THE FIRST SPECTRUM OF ANTIMONY

By William F. Meggers and Curtis J. Humphreys

ABSTRACT

The spectrum emitted by neutral antimony atoms has been photographed, measured, and analyzed. Measured wavelengths and estimated relative intensities are given for 466 lines, ranging from 1388.91 to 12466.75 A in wavelength and from 1 to 2500 in intensity. Nearly 80 percent of these lines are classified as combinations of 60 even energy levels arising from $5s^2 5p^2 ns$, $5s^2 5p^2 nd$, and $5s5p^4$ electron configurations and 31 odd levels from $5s^2 5p^3$, $5s^2 5p^2 np$, and possibly $5s^2 5p^2 nf$. The average difference between observed and computed wave numbers is 0.15 cm^{-1}. A paucity of lines in the visible spectrum and intense radiation of antimony atoms in the ultraviolet and infrared are seen to be consequences of the relative values of various groups of levels. Although it is not possible to give a complete quantum interpretation of all the levels, several spectral series of the type $5s^2 5p^3 - 5s^2 5p^2 ns$ are proposed, and an absolute value of 69700 cm^{-1} is deduced for the ground state, $5s^2 5p^3.{}^4S_{0\frac{1}{2}}$, of neutral antimony atoms. From spectroscopic data, the principal ionization potential of antimony is calculated to be 8.64 volts.

CONTENTS

I. INTRODUCTION

During the past 90 years the emission spectra of antimony have been described and discussed in scientific literature more than 100 times, but unfortunately it remained true that information on this subject was far from complete or satisfactory. Undoubtedly, this state of affairs for the first spectrum of antimony is attributable, at least in part, to the extraordinary character of this spectrum. When antimony atoms are excited to radiate in flames or in electric arcs they emit next to nothing in the visible range but radiate powerfully in the ultra-violet and infrared. Under similar circumstances most metals emit atomic spectra with maximum intensity in or near the visible and with relatively little strength in the shorter ultraviolet or longer infrared.

Several years ago when improved infrared-sensitive photographic plates became available we succeeded in recording all antimony waves previously observed only radiometrically, and in addition found many

463

new lines of long wavelength. Efforts to classify the new lines as combinations of known energy levels disclosed the fact that relatively little was known about the structure of this spectrum. Discrepancies among the data and interpretations of different workers appeared to be explained mainly by incomplete and unreliable descriptions. We, therefore, decided to observe the entire spectrum more carefully. The arc spectrum of antimony was accordingly photographed and measured from its limit below 1400 A in the ultraviolet to wavelengths exceeding 12000 A in the infrared. The results of this investigation are reported in this paper.

References to 54 publications dealing with the spectra of antimony previous to 1912 have been compiled and discussed by Kayser [1].[1] About 50 more papers concerned with antimony spectra have since appeared, but only those which are considered relevant to the description and analysis of the Sb I spectrum will be mentioned here. It may be noted that the first useful measurements of antimony arc spectra were made by Kayser and Runge [2] in 1893. They measured the wavelengths of 70 Sb arc lines (5730.52 to 2068.54 A) on Rowland's scale and at the same time discovered the first regularities in this spectrum. Schippers [3], a student of Kayser's, measured both the arc and the spark spectrum of antimony relative to international standards for the first time in 1912. In the arc spectrum he measured 94 lines (2068.38 to 6648.134 A), but 2 of these (5700, 5782) represent copper, and 15 others (5774 to 6648 A) have not been confirmed as characteristic of antimony. Walters [4] in 1921 photographed 75 antimony arc lines with wavelengths between 5531.89 and 9132.30 A, using plates sensitized by bathing in solutions of pinacyanol and dicyanin. The only other long-wave antimony data published heretofore are wavelengths and galvanometer deflections for 16 lines (9519.9 to 12118.9 A) detected radiometrically by Randall [5] in a 20-ampere carbon arc in which antimony metal was vaporized. An attempt by Lehmann [6] to observe the infrared arc spectrum of antimony by means of phosphorophotography did not yield any important results.

The first investigation of the arc spectrum of antimony for emission shorter than 2000 A was made in 1917 by Takamine and Nitta [7], who photographed, with a small quartz spectrograph, 13 lines with wavelengths ranging from 1989.3 to 1890.3 A. McLennan, Young, and Ireton [8], working with a small fluorite spectrograph in 1920, reported 36 lines (1931.0 to 1437.0 A) as characteristic of the antimony arc in a vacuum. During the past 20 years the only other attempt to describe the first spectrum of antimony in the extreme ultraviolet is that of L. and E. Bloch [9], who varied conditions in an electrodeless discharge and separated the observed lines into five successive stages of ionization. Unfortunately, the electrodeless discharge gave a very feeble Sb I spectrum, so that only six lines shorter than 2000 A (1970.88 to 1698.91 A) were assigned to the first spectrum. Comparison of the above lists with each other shows little or no agreement and brands each and all of them entirely inadequate as a useful description of the extreme ultraviolet Sb I spectrum.

