

Additional Results on the Ar V Spectrum

G. H. Cavalcanti*, F. R. T. Luna and A. G. Trigueiros

*Instituto de Física "Gleb Wataghin", Universidade Estadual de Campinas
13083-970, Campinas, SP, Brazil*

C. J. B. Pagan

*Faculdade de Engenharia Elétrica-DMCSI, Universidade Estadual de Campinas
13083-970, Campinas, SP, Brazil*

M. Raineri, F. Bredice, M. Gallardo and J. G. Reyna Almandos

Centro de Investigaciones Ópticas (CIOp), C.C. 124, 1.900 La Plata Argentina

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The atomic-emission spectrum of four times ionized argon, Ar V, has been observed in the vacuum ultraviolet (VUV). We studied in this work the $3s \sim 3p \sim 3s3p \sim 3s2p2 \sim 3s2p3d$ and $3s2p2 \leftarrow 3s2p4s$ transition arrays and 52 lines have been identified as transitions between levels of these configurations. Nine of these lines are reported here for the first time. Twenty one energy level values belonging to these configurations were determined and we propose 2 new energy level values. The identifications are supported by relativistic Hartree-Fock calculations.

I. Introduction

The ground state configuration of four times ionized argon, (Ar⁴⁺) is $3s^23p^2$ with the terms 3P , 1D , and 1S . The Ar V spectrum belongs to the Si I isoelectronic sequence. The spectra of the first and second elements in this sequence are presented in the book Atomic Energy Levels (AEL)^[1]. A complete tabulation of the silicon energy levels including Si I levels was made by Martin and Zalubas^[2]. Subsequent to this tabulation, Martin^[3] and Svendenius *et al.*^[4] reinvestigated and extended the knowledge of the spectrum of P II. Early results on the spectra of S III and Cl IV have been published in AEL. Later on, results for S III were published by Smitli *et al.*^[5]. The Ar V spectrum was studied using various kinds of spectral sources. The spectra of argon in the extreme ultraviolet were studied early by Boyce^[6], using an electrodeless light source, and by Phillips and Parker^[7] using a spark source. Using a capillary source, Schönheit^[8] studied the spectra of multiply ionized inert gases, including argon, and determined the degree

of ionization of the ions, but no classification of the lines was made. Some of these lines were later classified in the work of Ekberg *et al.*^[9]. An experimental study of the low lying configurations in the Si I sequence was made by Smitt *et al.*^[10]. Using a theta-pinch light source Fawcett *et al.*^[11] have classified some lines of Ar V. In the work of De-Ye *et al.*^[12] few lines of Ar V were also classified. Using the beam-foil technique Livingston *et al.*^[13] have studied the argon spectra from Ar V to Ar VIII. Ellis and Martinson^[14] predicted the $3s3p^3 \ ^5S^o$ level in the Si I sequence, that is the lowest energy level for quintet system. More recently, Trabert *et al.*^[15-18] studied the VUV spectrum of argon and other ions in a search for intercombination lines of Mg, Al, and Si-like ions. Recoil ions spectroscopy was used by Lesteven-Vaisse *et al.*^[19] who have studied the argon spectra from Ar I to Ar X.

Many sets of theoretical calculations for the Si I isoelectronic sequence including Ar V levels, transition probabilities, oscillator strengths and lifetimes have been published^[22-25]. Experimental data for higher degrees of ionization in the Si I isoelectronic sequence were

*Permanent address: Instituto de Física, Universidade Federal Fluminense, Niterói, 24040-005, RJ, Brazil.

used by Biémont^[20,21] (and references cited therein) to predict transitions from K VI through Ti IX, and energy levels and oscillator strengths from V X to Ni XV.

There is a renewed interest in spectroscopic data from rare gases due to applications in collision physics, laser physics, photoelectron spectroscopy and fusion diagnostics. In this last field the study of intercombination lines is important for the diagnostics of laboratory and astrophysical plasmas^[26,27].

In the present work we report additional results for Ar V, applied to the study of the energy levels of the configuration $3s^23p^2$, $3s^23p3d$ and $3s^24p4s$ and the transitions between them.

