Lifetimes of $ns(3/2)_2$ ($n=6,7,8,9$) levels and transition probabilities of 4*p*-*ns* lines of Ar I

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Forty-eight transition probabilities for lines belonging to the 4*p*-*ns* ($n=6,7,8,9$) transition arrays of Ar I have been determined by means of emission-line-intensity measurements. The single-photon delayed-coincidence method has been used to obtain the lifetime values of the $ns(3/2)_2$ ($n=6,7,8,9$) levels. With the taking into account of these lifetimes together with theoretical calculation in *jK* coupling for the lines beyond the experimental range, the relative transition probabilities were put on an absolute scale. The lifetime values obtained in the present work are original in the literature excepting the $7s(3/2)_2$-level lifetime. Four transition probabilities are also the first values found in the literature.

I. INTRODUCTION

The measurement of the lifetimes of the $ns(3/2)_2$ ($n=6,7,8,9$) levels together with the transition probabilities of lines belonging to the 4*p*-*ns* ($n=6,7,8,9$) transition arrays of Ar I have been the subject of this work. It was prompted by the lack of lifetime data for the $3p^5ns$ configurations of Ar I.

Three of the four measured lifetimes are new data in the bibliography. These results are compared with the present theoretical calculations performed in *jK* coupling with the use of Coulomb approximation and with the intermediate-coupling (IC) data given by Grudzdev and Loginov[1] (Hartree-Fock functions).

In this work 48 relative transition probabilities have been measured. Fifteen transition probabilities of lines arising from $ns(3/2)_2$ ($n=6,7,8,9$) levels have been put on an absolute scale taking into account the experimental lifetimes and the *jK* coupling calculations performed for this work.

The wavelengths of the spectral lines involved in this experiment range from 4834 to 8203 Å. The tables of Striganov and Sventitskii[2] and Norlén[3] have been used to identify the transitions. The energy value of the measured levels used in these calculations has been taken from the energy levels compilations of Moore[4] and Bashkin and Stoner.[5]

II. EXPERIMENTAL METHOD

The lifetimes of the $ns(3/2)_2$ ($n=6,7,8,9$) levels have been measured by the delayed coincidence method using modulated low-energy (<40-eV) electron-impact excitation[6]; the experimental setup was similar to that employed in previous studies.[7] The measurements were performed at gas pressure in the range from 3 to 30 mTorr, keeping a continuous gas flow during the measurements. Variation of the lifetime values with pressure have not been observed within the experimental error. Every level was measured in several steps, each one with an excitation electron energy closer to threshold than the previous one. The experimental curves obtained in these conditions were fitted to a single exponential function. Exception was the $6s(3/2)_2$ level where two exponential terms were needed.

The experimental method used to obtain the transition probabilities has been the measurement of the intensity of lines originating from the same upper level in optically thin source conditions. The source was an argon ac arc at 1-Torr pressure and the light path 10 mm.

For intensity measurement, lines were isolated by a 0.5-m Jarrell-Ash spectrometer, with a 1180 grooves/mm grating blazed at 6000 Å. The spectral resolution was 0.5 Å. Two different photomultipliers were used for single-photon detection, an XP 1005 (S-1 response) for wavelengths longer than 5400 Å and an XP 2000 (S-11 response) photomultiplier ($\lambda < 6000$ Å). The overlapping interval of detection was used to compare the results obtained with the two systems. The main experimental difficulties in the relative transition probability measurements come from the need of careful calibration of the spectroscopic system. Details of the calibration systems can be found in previous work.[8] Two light sources were used to calibrate the spectrometer: a tungsten strip lamp at a color temperature of 3200 K and a Bausch and Lomb monochromator calibrat-

TABLE I. Lifetimes of the $ns(3/2)_2$ ($n=6,7,8,9$) levels of Ar I.

Level	Line λ (Å)	Experimental lifetimes (ns) Present work	Ref. 10	Theoretical lifetimes (ns) Our work (jK)	Ref. 1 τ_r[a]	(IC) τ_v[a]
$6s(3/2)_2$	7030	75± 8		87	77	93
$7s(3/2)_2$	5452	171± 9	165±20	162	142	170
$8s(3/2)_2$	5421	256±10		270		
$9s(3/2)_2$	5394	301±16		444		

[a] τ_r and τ_v have been calculated from the line strengths in the length and velocity approximation, respectively, in single-configuration approximation.

ed by means of a Sensor L66 thermopile. It can be estimated that the error in the relative efficiency calibration of the spectrometer is 10% in the worst case.