The most direct manner of determining the normal state of any atom is to observe which of its characteristic atomic spectral lines are absorbed by unexcited atoms. Attempts to do this for antimony

---

[1] Figures in brackets indicate the literature references at the end of this paper.

have been made by Dobbie and Fox [10], Grotrian [11], Ruark, et al. [12], Narayan and Rao [13], McLennan and McLay [14], Frayne and Smith [15], Zumstein [16], and Charola [17]. Most of these observers found only banded and continuous absorption, indicating that unexcited antimony vapor is usually polyatomic. McLennan and McLay [14] reported finding four lines absorbed in the extreme ultraviolet (1525.2, 1514.1, 1483.5, and 1481.0 A), but it is doubtful if any of these represent antimony. By slowly admitting antimony vapor into a hot carbon tube at about 1,400° C, Zumstein [16] obtained a dissociation of the molecules into atoms, and observed five absorption lines with wavelengths 2311.50, 2175.88, 2127.46, 2068.38, and 2023.86 A. These lines are shown by analysis of spectral structure to result from combinations of the ground state with the first five excited states; they are the only ones longer than 2000 A that can be absorbed by neutral antimony atoms.

It has been observed repeatedly that many ultraviolet antimony lines are more or less self-reversed in the ordinary arc and in the underwater spark. An investigation of the latter phenomenon was made in 1924 by Hulburt [18], who found that for antimony the underwater spark reversals included all the observed arc reversals and seven lines in addition (2224.98, 2220.80, 2207.7, 2145.03, 2141.8, 2139.76, 2127.55 A). Buffam and Ireton [19] also studied the underwater spark of antimony but observed only eight lines (2790.50, 2769.97, 2670.81, 2652.73, 2598.24, 2528.68, 2311.71, 2288.99 A), the first of which belongs to Sb ii.

The Zeeman effect of antimony lines has been measured by van der Harst [20] and by Löwenthal [21]. The former observed 29 lines (2311 to 4352 A), but all patterns are given as triplets except 4 quartets and 1 quintet. Löwenthal published only 18 lines (2311 to 4033 A) but employed higher resolution, which permitted the calculation of precise values for the splitting factors and absolute determination of the inner quantum numbers of the atomic energy levels.

Further publications dealing with antimony spectra will be noted below in connection with the discussion of our results.

II. EXPERIMENTS

This new description of the Sb I spectrum was obtained by employing conventional arcs (and sparks) at atmospheric pressure and photographing the spectra from 2000 to 13000 A with large concave gratings. Arcs were operated on a direct-current circuit with 220 volts applied potential, and with a series resistance to regulate the current between 6 and 12 amperes, except for the ultraviolet, as described below. Antimony has a relatively low melting point (630°C), and for this reason it is not possible to use solid electrodes in the arc. Lumps of pure antimony were burned in an arc having a pure copper rod (6 mm in diameter) as upper electrode and a pool of molten antimony in a cupped lower electrode of copper (12 mm in diameter). Comparison spark spectra of antimony were made throughout the visible and ultraviolet to 2000 A, so that any lines belonging to ionized atoms which might appear on the arc spectrograms could be recognized and removed from the final list of Sb I lines.

The extreme ultraviolet data for wavelengths shorter than 2000 A were obtained from arc spectrograms made by A. G. Shenstone at

Princeton University. Shenstone used arcs of 1 to 2½ amperes between water-cooled electrodes of pure antimony, or antimony versus copper or carbon, in an atmosphere of pure nitrogen. The interval 1200 to 2200 A was recorded on Ilford Q plates with a normal-incidence vacuum spectrograph [22] having a 2–m glass grating ruled 30,000 lines to the inch. The dispersion is 4.2 A/mm and the definition and resolving power are excellent, although the photographic contrast of the plates used is rather low. Full exposures were obtained in 30 minutes.

On spectrograms made by Shenstone, it was easy to distinguish between lines characteristic of neutral atoms and those arising from ionized atoms because the latter appeared only (or greatly enhanced) at the electrodes. Among some 300 antimony lines appearing in arc spectrograms from 1239 to 2200 A, at least 70 were recognized as belonging to ionized atoms.

Spectrograms covering the range 2000 to 13000 A were made at this Bureau with stigmatic concave-grating spectrographs [23]. An aluminized Pyrex grating (22 ft in radius) ruled 30,000 lines per inch was used in the first order from 2000 to 8200 A and in the second order from 2500 to 4300 A. In the second order the dispersion averages 1 A/mm. The entire infrared photographically accessible was recorded with a speculum grating ruled with 7,500 lines per inch, giving a scale of 10 A/mm. With these spectrographs and with the photographic plates listed below, exposure times required to photograph the arc spectrum of antimony ranged from 1 or 2 minutes in the near ultraviolet to 4 hours for the infrared limit. The following types of spectroscopic plates supplied by the Research Laboratory of the Eastman Kodak Co. [24] were used. Plates coated with No. 33 emulsion were employed in the range 2000 to 4800 A, *F*-sensitized plates from 4500 to 6800 A, *N*-sensitized from 6500 to 8500 A, *Q*-sensitized from 8000 to 11000 A, and *Z*-sensitized from 10000 to 13000 A.

The wavelengths of antimony lines were measured by interpolating between standard lines of iron, the iron arc spectrum being photographed adjacent to antimony on all spectrograms except those in the extreme ultraviolet, which had sufficient lines of copper, carbon, nitrogen, or oxygen to fix the scale and corrections for each exposure. These antimony wavelengths are thus based on international secondary standards of iron [25] or on interferometer values of iron and copper lines by Burns and Walters [26], supplemented in the extreme ultraviolet by values of carbon, nitrogen, and oxygen "impurity" lines recommended as tentative standards by Boyce and Robinson [27]. In the infrared and ultraviolet, outside the present limits of international secondary standards (6700 to 2500 A) interferometer values of iron lines measured at this Bureau [28] were used as standards. Beyond 8600 A the first-order grating spectrum of antimony was usually measured relative to iron lines in the second or third order, doubling or trebling the interpolated values of the apparent wavelengths of antimony lines to obtain their true values. It will be understood that the first-order was photographed with an infrared filter interposed between source and slit, whereas the second and third orders were recorded by removing the filter.