III. Experiment

The light source used in the present work is a discharge tube built at Centro de Investigaciones Ópticas (CIOp), La Plata, Argentina., to study highly ionized gases^[28]. It is made with a pyrex tube with an inner diameter of 3 mm and 300 mm long, with one end of the tube connected directly to a vacuum spectrograph through a nylon flange adaptor. The other end has a glass window for observations of discharge and alignment of the tube. The electrodes, placed 200 mm apart, were made of tungsten covered with indium. Gas excitation was produced by discharging through the tube a low inductance capacitor varied from 2.5 to 100 nF voltage up to 19 kV.

Light emitted axially was analyzed using a 3 m normal incidence vacuum spectrograph with a concave diffraction grating with 1200 lines/mm, blazed for 1200 Å. The plate factor in the first order is 2.77 Å/mm. Ilford Q-2 plates were used to record the spectra. C, N, O, and known lines of argon were also recorded as internal wavelength standards. Exposing the plates with 10^3 shots we were able to obtain good lines of argon spectra. A number of experimental parameters, e. g., gas pressure, discharge voltage, and capacitance, were varied to distinguish among different states of ionization. A well developed Ar V spectrum was obtained with the following parameters: 175 mTorr, 18 kV, and 20 nF. The positions of spectral lines on the plates were determined with a rotating prism photoelectric automatic

Grant comparator, with a precision of 1 μ m. The wavelength determined by this procedure is estimated to be ± 0.01 Å in the first diffraction order.

A similar experiment using a theta-pinch built at the Instituto de Física at the Universidade Estadual de Campinas, Brazil^[29], confirmed the lines obtained in Argentina and was very helpful in the task of assigning ionization stages to the individual spectral lines observed^[31]. However we prefer to publish the lines of the first experiment because in Brazil the 2-m normal incidence spectrograph has a less favourable plate factor (4.61 Å/mm).

III. Analysis

Line identifications were guided by theoretical predictions obtained from Cowan's computer codes^[30]. The calculations were made at the Instituto de Física, UNICAMP. The predictions were obtained by diagonalizing the energy matrices with appropriate relativistic Hartree-Fock (HFR) values for the energy parameters. The interpretation of configuration level structures was made by a least-square fit of the energy parameters to the observed levels.

Table I shows the 53 identified lines in the $3s^23p^2 \leftarrow 3s3p^3$, $3s^23p^2 \leftarrow 3s^23p3d$ and $3s^23p^2 \leftarrow 3s^23p4s$ transition arrays. For 9 of these lines the classification is new. Table II shows the 24 determined energy levels belonging to the $3s^23p^2$, $3s3p^3$, $3s^23p3d$ and $3s^23p4s$ configurations with the uncertainty for each level. Optimization of the energy level values was done from the observed wavelengths by an iterative procedure^[32,33] in which the individual wavelengths are weighted according to their uncertainties, where 3 of these levels are new. Table III shows the energy parameters for the $3p^23p^2$ ground configuration. The standard deviation of the fit of the energy levels is 24 cm^{-1} for 5 observed levels. Table IV shows the energy parameters for $3s3p^3$, $3s^23p3d$ and $3s^23p4s$ configurations. The standard deviation of the fit is 151 cm^{-1} for 23 observed levels. In order to obtain a better interpretation of the $3s^23p^2$ ground configuration it was necessary to introduce in the calculation the $3p^4$, $3s3p^23d$ and $3s^23d^2$ excited configurations. The $3s^23p^2$ configuration is mainly affected

Table I. Classified lines in the $3s^23p^2 \leftarrow 3s3p^3$, $3s^23p^2 \leftarrow 3s^23p3d$ and $3s^23p^2 \leftarrow 3s^23p4s$ transition arrays in Ar V.