III. MEASUREMENTS AND DISCUSSION

A. Lifetimes

Table I shows the experimental results obtained in the lifetime measurements of the $ns(3/2)_2$ ($n=6,7,8,9$) levels. These results are compared with the theoretical data of Ref. 1 for the $ns(3/2)_2$ ($n=6,7$) levels. For the $ns(3/2)_2$ ($n=8,9$) levels our experimental and theoretical values are the first found in the literature.

If the excitation energy is slightly higher than the threshold energy of the $6s(3/2)_2$ level, its decay curves show a cascading component of (275±25)-ns lifetime that can be attributed to deexcitation of the $6p(5/2)_3$ level. For this identification the experimental intensity of cascade lines and the theoretical transition probabilities of the probable candidates were taken into account.[9] The lifetime value of the present jK calculations is 274 ns for the $6p(5/2)_3$ level. In the same excitation conditions, the decay of the $ns(3/2)_2$ ($n=7,8,9$) levels do not show cascading components because these levels belong to

TABLE II. Transition probabilities for lines with origin in the $ns(3/2)_2$ ($n=6,7,8$) levels of Ar I.

Transition	Line λ (Å)	Absolute transition probabilities (10^5 s^{-1}) Experimental values: Present work	Ref. 13	Ref. 11	Ref. 12	Theoretical data Ref. 14
$4p(1/2)_1$-$6s(3/2)_2$	6416.31	15	12 ±4	13	10 ±1.5	17
$4p(5/2)_3$	7030.25	36	28 ±7	38	22 ±3	43
$4p(5/2)_2$	7107.48	6	5 ±2.5	5	4 ±1	8
$4p(3/2)_2$	7435.33	13	9 ±4.5	13	8 ±2	16
$4p'(3/2)_2$	8066.60	1.3	1.5±0.7		1.2±0.2	2.2
$4p'(1/2)_1$	8203.42	1.0	1.6±0.8		<0.03	1.6
$4p(1/2)_1$-$7s(3/2)_2$	5451.65	5.6	4.9±2.2	5.5	3.9±0.8	6.6
$4p(5/2)_3$	5888.59	14	13 ±3	12	11 ±2	17
$4p(5/2)_2$	5942.67	2.3	1.9±0.9	2.4	1.5±0.5	3.4
$4p(3/2)_2$	6170.18	4.1	5.2±1.3	4.2	4.2±0.6	6.6
$4p(1/2)_1$-$8s(3/2)_2$	5048.81	3.4	4.8±2.4	2.1	3.8±1.2	
$4p(5/2)_3$	5421.35	8.2	6.2±3.1	6.7		
$4p(5/2)_2$	5467.16	1.5	0.8±0.4	0.9	0.6±0.2	
$4p(3/2)_1$	5611.35	0.6				
$4p(3/2)_2$	5659.13	3.2	2.7±0.7	2.4	2.1±0.5	

more excited configurations. Thus the estimated error for these level lifetimes range from 4% to 5%, while the statistical error for the $6s(3/2)_2$-level lifetime is 11%.

The only previous experimental result found in literature[10] agrees with our value for the $7s(3/2)_2$ level. Between our experimental and calculated results, discrepancies lower than 16% are found except for the $9s(3/2)_2$ level.

B. Transition probabilities

Absolute transition probabilities for the $4p$-$ns(3/2)_2$ ($n=6,7,8$) lines of Ar I are given in Table II. In Table III, relative transition probabilities for lines arising from the $ns(3/2)_1$ ($n=6,7,9$), $ns'(1/2)_1$ ($n=6,7$), $6s'(1/2)_0$, and $9s(3/2)_2$ levels are shown. The estimated accuracy is 15% for lines of relative transition probabilities greater than 20% and 25% for the rest of lines. In both tables our re-

TABLE III. Relative transition probabilities for $4p$-ns ($n=6,7,9$) lines of Ar I.