All spectrograms were measured both direct and reversed on a comparator reading to 0.001 mm, and all lines were observed on four

or more spectrograms except the faintest, which were discarded unless confirmed by a second exposure. It is difficult to determine the wavelengths of antimony lines from conventional sources within 0.01 A because most of the line images are either hazy, wide, and unsymmetrical, or wide and more or less self-reversed. Nevertheless, the agreement between results from different spectrograms, and the establishment of additional energy levels reported below, indicate that the description of the first spectrum of antimony has been improved as well as greatly extended.

III. RESULTS

1. WAVELENGTHS OF Sb I LINES

Data for 466 lines characteristic of neutral antimony atoms are presented in table 1, where wavelengths, relative intensities, vacuum wave numbers, term combinations of classified lines, and differences of observed and calculated wave numbers appear in successive columns. Since the wavelengths shorter than 2000 A are vacuum values, the corresponding wave numbers are direct reciprocals of the observed wavelengths. The remaining wavelengths are valid for standard air and must be multiplied by the refractive index of air to convert them to vacuum values. Vacuum wave numbers for lines between 2000 and 10000 A were taken directly from Kayser's "Tabelle der Schwingungszahlen" [29], but for lines of longer wavelengths the values were obtained by computing the reciprocals of the wavelengths which have been corrected to vacuum with the aid of the dispersion formula of Meggers and Peters [30].

TABLE 1.—*First spectrum of antimony* (Sb I)

λ_{air} A	Intensity, character	$\nu_{vac.}$ cm⁻¹	Combination	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm⁻¹	λ_{air} A	Intensity, character	$\nu_{vac.}$ cm⁻¹	Combination	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm⁻¹
12466.75	2	8019.14	5—13°	−1	10794.11	80	9261.79	{10°—36 / 5—16°	0 / 0
12276.6	2	8143.35	4—8°	0	10773.84	10	9279.21	10—21°	+1
12116.06	5	8251.25	2—7°	−2	10741.94	800	9306.76	2—10°	−2
11957.7	1	8360.5	12—21°	+3	10717.89	4h	9327.64	12—27°	+1
11863.37	30	8427.01	10—19°	−2	10711.94	6h	9332.82	13°—48	−2
11518.7	2h	8649.1	11°—36	−3	10677.41	1000	9363.01	1—6°	+1
11455.2	10d+Sn	8727.3	14—25°	+4	10648.9	15h	9388.1		
11403.72	3	8766.67			10645.19	5h	9391.35	8—21°	−2
11381.25	6	8783.98	11—21°	0	10620.32	2h	9413.33		
11318.8	1	8832.4	12—24°	+1	10616.57	2	9416.67		
11315.08	3h	8835.34			10585.60	200	9444.22	5—17°	0
11274.93	3	8866.81			10576.1	4h	9452.7	7°—31	0
11272.27	9h	8868.90			10488.3	50H	9531.8		
11266.23	150	8873.66	4—11°	0	10460.56	6h	9557.10	13°—50	+1
11227.61	10h	8904.18			10405.1	5h	9608.0		
11189.61	30	8934.42			10382.2	3h	9629.2	7°—32	−3
11183.66	2h	8939.17			10364.33	50	9645.83	10—22°	+1
11112.82	4h	8996.16	7°—29	−2	10265.2	6h	9739.0	11—26°	−2
11108.52	50h	8999.64	11—*64728.0*	−1	10261.01	300	9742.96	4—14°	0
11104.84	50h	9002.62	4—12°	−1	10252.14	2h	9751.39	{10—24° / 11—27°	+2 / +1
11084.98	30h	9018.75	6°—25	0	10245.15	5	9758.04	8—22°	−2
11079.95	40h	9022.84			10163.77	6h	9836.18	8—23°	−1
11012.79	300	9077.87	4—13°	+1	10135.70	2h	9863.41	8—24°	−3
10925.29	15	9150.57	11—22°	0	10108.8	2	9889.7	6°—27	0
10879.55	400	9189.04	2—8°	0	10078.49	200	9919.40	2—11°	0
10868.58	200	9198.32	5—15°	−1	10060.5	1H	9937.1	17—31°	+1
10848.0	4h	9215.8			10045.24	1	9952.24		
10839.73	600	9222.79	2—9°	−1	9987.3	2H	10010.0	8°—39	−4
10832.8	8h	9228.7	11—23°	0	9973.1	2H	10024.2		
10801.0	3h	9255.9	11—24°	−2	9949.14	400	10048.37	2—12°	0

