	N_{Pr}/N_H
4143.136	12			4.26×10^{-12}
4510.160	1.5		1.69	2.99
5173.898	3.5	3.9		4.50
5219.053	2.5	3.3		5.83
5259.743	3	4.4	3.16	5.02
			mean	4.57 ± 0.42

$\log (N_{Pr}/N_H) + 12 = 0.66 \pm 0.15$

We display a graphical comparison of our (CIT) transition probabilities with those of CORLISS and BOZMAN[8] in Figs. 1–3. Figure 1 shows a systematic variation of the ratio A_{CIT}/A_{CB} with wavelength. If the A_{CB} were correct, one would expect our solar abundance derived from the three long wavelength lines to be smaller than the abundance derived from the two shorter wavelength lines, whereas our abundance results in Table 2 show just the opposite behavior. We

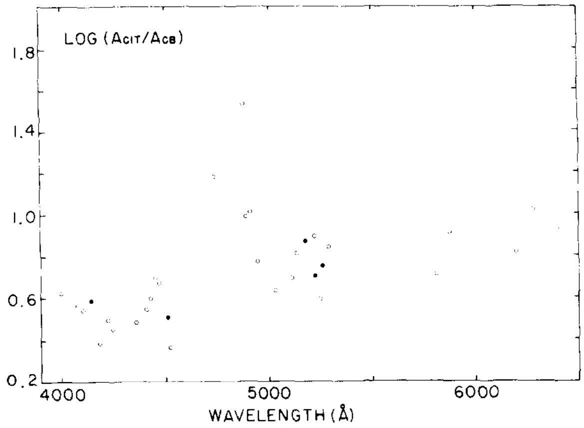

Fig. 1. Comparison of our transition probabilities with those of Corliss and Bozman as a function of wavelength. The full circles represent the lines used to compute the solar Pr abundance.

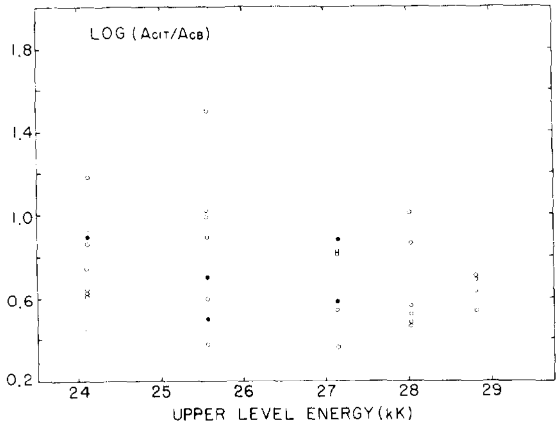

Fig. 2. Comparison of our transition probabilities with those of Corliss and Bozman as a function of upper level excitation energy. The full circles represent the lines used to compute the solar Pr abundance.

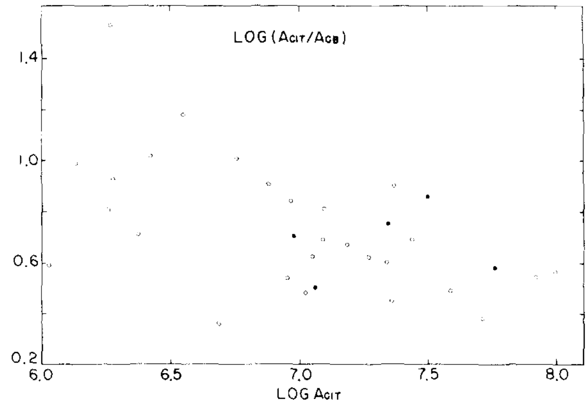

Fig. 3. Comparison of our transition probabilities with those of Corliss and Bozman as a function of the logarithm of the transitio probability. The full circles represent the lines used to compute the solar Pr abundance.

believe that Fig. 1 indicates a wavelength dependent error in the CB relative transition probabilities.