Intensity ^a	Wavelength ^b (Å)	Transition
1	336.57	$3s^23p^2\ ^3P_1 - 3s^23p4s\ ^3P_2^0$
1	337.58	$3s^23p^2\ ^3P_0 - 3s^23p4s\ ^3P_1^0$
1	338.01	$3s^23p^2\ ^3P_2 - 3s^23p4s\ ^3P_2^0$
1	338.45	$3s^23p^2\ ^3P_1 - 3s^23p4s\ ^3P_1^0$
1	339.02	$3s^23p^2\ ^3P_1 - 3s^23p4s\ ^3P_0^0$
1	339.89	$3s^23p^2\ ^3P_2 - 3s^23p4s\ ^3P_1^0$
2	350.88	$3s^23p^2\ ^1D_2 - 3s^23p4s\ ^1P_1^0$
1	357.23 ^b	$3s^23p^2\ ^1D_2 - 3s^23p4s\ ^3P_1^0$
3	379.69	$3s^23p^2\ ^1S_0 - 3s^23p4s\ ^1P_1^0$
1	411.01 ^b	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^1F_3^0$
3	436.63	$3s^23p^2\ ^1D_2 - 3s^23p3d\ ^1F_3^0$
3	445.97	$3s^23p^2\ ^3P_0 - 3s^23p3d\ ^3D_1^0$
2	446.96	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^3D_2^0$
3	447.53	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^3D_1^0$
2	449.08	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^3D_3^0$
3	449.50	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^3D_2^0$
3	452.39 ^b	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^1D_2^0$
2	454.99 ^b	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^1D_2^0$
3	458.09	$3s^23p^2\ ^3P_0 - 3s^23p3d\ ^3P_1^0$
3	458.96	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^3P_0^0$
3	459.73	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^3P_1^0$
2	461.24	$3s^23p^2\ ^3P_1 - 3s^23p3d\ ^3P_2^0$
2	462.41	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^3P_1^0$
3	463.94	$3s^23p^2\ ^3P_2 - 3s^23p3d\ ^3P_2^0$
1	466.79	$3s^23p^2\ ^1S_0 - 3s^23p3d\ ^1P_1^0$
3	486.57 ^b	$3s^23p^2\ ^1D_2 - 3s^23p3d\ ^1D_2^0$
1	495.09	$3s^23p^2\ ^1D_2 - 3s^23p3d\ ^3P_1^0$
2	511.89	$3s^23p^2\ ^3P_0 - 3s3p^3\ ^1P_1^0$
2	513.90	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^1P_1^0$
2	517.26	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^1P_1^0$
3	522.08	$3s^23p^2\ ^3P_0 - 3s3p^3\ ^3S_1^0$
3	524.19	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^3S_1^0$
3	527.68	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^3S_1^0$
2	536.75	$3s^23p^2\ ^1S_0 - 3s3p^3\ ^3D_1^0$
3	558.48	$3s^23p^2\ ^1D_2 - 3s3p^3\ ^1P_1^0$
2	570.65	$3s^23p^2\ ^1D_2 - 3s3p^3\ ^3S_1^0$
4	635.17	$3s^23p^2\ ^1S_0 - 3s3p^3\ ^1P_1^0$
2	650.95 ^b	$3s^23p^2\ ^1S_0 - 3s3p^3\ ^3S_1^0$
3	651.68	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^1D_2^0$
4	705.33	$3s^23p^2\ ^3P_0 - 3s3p^3\ ^3P_1^0$
2	708.57 ^b	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^3P_0^0$
5	709.20	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^3P_2^0$
5	715.64	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^3P_2^0$
4	725.09	$3s^23p^2\ ^1D_2 - 3s3p^3\ ^1D_2^0$
4	822.17	$3s^23p^2\ ^3P_0 - 3s3p^3\ ^3D_1^0$
4	827.03	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^3D_2^0$
4	827.35	$3s^23p^2\ ^3P_1 - 3s3p^3\ ^3D_1^0$
4	834.91	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^3D_3^0$
4	835.79	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^3D_2^0$
4	836.13	$3s^23p^2\ ^3P_2 - 3s3p^3\ ^3D_1^0$
2	948.98 ^b	$3s^23p^2\ ^1D_2 - 3s3p^3\ ^3D_2^0$
2	949.38 ^b	$3s^23p^2\ ^1D_2 - 3s3p^3\ ^3D_1^0$

^aThe intensities of the lines are visual estimates of plate blackening. They vary from 1 to 5. ^bNew identification.

