TRANSITION PROBABILITIES FOR SEVERAL u.v. LINES OF Pb II

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Abstract—Relative transition probabilities for 30 lines arising from excited doublets levels of Pb II have been determined from emission lines intensities in a hollow-cathode discharge. These values were put on an absolute scale by using, where possible, the experimental lifetimes published by other authors. In addition, absolute transition probabilities were obtained by using line-strength sum rules and the results were found to be in agreement with data derived from lifetime measurements. Our experimental results are compared with experimental and theoretical data given by other authors.

1. INTRODUCTION

Relative transition probabilities of the levels of singly ionized lead have been the subject of few experimental and theoretical studies. Measurements of absolute transition probabilities in the visible Pb II spectrum have been previously performed by Miller et al,[1] Trukhan et al[2] and Brown[3]. Kunisz[4] and Migdalek[5] have performed theoretical calculations providing transition probabilities and lifetimes for some of these levels.

In this work we present transition probabilities for 30 lines involving the S, P, D and F levels of Pb II. Relative values have been obtained from measurements of emission line intensities in a hollow-cathode discharge. We have used two different methods in order to place the data on an absolute scale. First, where possible, experimentally determined lifetime published by other authors, Gorshkov et al[6] have been used. Secondly, we report the results obtained from line strength sum rules[7] for all of our measurements. The experimental results are compared with theoretical calculations and experimental results performed by other authors and with our present calculations. To provide level energies for our calculations, the table of Moore[8] have been used.

2. EXPERIMENTAL SET-UP AND PROCEDURE

The experimental set-up is similar to that described in a previous publication.[9,10] Emission intensities of lines with a common upper level have been measured by means of single-photon counting. The light source was a hollow-cathode lamp of Pb. The cathode was a 15 mm-long cylinder of 5 mm dia. The gas used to fill the tube was Ne at a pressure of 10 torr. The operating current was typically 8 mA. The transition wavelengths range, from 2000 to 7500 Å, were isolated by using a 1.2 m monochromator(Czerny-Turner) with 0.36 Å resolution in the first order and 0.18 Å in the second order. Photons were detected with an EMI 9558 QB (u.v. extended S-20 response) photomultiplier cooled with dry ice. Calibrated tungsten-strip and deuterium lamps were used to determine the spectral response. Several emission spectra were recorded in order to obtain relative transition probabilities with statistical uncertainties of 3%.

The relative values of lines arising from the $6s^2\ 7p^2P^0_{1/2,3/2}$ and $6s^25f^2F^0_{5/2.7/2}$ levels were put on an absolute scale by using the corresponding experimental lifetimes given by Gorshkov et al, namely 15.20 ± 1.70, 10.20 ± 1.20, 5.90 ± 0.60 and 5.80 ± 0.60 nsec, respectively. Absolute transition probabilities have also been obtained by combining our experimentally-measured branching ratios with line-strength sum rules:

$$\sum_{J'} S_{JJ'} = [(2J+1)/(2l+1)]\cdot l_{\max}\cdot|\int P_{nl}(r)\cdot r\cdot P'_{n'l'}(r)\,\mathrm{d}r|^2$$

where $S_{JJ'}$ is the lines strength for $|nl,J\rangle \rightarrow |n'l',J'\rangle$ transitions and $\int P_{nl}(r)\cdot r\cdot P'_{n'l'}(r)\,\mathrm{d}r$ is the single electron radial integral.

The radial wavefunctions $[P_{nl}(r)]$ were obtained by numerical integration of the radial Schrödinger equation including three terms in the Hamiltonian (Cowan[7]):

$$-\frac{\alpha^2}{2}(E-V)^2-\frac{\alpha^2}{4}\left(\frac{\mathrm{d}V}{\mathrm{d}r}\right)r\frac{\mathrm{d}}{\mathrm{d}r}r^{-1}+\frac{\alpha^2}{2}\left(\frac{\mathrm{d}V}{\mathrm{d}r}\right)\frac{l\cdot s}{r}$$

where α is the fine structure constant, E is the eigenvalue of the Schrödinger equation, l and s are orbital and spin angular-momentum operators and V a semiempirical potential given for Green et al[11] that includes "core" polarization effects, Migdalek and Baylis[12], and incorpore the finite size of nucleus. The "core" polarization effect in the transition matrix was taken into account. The results are in Table 1.

In order to check possible self-absorption effects for the strong lines, we have measured absolute transition probabilities for resonants lines of Pb I, Table 2. The agreement is also satisfactory with the values obtained from a others authors, indicating that no significant self-absorption exists and no corrections are necessary.

Table 1. Absolute transition probabilities of lines arising from doblets levels of Pb II.