TABLE 1.—*First spectrum of antimony* (Sb I)—Continued

λair A	Intensity, character	νvac. cm⁻¹	Combination	νobs.-νcalc. 0.1 cm⁻¹	λair A	Intensity, character	νvac. cm⁻¹	Combination	νobs.-νcalc. 0.1 cm⁻¹
9866.78	30	10132.24	7—19°	+1	7834.2	5H	12761.0		
9854.67	2	10144.69	11°—44	0	7817.0	7Hw	12789.1		
9847.80	4	10151.77	10°—42	0	7765.4	20Hw	12874.1		
9775.13	20	10227.24	10—25°	+1	7755.83	15	12889.98	2—17°	+1
9766.88	5	10235.88	{7°—35 / 9°—42}	−1 / 0	7648.28	30h	13071.24		
					7593.06	8h	13166.30		
9756.72	25	10246.54	10—27°	+1	7556.32	3h	13230.32	7°—52?	−5
9746.69	2	10257.08	4—15°	+1	7405.05	8H	13500.58	6°—45	+1
9705.38	2H	10300.75	11—29°	0	7361.84	4h	13579.82	7—67108.0	+1
9675.69	4	10332.35	9—26°	0	7136.40	5h	14008.81	3—18°	−1
9672.8	1	10335.4	10—28°	0					
					7033.04	4h	14216.7		
9669.16	4	10339.33	8—25°	−3	7006.17	4h	14269.2	5—19°	−1
9662.5	20	10346.5	8—26°	−3	6811.38	2	14677.3		
9661.6	7	10347.4	6°—28	−4	6640.63	2h	15054.7	2—18°	+1
9602.94	20	10410.62			6611.49	20	15121.0	5—21°	−2
9568.94	4h	10447.61	8—28°	−3					
					6517.07	6	15340.1	1—15°	0
9546.12	10h	10472.59	16—31°	0	6490.23	4	15403.5	1—16°	0
9518.68	400	10502.78	4—17°	0	6454.97	8	15487.7	5—22°	−1
9455.80	4h	10572.62	7°—37	0	6221.44	15h	16069.0	5—25°	−2
9448.75	1	10580.51	6°—29	−3	6213.94	6h	16088.4	5—27°	−1
9392.77	4	10643.57							
					6179.81	5h	16177.3	5—28°	−2
9390.2	1	10646.5	7°—38	+2	6178.82	7h	16179.8	4—21°	0
9386.8	2h	10650.3			6097.71	4	16395.1		
9315.4	8H	10732.0			6097.53	5	16395.5	4—64728.0	0
9265.9	1	10789.3			6013.53	2h	16624.6	4—23°	+1
9262.8	2	10792.9							
					5948.27	3h	16807.0	3—63798.1	0
9260.3	2h	10795.8	10—29°	0	5912.32	9h	16909.2	3—20°	0
9251.9	2h	10805.6			5830.34	60h	17446.2	5—30°	+1
9212.93	1	10851.33			5707.48	8h	17516.0		
9164.8	2h	10908.3	8—29°	0	5691.15	4h	17566.3		
9132.21	30	10947.25	1—7°	−2					
					5660.72	4h	17660.7		
9019.24	10	11084.37	3—14°	0	5632.02	100hl	17750.7	1—18°	+1
8999.52	1	11108.66	11—30°	−1	5602.19	30hl	17845.2		
8860.0	7h	11283.6	10°—47	0	5599.83	15hl	17852.7	2—63798.1	0
8816.6	6H	11336.6	14—31°	+1	5567.97	8h	17954.9	2—20°	0
8789.34	5h	11374.30							
					5556.10	40h	17993.2	3—24°	0
8742.1	2H	11435.8	6—22°	+2	5531.67	4h	18072.7		
8734.8	20Hl	11445.3			5490.32	30h	18208.8	4—66541.3	0
8719.87	7	11464.91	2—13°	0	5473.85	2h	18263.6		
8700.1	10H	11491.0	10°—48	−1	5414.38	8	18464.2		
8682.7	30h	11514.0	6—23°	+3					
					5402.57	15hl	18504.6	4—30°	0
8667.2	8H	11534.6			5384.44	15	18566.9	2—21°	0
8619.55	100	11598.35	3—15°	0	5280.17	8	18933.5	2—22°	0
8617.6	10Hl	11601.0	6°—33	−3	5250.90	4h	19039.1	2—24°	+1
8611.8	4h	11608.8	{5—18° / 8°—48}	−1 / −1	5117.82	3	19534.1	2—27°	−1
					4854.00	2	20595.8	2—665 413	−1
8594.6	4h	11632.0			4841.06	6	20650.9	1—20°	0
8572.64	150	11661.82	4—16°	0	4754.99	6h	21024.7		
8533.4	3h	11715.4	10°—50?	+5	4742.81	4h	21078.7	3—31°	−1
8532.7	1h	11716.4	8—30°	0	4599.60	4	21735.0	1—24°	0
8526.9	7h	11724.4	12—67876.6	−1					
8463.2	6h	11812.6	7°—44	0	4033.55	200	24785.1	5°—1	+2
					3722.79	200r	26854.0	4°—1	+2
8457.9	2h	11820.0			3637.83	250	27481.1	5°—2	+2
8411.69	60	11884.95	1—8°	0	3504.48	50	28526.8	5°—3	+2
8388.5	4H	11917.8	12—31°	0	3383.15	100	29549.8	4°—2	0
8378.40	8h	11932.18	7—25°	+2					
8349.94	4h	11972.85	9—67108.0	0	3347.10	5	29868.0	5°—4	+1
					3267.51	700r	30595.6	4°—3	+1
8314.25	20h	12024.24	6—26°	0	3232.52	600r	30926.7	5°—5	+1
8302.99	2h	12040.55	7—28°	+3	3029.83	500r	32995.6	4°—5	+1
8289.3	20Hw	12060.4			2877.92	1000R	34737.2	2°—1	−1
8270.11	20h	12088.48							
8257.8	15H	12106.4			2858.03	20	34978.9	5°—6	+1
					2851.11	100	35063.8	5°—7	0
8244.8	2h	12125.5	6—28°	+2	2769.95	400R	36091.1	3°—2	−2
8241.71	7	12130.07	2—14°	0	2727.23	80	36656.4	5°—8	+2
8238.9	3h	12134.2			2726.20	4	36670.2	5°—9	−4
8062.2	20Hw	12400.2							
7969.55	40H	12544.30			2718.90	150r	36768.7	5°—10	0
					2692.25	120	37132.6	4°—7	0
7924.65	200	12615.38	1—11°	0	2682.76	200r	37264.0	5°—11	+2
7906.67	10	12644.08	2—15°	0	2670.64	300r	37433.1	2°—2	−2
7867.17	20	12707.56	2—16°	+1	2652.60	200r	37687.7	5°—12	+1
7844.44	80	12744.39	1—12°	0					
7837.29	10h	12756.01	8—67876.6	+1					