Table II. Energy levels of the $3s^23p^2$, $3s3p^3$, $3s^23p3d$ and $3s^23p4s$ configurations of Ar V

Configuration	Term Designation	Energy cm ⁻¹	Uncertainty cm ⁻¹
$3s^23p^2$	3P_0	0.0	2.0
	3P_1	767.1	2.0
	3P_1	2032.1	1.0
	1D_2	16302.0	1.0
	1S_0	37919.4	2.0
$3s3p^3$	3D_1	121631.8	1.0
	3D_2	121678.8	1.0
	3D_3	121803.9	2.0
	3P_2	141768.6	1.0
	3P_1	141782.1	3.0
	3P_0	141879.5 ^[a]	3.0
	1D_2	154216.2 ^[a]	1.0
	3S_1	191545.4	1.0
	1P_1	195356.8	1.0
$3s^23p3d$	3P_2	217575.6	3.0
	3P_1	218290.0	3.0
	1P_0	218651.1	14.0
	1D_2	221817.5 ^[a]	3.0
	3D_1	224223.5	4.0
	3D_2	224501.3	8.0
	3D_3	224710.3	10.0
	1F_3	245335.9 ^[a]	6.0
	1P_1	252135.0	5.0
$3s^23p4s$	3P_0	295735.0	9.0
	3P_1	296234.9	5.0
	3P_2	297882.2	6.0
	1P_1	301295.7	6.0

^[a] New level determined in this work.

Table III. Energy Parameters for the $3s^23p^2$ configurations of Ar V

Configuration	Parameter	HFR Value (cm^{-1})	Fitted Value ^[a] (cm^{-1})	ratio Fitted/HF
$3s^23p^2$	E_{av}	0	26254 ± 13	
	$F^2(3p, 3p)$	75818	62651 ± 53	0.83
	ζ_{3p}	1246	1378 ± 22	1.11

[a]The *rms* deviation of the fit is 24 cm^{-1} for 5 observed levels.

Table IV. Energy Parameters for the $3s^23p^3$, $3s^23p3d$ and $3s^23p4s$ configurations of Ar V.

configuration	parameter	HFR Value (cm^{-1})	Fitted Value ^[a] (cm^{-1})	ratio Fitted/HF
$3s3p^3$	E_{av}	136214	164465 ± 80	1.21
	$F^2(3p, 3p)$	75647	65985 ± 283	0.87
	$G^1(3s, 3p)$	102393	93546 ± 144	0.91
	ζ_{3p}	1246	1395 ± 101	1.12
$3s^23p3d$	E_{av}	198613	221995 ± 122	1.12
	$F^2(3p, 3d)$	69452	62913 ± 364	0.91
	$G^1(3p, 3d)$	86465	74797 ± 399	0.86
	$G^3(3p, 3d)$	53372	40386 ± 415	0.76
	ζ_{3p}	1267	1419 ± 103	1.12
	ζ_{3d}	49 ^[b]		
$3s^23p4s$	E_{av}	289964	298223 ± 81	1.13
	$G^1(3p, 4s)$	7978	6516 ± 109	0.82
	ζ_{3p}	1349	1510 ± 109	1.12

[a]The *rms* deviation of the fit is 24 cm^{-1} for 10 observed levels.

[b]Fixed during the fitting procedure.

by the $3p^4$ configuration through the $s^2 \leftarrow p^2$ interaction. The $3s^2 3p^2$, $3s 3p^2 3d$ and $3s^2 3d^2$ configurations are also interacting very strongly. In the calculations for the $3s 3p^3$, $3s^2 3p 3d$ and $3s^2 3p 4s$ configurations we have included the $3s^2 3p 4d$, $3p^3 3d$ and $3s 3p 3d^2$ configurations to take into account their interaction.

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