Transition	Line λ (Å)	This work	Experimental values Ref. 13	Ref. 11	Ref. 12	Theoretical data Ref. 14 (IC)
$4p(1/2)_1$-$6s(3/2)_1$	6384.72	14	21		21	17
$4p(5/2)_2$	7068.73	100	100		100	100
$4p(3/2)_1$	7311.72	48	86		56	54
$4p(3/2)_2$	7392.97	32	36		36	37
$4p(1/2)_0$	7868.20	14	17		17	16
$4p'(3/2)_1$	7916.45	8			6	
$4p(1/2)_1$-$6s'(1/2)_0$	5882.62	40	58	61	59	18
$4p(3/2)_1$	6660.68	33	37	29	37	28
$4p'(3/2)_1$	7158.83	100	100	100	100	100
$4p'(1/2)_1$	7350.78	48	54	48	54	50
$4p(1/2)_1$-$6s'(1/2)_1$	5860.31	9	11	12	10	12
$4p(5/2)_2$	6431.56	2.6	2.0	2.5	2.0	3.6
$4p(3/2)_2$	6698.86	7	7	6	7	12
$4p(1/2)_0$	7086.70	7	6	6	6	5
$4p'(3/2)_1$	7125.82	29	24	27	24	21
$4p'(3/2)_2$	7206.98	100	100	100	100	100
$4p'(1/2)_1$	7316.01	38	39	31	39	36
$4p'(1/2)_0$	8037.23	13	14		14	13
$4p(1/2)_1$-$7s(3/2)_1$	5439.99	18	18	16	18	13
$4p(5/2)_2$	5928.81	100	100	100	100	100
$4p(3/2)_1$	6098.80	46	49	49	50	52
$4p(1/2)_1$-$7s'(1/2)_1$	5054.18	23	50	57	50	
$4p(5/2)_2$	5473.45	29	22	31	23	
$4p(3/2)_1$	5618.01	22	23	22	23	
$4p'(3/2)_2$	6025.15	100	100	100	100	
$4p(5/2)_2$-$9s(3/2)_1$	5216.28	31	64	64		
$4p(3/2)_1$	5347.41	60				
$4p(1/2)_0$	5639.11	100	100	100		
$4p(1/2)_1$-$9s(3/2)_2$	4836.70	48	42	41		
$4p(5/2)_3$	5177.54	100	100	100		
$4p(5/2)_2$	5219.30	21				
$4p(3/2)_1$	5350.58	25				
$4p(3/2)_2$	5393.97	53	40	39		

TABLE IV. Transition probabilities of *s-p* lines of Ar I calculated in *jK* coupling ($10^5\ s^{-1}$).

Lower level \ Upper level	$6s(3/2)_2$	$7s(3/2)_2$	$8s(3/2)_2$
$7p(3/2)_2$			1.61
$7p(3/2)_1$			0.18
$7p(5/2)_2$			0.19
$7p(5/2)_3$			2.81
$7p(1/2)_1$			1.06
$6p(3/2)_2$		4.04	1.48
$6p(3/2)_1$		0.45	0.17
$6p(5/2)_2$		0.49	0.19
$6p(5/2)_3$		7.08	2.78
$6p(1/2)_1$		2.74	1.13
$5p(3/2)_2$	13.27	4.36	2.32
$5p(3/2)_1$	1.50	0.49	0.26
$5p(5/2)_2$	1.60	0.55	0.29
$5p(5/2)_3$	23.06	8.09	4.35
$5p(1/2)_1$	9.03	3.35	1.82
$4p(3/2)_2$	17.73	7.91	4.35
$4p(3/2)_1$	2.03	0.90	0.49
$4p(5/2)_2$	2.21	0.88	0.54
$4p(5/2)_3$	31.60	14.16	7.78
$4p(1/2)_1$	12.94	5.82	3.19

sults are compared with the experimental ones obtained in stabilized arc experiments,[11,12] with the compilation work of Wiese *et al.*[13] and also with the theoretical calculations performed in IC by Johnston.[14]

In order to obtain absolute transition probabilities, experimental lifetimes and branching ratios have been used. As it is deduced from the values of Table I, the present *jK* coupling calculations give account of the measured lifetimes for the $ns(3/2)_2$ ($n=6,7,8$) levels. Therefore we have used the calculated transition probabilities of infrared lines out of the spectral measurement range to evaluate their contribution to the branching ratios. In Table IV the *jK* coupling transition probabilities of lines originating in $ns(3/2)_2$ levels are given. The values of Table II agree with the results of Ref. 11 and of Ref. 13 within their confidence range. Comparing with the IC theoretical calculations[14] discrepancies are less than 38%.

In regard to the relative transition probabilities shown in Table III, we found good agreement in comparing our results with the values existing in literature,[11–14] the exceptions being the 5054.18, 5216.28, and 6384.72 Å lines.

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