TABLE 1.—*First spectrum of antimony* (Sb I)—Continued

λ_{air} A	Intensity, character	$\nu_{vac.}$ cm^{-1}	Combi- nation	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm^{-1}	λ_{air} A	Intensity, character	$\nu_{vac.}$ cm^{-1}	Combi- nation	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm^{-1}
2614.66	30	38234.5	5°−13	0	2098.01	10h	47649.0	5°−45	+5
2612.31	300r	38268.9	5°−14	0	2090.25	30	47825.9	4°−34	+1
2598.09	500R	38478.3	3°−4	−1	2087.47	25	47889.6	5°−46	+1
2598.05	1500R	38478.9	2°−3	−1	2081.05	10	48037.3	4°−35	0
2575.03	5	38822.9	5°−15	+2	2079.56	100	48071.7	5°−47	+2
2574.06	150	38837.5	4°−10	−1	2074.60	4	48186.6	2°−13	−3
2554.64	80	39132.7	5°−16	−1	2073.11	40	48221.3	2°−14	0
2528.52	2000R	39536.9	3°−5	−1	2068.33	1000R	48332.7	1°− 4	+2
2520.14	50	39668.4	5°−17	0	2066.57	7	48373.8	4°−37	−1
2514.56	40	39756.4	4°−12	−1	2063.43	50	48447.4	4°−38	−2
2510.54	100	39820.1	2°−4	−3	2057.36	10h	48550.3	5°−51?	
2481.74	40	40282.1	5°−18	0	2051.62	3	48726.3		
2480.44	150	40303.2	4°−13	−1	2049.57	150R	48775.0	2°−15	−1
2478.32	400	40337.7	4°−14	−1	3046.57	20	48846.5	4°−40	−9
2474.57	80	40398.8	5°−19	0	2045.93	2	48861.8	4°−41	−4
2445.51	400r	40878.9	2°−5	−1	2044.63	25	48892.8	3°−18	+3
2426.35	250	41201.7	4°−16	0	2040.96	4	48980.7		
2422.13	150	41273.4	5°−20	0	2039.77	70r	49009.3	{ 3°−19	0
2395.22	100	41737.1	4°−17	−2				4°−42	+7
2383.64	300h	41939.8	5°−21	+2	2036.62	9	49085.1	2°−16	−1
					2036.39	7	49090.7		
2373.67	400h	42116.0	5°−22	+3					
2360.50	80	42350.9	4°−18	−1	2031.53	3	49208.1		
2352.21	50	42500.2	5°−23	0	2029.49	60r	49257.5	4°−43	−1
2329.10	50	42921.8	5°−24	0	2027.45	2	49307.1		
2315.89	150	43166.6	5°−25	−1	2024.00	50	49391.1	1°− 5	0
					2014.91	3	49613.9	4°−44	0
2311.47	2500R	43249.2	1°−1	−2					
2306.46	300r	43343.1	{ 4°−20	+8	2014.63	20	49620.8	2°−17	0
			5°−26	−12	2012.33	20h	49677.5	5°−56	+5
2293.44	150r	43589.2	3°−6	0	2001.01	3	49958.5	4°−46	+1
2288.98	120	43674.1	3°−7	−1	$\lambda_{vac.}$ A				
2270.07	80	44037.8	5°−27	+1					
					1996.25	15h	50093.9		
2262.51	300r	44185.0	4°−22	−2	1990.67	40	50234.3	2°−18	−2
2235.00	4	44728.8	5°−29	0	1987.16	2	50323.1		
2224.93	120r	44931.2	2°−6	0	1986.05	60	50351.2	2°−19	−1
2221.98	100	44990.9	4°−24	+2	1982.82	15h	50433.2	4°−49	+2
2220.73	150r	45016.2	2°−7	0					
					1979.15	20h	50526.7	5°−58	+2
2218.96	5	45052.1	5°−30	0	1978.23	30	50550.2	3°−21	+2
2212.42	20	45185.2	5°−31	+1	1974.07	5	50656.8	4°−51	−2
2208.45	300r	45266.5	3°−8	−1	1971.34	20	50726.9	3°−22	+2
2207.73	20	45281.2	3°−9	+1	1966.03	10h	50863.9		
2203.81	10	45361.8	5°−32	−1					
					1964.3	80H	50909.		
2202.97	10	45379.0	3°−10	−1	1959.55	2	51032.1	4°−52	0
2201.32	200r	45413.1	4°−26	−1	1957.00	7h	51098.6		
2190.81	5	45630.9			1956.54	20	51110.6	3°−23	0
2185.15	20	45749.1	5°−33	−2	1952.15	10	51225.6	2°−20	−2
2184.7	5	45758.	5°−34						
					1950.39	200r	51271.8		
2183.54	20	45782.8			1944.42	3	51429.2	5°−59	+4
2179.19	250r	45874.2	3°−11	0	1943.82	10h	51445.1	4°−54	+4
2175.81	1500R	45945.4	1°− 2	0	1931.36	40	51777.0	3°−25	−1
2174.72	10	45968.5	5°−35	+1	1927.08	100	51892.0	2°−21	0
2170.88	15	46049.8	5°−36	+1					
					1925.82	10	51925.9		
2159.24	40	46298.0	3°−12	0	1924.74	8	51955.1	3°−25	+4
2158.91	50	46305.1	5°−37	+1	1920.53	10	52069.0	2°−22	+3
2155.48	20	46378.7	5°−38	0	1913.48	30H	52260.8		
2149.14	10	46515.5			1907.82	5h	52415.8	5°−60	0
2146.88	15	46564.5	4°−28	+1					
					1906.47	7	52453.0	2°−23	+4
2144.86	100R	46608.4	2°− 8	−2	1904.2	10H	52516.		
2144.17	10	46623.2	2°− 9	+1	1900.72	2	52611.6		
2141.83	50r	46674.3			1899.39	70	52648.5	3°−27	+4
2141.55	20	46680.4	5°−39	+1	1893.16	2	52821.7		
2139.69	100R	46721.0	2°−10	−1					
					1891.28	70	52874.2	2°−24	0
2137.05	50r	46778.7	5°−40	+2	1890.41	2	52898.6		
2136.4	3	46793.	5°−41		1887.5	40Hw	52980.		
2136.15	5	46798.4	4°−29	+7	1882.56	150r	53119.2	2°−25	+1
2132.46	2	46879.3	3°−14	0	1876.29	20	53296.7	2°−26	0
2127.39	100R	46991.0	1°− 3	−1					
					1874.80	40	53339.0	3°−29	−2
2118.48	80r	47188.7	5°−43	0	1871.15	300R	53443.1	1°− 6	−2
2117.25	40	47216.1	2°−11	−1	1869.23	5	53498.0	4°−59	+3
2107.66	20	47430.9	4°−32	+1	1868.17	50r	53528.3	1°−7	0
2100.53	4	47591.8			1863.50	30	53662.5	3°−30	0
2098.41	50r	47639.9	2°−12	−1					