			Absolute transition probabilities ($\times 10^6\,\mathrm{s}^{-1}$)				
			Experimental				
Transition levels			This work			Theory	
Upper	Lower	λ (Å)	(a)	(b)	Ref. 1	This work	Ref. 5
$9s^2S_{1/2}$ →	$7p^2P^0_{1/2}$	3718.3		17.5 ± 2.8		16.3	14.1
	$7p^2P^0_{3/2}$	4152.8		22.6 ± 3.6	24 ± 10	23.4	29.9
$10s^2S_{1/2}$ →	$7p^2P^0_{1/2}$	2986.9		8.4 ± 1.2		7.3	8.1
	$7p^2P^0_{3/2}$	3260.9		10.4 ± 1.5		11.3	12.4
$11s^2S_{1/2}$ →	$7p^2P^0_{1/2}$	2693.6		5.3 ± 0.7		3.8	4.8
	$7p^2P^0_{3/2}$	2914.4		4.8 ± 0.7		6.0	7.2
$7p^2P^0_{1/2}$ →	$7s^2S_{1/2}$	6660.0	59.1 ± 5.9		62 ± 21	56.3	73.8
	$6d^2D_{3/2}$	21190.9				2.7	
	$6p^2P_{1/2}$	6041.4	0.62 ± 0.06				
$7p^2P^0_{3/2}$ →	$7s^2S_{1/2}$	5602.9	83.1 ± 8.3		124 ± 43	94.4	124.9
	$6d^2D_{3/2}$	13276.7				1.08	
	$6d^2D_{5/2}$	12036.6				1.3	
	$6p^2P_{1/2}$	5163.6	1.6 ± 0.2				
$7d^2D_{3/2}$ →	$7p^2P^0_{1/2}$	5042.6		101.7 ± 15.2	77 ± 23	106.7	
	$7p^2P^0_{3/2}$	5876.6		16.8 ± 2.5		13.5	
$7d^2D_{5/2}$ →	$7p^2P^0_{3/2}$	5544.6			104 ± 31	96.6	
$8d^2D_{3/2}$ →	$7p^2P^0_{1/2}$	3455.1		43.7 ± 7.0		42.9	
	$7p^2P_{3/2}$	3827.2		5.8 ± 0.9		6.3	
$10d^2D_{3/2}$ →	$7p^2P^0_{1/2}$	2634.3		10.4 ± 1.5		10.2	
	$7p^2P^0_{3/2}$	2845.2		1.5 ± 0.2		1.6	
$5f^2F^0_{5/2}$ →	$6d^2D_{3/2}$	4386.5	147.1 ± 14.7	159.0 ± 23.8	44 ± 15	167.7	
	$6d^2D_{5/2}$	4242.1	9.3 ± 0.9	10.5 ± 1.5		12.6	
	$6p^2\,{}^4P_{3/2}$	3785.9	9.6 ± 1.4		3.3 ± 1.4		
	$6p^2\,{}^4P_{5/2}$	5367.6	3.0 ± 0.3				
$5f^2F^0_{7/2}$ →	$6d^2D_{5,2}$	4245.1	112.1 ± 16.8		29 ± 10	133.7	
	$6p^2\,{}^4P_{5/2}$	5372.3	60.0 ± 6.1		128 ± 38		
$6f^2F^0_{5/2}$ →	$6d^2D_{3/2}$	3016.4		41.1 ± 6.2		41.8	
	$6d^2D_{5/2}$	2947.4		3.5 ± 0.5		3.1	
$7f^2F^0_{5/2}$ →	$6d^2D_{3/2}$	2576.6		12.8 ± 1.9		12.8	
	$6d^2D_{5/2}$	2525.8		0.96 ± 0.14		0.9	

a, Values obtained from lifetime measurements.
b, Values obtained from lines strength sum rules.

Table 2. Comparisons of experimentally determined transition probabilities (column 3) of Pb I with other results. Data in column 4 are from Lotrian et al;[22] in column 5 from Penkin and Slavenas;[23] in column 6 from Saloman and Happer[14] and in column 7 from Baghdadi et al.[21]