The two lines at 4879 and 4734 Å for which we disagree most seriously with CB have been carefully re-examined with Ar as well as He carrier gas, at various levels of discharge power, and with a blank Al cathode, to see if unknown blends might account for our higher value. The line at 4734.177 is not cleanly resolved from an unknown Pr line at 4734.0, but we believe that this close neighbor does not introduce error in our result. λ4879 shows no evidence for abnormal width or other interference.

In Fig. 2 we plot log $A_{\text{CIT}}/A_{\text{CB}}$ as a function of the excitation energy of the upper level. There is no indication of a systematic variation in the ratio and we conclude that the CB temperature scale is correct for the case of Pr^+, so that their values for transitions from other Pr^+ levels should be corrected by the same factor that applies to the levels under study here. Figure 3 shows that the $A_{\text{CIT}}/A_{\text{CB}}$ ratio is slightly higher for the very weak lines than for stronger lines. However, these very weak lines are red lines, and we believe that the slight trend shown in Fig. 3 is simply a reflection of the more pronounced trend shown in Fig. 1. Figures 2 and 3 show that the CB absolute values are too small by a factor $10^{0.65} = 4.5$. This discrepancy has already been pointed out by ANDERSEN and SØRENSEN on the basis of their lifetime measurements.

3. SOLAR PRASEODYMIUM ABUNDANCE

Five of the lines in Table 1 are seen in the sun. These lines are listed in Table 2 with the equivalent widths as measured by MOORE *et al.*[2] from the Utrecht Atlas, by GREVESSE and BLANQUET[9] from the Jungfraujoch spectrum, and in this experiment from the Preliminary Edition of the Kitt Peak Solar Atlas.[10] These lines are sufficiently weak that one can assume $N_{\text{Pr}}/N_H = W/(gf\Gamma\lambda)$. The solar model parameter Γ has been evaluated by RIGHINI and RIGUTTI[11] for these lines on the basis of the Mutschlecner solar model.[12] From their Γ-values and the widths underlined in Table 2, we find the values for the $N_{\text{Pr}}/N_{\text{H}}$ number density listed in the table. The log of the mean value of the abundance is 0.66, and we assign an uncertainty to this abundance of ±0.15. This uncertainty encompasses four of the five individual values in the table, and it is consistent with the systematic error in the transition probabilities (0.06 dex), the equivalent widths (0.06 dex), and the statistical deviation of the five values in Table 2 from the mean (0.04 dex). No allowance has been made for the uncertainty in the solar model since one expects little model dependency for such weak lines, as was pointed out by GREVESSE and BLANQUET.[9]

GREVESSE and BLANQUET derived a photospheric Pr abundance of 1.63 ± 0.12 using the CB transition probabilities and the equivalent widths from the Jungfraujoch spectrum in Table 2. ANDERSEN and SØRENSEN,[1] who first noted the error in the CB transition probabilities, proposed a Pr abundance of 0.98 ± 0.12 which they obtained by lowering the Grevesse value by a factor of 4.5 or 0.65 dex, the factor by which the CB transition probabilities are too large. The fact that our abundance is even lower than that proposed by Andersen and Sørensen comes from the equivalent widths: the Jungfraujoch widths are larger than the Utrecht widths as can be seen from Table 2. We have attempted to remeasure the widths on the new Preliminary Edition of the Kitt Peak Solar Atlas using the KPNO non-linear spectrum synthesis code. The lines are very weak and badly blended and we were able to obtain good fits for only two of the five lines. For both of these lines, our remeasurements support the older Utrecht widths. We believe that the Pr abundance proposed by Andersen and Sørensen is too large because the Grevesse widths are too large. If we divide our solar $N_{\text{Pr}}/N_{\text{H}}$ ratio by the solar $N_{\text{Si}}/N_{\text{H}}$ ratio of 3.55×10^{-5} as adopted by WITHBROE,[13] we find for the solar ratio $N_{\text{Pr}}/N_{\text{Si}} = 1.29 \times 10^{-7}$, in excellent agreement with the meteoritic number ratio 1.49×10^{-7} adopted by CAMERON.[14]

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