TABLE 1.—*First spectrum of antimony* (Sb i)—Continued

$\lambda_{vac.}$ A	Intensity, character	$\nu_{vac.}$ cm⁻¹	Combination	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm⁻¹	$\lambda_{vac.}$ A	Intensity, character	$\nu_{vac.}$ cm⁻¹	Combination	$\nu_{obs.}-\nu_{calc.}$ 0.1 cm⁻¹
1858.89	60	53795.5	3°−31	0	1644.37	20h	60813.6		
1852.18	20	53990.4	2°−27	+3	1640.32	15	60963.7	1°−23	−10
1842.72	20	54267.6			1638.65	8	61025.8	3°−60	−4
1839.59	4	54359.9	3°−33	+2	1629.17	10	61380.9	2°−59	−3
1839.33	7	54367.6	3°−34	+3	1629.03	10	61386.2	1°−24	−1
1836.61	20	54448.1	2°−28	+2	1623.3	100Hw	61600.		
1832.21	40	54578.9	3°−35	+1	1622.55	8	61631.4	1°−25	+2
1829.50	100	54659.7	3°−36	−4	1617.90	10	61808.5	1°−26	−3
1828.78	10	54681.3	2°−29	+1	1612.8	200Hw	62004.		
1818.02	3	55004.9	2°−30	+4	1600.91	3h	62464.5		
1814.20	80r	55120.7	1°−8	0	1599.96	80R	62501.6	1°−27	−6
1813.65	20	55137.4	2°−31	−1	1588.32	8	62959.6	1°−28	−4
1810.50	50r	55233.4	1°−10	+2	1582.46	40R	63192.8	1°−29	−5
1808.62	25	55290.8	3°−39	+1	1574.41	30R	63515.9	1°−30	−7
1807.84	8	55314.6	2°−32	+3	1571.10	15	63649.7	1°−31	+1
1805.40	30	55389.4	3°−40	+5	1566.76	15r	63826.0	1°−32	−4
1800.18	150	55550.0	3°−42	−4	1557.29	30r	64214.1	1°−33	+3
1795.28	10	55701.6	2°−33	−1	1557.13	10	64220.7	1°−34	−7
1795.03	3	55709.4	2°−34	+1	1552.01	3	64432.6	1°−35	−3
1788.24	100r	55920.9	2°−35	+1	1543.96	20r	64768.5	1°−37	−10
1785.64	15	56002.3	2°−36	+2	1535.06	80R	65144.0	1°−39	−8
1782.79	9	56091.9			1532.74	120R	65242.6	1°−40	−4
1780.87	100r	56152.3	1°−12	+2	1532.38	15r	65258.0	1°−41	+2
1777.50	20	56258.8	{3°−45 / 2°−37?	−1	1523.15	4	65653.4	1°−43	+2
1775.21	20	56331.4	2°−38	+3	1516.35	8r	65947.8		
1765.76	100h	56632.8	2°−39	+1	1514.64	6r	66022.3		
1764.23	15	56681.9	3°−47	0	1512.57	50R	66112.6	1°−45	−4
1763.69	40r	56699.3	1°−13	+3	1503.50	2	66511.5		
1762.68	40r	56731.8	{1°−14 / 2°−40		1491.36	40h	67052.9	1°−51	+3
1762.24	20	56746.0	2°−41	+3	1486.57	20r	67268.9		
1757.79	50	56889.6	3°−48	0	1483.07	5	67427.7	1°−52	0
1755.18	10h	56974.2	3°−49	−3	1481.47	5r?	67500.5		
1750.91	15	57113.2	3°−50	0	1475.04	R10	67794.8	1°−53	+2
1750.06	15	57140.9	2°−43	−2	1474.05	R3	67840.3	1°−54	0
1748.30	6h	57198.4	3°−51	−1	1469.60	R5	68045.7	1°−55	−1
1745.59	9	57287.2	1°−15	0	1468.76	R60	68084.6		
1739.21	20	57497.4	2°−44	0	1467.54	R10	68141.2	1°−56	−3
1738.95	25	57506.0			1467.05	R5	68164.0		
1736.19	100r	57597.4	1°−16	0	1464.19	10h?	68297.1		
1728.86	15	57841.6	2°−46	−3	1463.96	R15	68307.9		
1724.56	2	57985.8	3°−54	−4	1463.45	R10	68331.7		
1723.43	150r	58023.8	2°−47	−1	1463.08	R10	68349.0	1°−57	0
1720.19	4	58133.1	1°−17	+2	1462.20	R20	68390.1		
1717.45	150r	58225.9			1459.79	R8	68503.0	1°−68503	
1716.93	80r	58243.5			1458.88	R20	68545.7		
1715.64	2	58287.3	3°−56	−1	1456.62	R30	68652.1	1°−68652	
1714.78	2	58316.5	2°−49	0	1449.46	R5	68991.2	1°−58	+2
1709.21	15h	58506.6			1442.40	R10	69328.9		
1703.45	30	58704.4			1441.39	R40	69377.5		
1702.22	20	58746.8	1°−18	+2	1430.76	10	69892.9	1°−59	−4
1698.85	50	58863.4	1°−19	0	1420.60	R10	70392.8		
1697.34	2	58915.7	2°−52	+1	1416.95	R10	70574.1		
1695.15	7h	58991.8			1415.79	R100	70631.9		
1691.02	30h	59135.9	3°−58	−10	1413.98	R100	70722.4		
1688.06	30h	59239.6			1410.82	R5	70880.8	1°−60	+5
1686.84	20h	59282.4	2°−53	−1	1406.68	R20	71089.4	1°−71089	
1679.72	R5	59533.7	2°−55	0	1401.60	R10	71347.0		
1676.48	6h	59648.8			1393.96	R15	71738.1		
1673.98	10	59737.9	1°−20	0	1392.12	R10	71832.9		
1671.21	5	59836.9	2°−57	0	1391.46	R25	71867.0		
1665.35	3	60047.4			1390.32	R50	71925.9		
1662.6	100Hw	60145.			1389.63	R10	71961.6		
1655.52	10r	60403.9	1°−21	−2	1388.91	R40	71998.9		
1651.20	50h	60562.0							
1650.70	3	60580.4	1°−22	−4					