Transition levels			Absolute transition probabilities ($\times 10^6\, s^{-1}$)				
			Experimental				
Up	Lower	λ (Å)	This work	Ref.22	Ref.23	Ref.14	Ref.21
$6p7s^3P_1^0 \rightarrow$	$6p^2\ {}^3P_0$	2833.1	43.0 ± 6.1	58.0	59.0 ± 5.9	47.0 ± 9.4	
	$6p^2\ {}^3P^1$	3639.6	32.0 ± 5.0	33.5	32.0 ± 3.2	20.0 ± 7.0	
	$6p^2\ {}^3P_2$	4057.9	93.1 ± 13.9	89.0	103.0 ± 36.8	105.4 ± 36.8	
	$6p^2\ {}^1D_2$	7229.0	2.6 ± 0.5				
τ = (5.89 ± 0.10) nsec							
$6p7s^1P_1^0 \rightarrow$	$6p^2\ {}^3P_0$	2022.1	6.8 ± 0.6	5.2			11.0 ± 4.9
	$6p^2\ {}^3P_1$	2402.0	29.8 ± 3.0	19.0	28.0 ± 2.8		
	$6p^2\ {}^3P_2$	2577.3	55.2 ± 5.5	50.0	67.0 ± 6.7		
	$6p^2\ {}^1D_2$	3572.8	102.9 ± 10.3	99.0			
	$6p^2\ {}^1S_0$	5005.5	12.1 ± 1.2	27.0			
τ = (4.99 ± 0.13) nsec							
$6p8s^3P_1^0 \rightarrow$	$6p^2\ {}^3P_0$	2053.4	14.0 ± 2.1	12.0			22.0 ± 5.5
	$6p^2\ {}^3P_1$	2446.3	22.6 ± 3.4	24.5	15.0 ± 1.5		
	$6p^2\ {}^3P_2$	2628.3	7.0 ± 1.1	3.1			
	$6p^2\ {}^1D_2$	3671.5	34.5 ± 4.9	44.0			
	$6p^2\ {}^1S_0$	5201.5	5.8 ± 0.7	19.0			
τ = (12.92 ± 0.43) nsec							
$6p6d^3D_1^0 \rightarrow$	$6p^2\ {}^3P_0$	2170.0	165.0 ± 16.3	149.0	184.0 ± 18.4		
	$6p^2\ {}^3P_1$	2613.7	21.2 ± 2.1	26.5	18.5 ± 8.3		
	$6p^2\ {}^1D_2$	4062.2	70.1 ± 6.0	92.0			
τ = (4.09 ± 10.24) nsec							

Table 3 contains a summary of the lifetimes of the $^3P_1^0$ (6p7s, 6p8s), $^1P_1^0$ (6p7s) and $^3D_1^0$ (6p6d) states of Pb I found in the literature. The relative values of lines arising from these levels were put on an absolute scale by using mean value pondered of all the lifetimes of these authors.

3. RESULTS AND DISCUSSION

The absolute transition probabilities obtained from lifetime and branching-ratio measurements are shown in the third column of Table 1. The experimental errors for these values are the result of statistical uncertainties, errors in the lifetimes measurements and uncertainties in the spectral response determination. The fourth column of this table shows values obtained from the combination of branching-ratio measurements and line strength sum rules. In these results, only statistical and spectral calibration errors have been included. The sixth column of this table shows values calculated in this work. There is agreement within 8% between the results obtained by us using experimental lifetime and using line-strength sum rule and 10% with theoretical results. As can be seen in the table, there is fair agreement between experimental values and also with theoretical results. Data given by other authors have been included in Table 1 for comparison.

Table 3. Lifetime for states of Pb I.

State	Measurement lifetimes (nsec)		
$6p7s^3P_1^0$	5.75 ± 0.20 (a)	6.05 ± 0.30 (b)	5.58 ± 0.72 (c)
	5.59 ± 0.23 (d)	6.60 ± 0.30 (e)	5.85 ± 0.20 (f)
	6.10 ± 0.50 (g)		
$6p7s^1P_1^0$	5.85 ± 0.27 (d)	6.10 ± 0.50 (e)	6.60 ± 0.70 (g)
$6p8s^3P_1^0$	12.90 ± 1.40 (h)	14.20 ± 1.00 (g)	12.60 ± 0.50 (i)
$6p6d^3D_1^0$	3.74 ± 0.28 (d)	5.20 ± 0.50 (g)	

Source of data: a, level-crossing effect (Saloman and Happer[14]); b, phase shift (Cunningham and Link[15]); c, Hanle effect (Zaffra and Marshall[16]); d, Hanle method (Garpman et al[17]); e, beam-foil (Andersen[18]); f, delayed coincidences (Giers and Atkins[19]); g, delayed coincidences (Gorshkov and Verolainen[6]); h, Hanle-effect (Saloman[20]); f, level-crossing (Baghdadi et al[21]).

Trukha et al[2] measured the line-strength ratio 4245.1 Å Pb II/4168.0 Å Pb I in a pulsed discharge and used the neutral-lead A_{ij} values of Corliss and Bozman[13] for reference, getting the value of 128×10^6 sec^{-1}, Brown[3] lower-limit determinations via a gas-driven shock tube are limited to two lines of $5f$–$6d$, obtaining a value of 4.0×10^8 sec^{-1} and from the transition probabilities of 4245.1 Å line, and from the 4386.5 Å a value of 8.6×10^8 sec^{-1}. The theoretical data of Kunisz and Migdalek are in agreement with the present results.

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