Our relative intensities of antimony lines, being based on visual estimates of the densities and widths of photographic images, are subject to progressive errors near the infrared limit of photographic sensitivity, but should be comparable elsewhere because sensitivity variations were usually compensated by choosing exposures which gave a nearly uniform background throughout the spectrum. Besides intensities, column 2 of table 1 contains some notes on the character of certain lines, the symbols for this purpose being those adopted by the International Astronomical Union [31]. The physical appearance of line images is an important aid in the analysis of spectral structure, remembering that self-reversals are always associated with low energy states and haziness with highly excited states. The widest reversals (R) involve the ground state of the atom, and narrower ones (r) usually indicate that the transition is to some metastable low state. Many of the emission lines of antimony between 3723 and 1500 A exhibit more or less self-reversal. Scarcely any Sb I lines appear in emission shorter than 1500 A, but several groups of absorption lines can be seen against the continuous background to 1388 A, which appears to be the short wave limit of the Sb I spectrum. Only a portion of these absorbed lines has been classified, but it is significant that all thus far interpreted as resulting from transitions between established levels possess the ground level as their final state.

Seventy-four percent of the observed Sb I lines have now been interpreted as transitions between established atomic energy states. Applying the combination principal as a test of the precision with which relative values of wavelengths have been measured, it is found that the average difference, $\nu_{obs} - \nu_{calc}$, is 0.15 cm^{-1}, which corresponds to 0.15 A in the infrared at 10000 A, 0.05 A in the yellow at 5800 A, 0.01 A in the ultraviolet at 2600, and 0.003 A at 1500 A.

The most intense line of the Sb I spectrum has the wavelength 2311.47 A and the term combination $(5s^2\ 5p^3)\ {}^4S^\circ{}_{1\frac{1}{2}} - (5s^2\ 5p^2\ 6s)$ ${}^4P_{0\frac{1}{2}}$. It is the *raie ultime* for spectrographic detection of traces of antimony, and as such it obeys the rule [32] that these lines arise from the electronic transition $s \leftrightarrow p$. It is also the resonance line of neutral antimony atoms and therefore susceptible of the widest self-reversal in the arc or the strongest absorption in atomic vapor. Other things being equal, the relative intensities of spectral lines are proportional to the statistical weights $(2J+1)$ of the levels involved, and we might expect the combination $(5s^2\ 5p^3)\ {}^4S^\circ{}_{1\frac{1}{2}} - 5s^2\ 5p^2\ 6s)$ ${}^4P_{2\frac{1}{2}}$ with wavelength 2068.33 A to represent the strongest Sb I line [33]. According to our intensity estimates, however, 2068.33 A appears to be much weaker than 2311.47 A. Increased excitation energy and decreased photographic sensitivity both conspire against the former and favor the latter, so that without quantitative measurement it is not possible to fix the intensity ratio of these two lines.

Table 1 shows at a glance the general features of the first spectrum of antimony, intense emission in the ultraviolet, weak radiation in the visible, and relative richness in the infrared. Since the distribution of lines and of intensity in any atomic spectrum is a consequence of the atomic-energy states associated with various configurations of the valence electrons, it will be of interest to discuss these properties of antimony atoms.

2. TERM STRUCTURE OF THE Sb I SPECTRUM

Antimony has atomic number 51, and the atoms have electronic structures as follows: $1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,3d^{10}\,4s^2\,4p^6\,4d^{10}\,5s^2\,5p^3$. The first spectrum of antimony is mainly accounted for by the three outermost valence electrons, various configurations of which give rise to theoretical spectral terms [34] shown in table 2. In addition to the terms indicated in table 2, it is probable that the even terms $^4P_{0\frac12}$, $^4P_{1\frac12}$, $^4P_{2\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, and $^2S_{0\frac12}$ given by the electron configuration $5s\,5p^4$ may appear in the Sb I spectrum, since terms of this character have been identified by Bowen [35] in the analogous N I spectrum.

TABLE 2.—*Theoretical terms of the* Sb I *spectrum*

Electron configurations	Spectral terms		
$5s^2\,5p^3$ ----------	$^4S_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$		
	Convergence limit, $5p^2\cdot{}^3P_{0,1,2}$(Sb II)	Convergence limit, $5p^2\cdot{}^1D_2$(Sb II)	Convergence limit, $5p^2\cdot{}^1S_0$(Sb II)
$5s^2\,5p^2\,ns$ --------	$^4P_{0\frac12}$, $^4P_{1\frac12}$, $^4P_{2\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$	$^2D_{1\frac12}$, $^2D_{2\frac12}$	$^2S_{0\frac12}$
$5s^2\,5p^2\,np$ --------	$^4S_{1\frac12}$, $^4P_{0\frac12}$, $^4P_{1\frac12}$, $^4P_{2\frac12}$, $^4D_{0\frac12}$, $^4D_{1\frac12}$, $^4D_{2\frac12}$, $^4D_{3\frac12}$, $^2S_{0\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$	$^2P_{0\frac12}$, $^2P_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, $^2F_{2\frac12}$, $^2F_{3\frac12}$	$^2P_{0\frac12}$, $^2P_{1\frac12}$
$5s^2\,5p^2\,nd$ --------	$^4P_{0\frac12}$, $^4P_{1\frac12}$, $^4P_{2\frac12}$, $^4D_{0\frac12}$, $^4D_{1\frac12}$, $^4D_{2\frac12}$, $^4D_{3\frac12}$, $^4F_{1\frac12}$, $^4F_{2\frac12}$, $^4F_{3\frac12}$, $^4F_{4\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, $^2F_{2\frac12}$, $^2F_{3\frac12}$	$^2S_{0\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, $^2F_{2\frac12}$, $^2F_{3\frac12}$, $^2G_{3\frac12}$, $^2G_{4\frac12}$	$^2D_{1\frac12}$, $^2D_{2\frac12}$

The first regularities among antimony arc lines were discovered in 1894 by Kayser and Runge [2], who found 12 pairs of ultraviolet lines with the wave-number difference 2069 cm^{-1}, 5 pairs separated 6543 cm^{-1} and 5 pairs separated 1342 cm^{-1}. These three constant differences measure the energy differences between four metastable states from highest to lowest (the ground state being 8512 cm^{-1} lower still), but a third of a century elapsed before the quantum interpretation of these levels could be given. An attempt by van Lohuizen [36] in 1913 to arrange antimony lines in spectral series appears to be artificial. Further progress in the classification of Sb I lines was made in 1923 by Ruark et al. [12], who added the deepest level, and fixed 25 high levels by means of 80+ combinations.

The first quantum interpreations of Sb I levels were made practically simultaneously by McLennan and McLay [37] and by Malurkar [38]. Both conjectured the first 5 levels to be $^4S_{1\frac12}$, $^2D_{1\frac12}$, $^2D_{2\frac12}$, $^2P_{0\frac12}$, $^2P_{1\frac12}$ (arising from the electron configuration $5s^25p^3$) and the next 5 levels as $^4P_{0\frac12}$, $^4P_{1\frac12}$, $^2P_{0\frac12}$, $^4P_{2\frac12}$, $^2P_{1\frac12}$ (the lowest from $5s^2\,5p^2\,6s$). Malurkar also suggested identification of 15 higher levels but not without much arbitrariness. A step backward seems to have been made in 1930 by Charola [17], who claims to have classified 64 Sb lines and discovered 25 new levels. His interpretation of 11 levels also in Malurkar's list is totally different, and the 14 remaining levels appear to be unreal.

Positive information about the nature of Sb I levels was not at hand until 1929, when the Zeeman-effect investigation by Löwenthal [21] supplied absolute values of g and j for 14 levels. Departures

from the g's representative of LS-couping are found even among the low levels, and a great deal of g-sharing may be expected among higher levels from various configurations. Löwenthal also established 11 levels due to $5s^2\,5p^2\,6p$ from infrared wavelength data then available.

TABLE 3.—*Levels and terms of* Sb I

Level number	Level value	Quantum number, j	Splitting factor, g	Electron configuration	Term symbol	Level number	Level value	Quantum number, j	Splitting factor, g	Electron configuration	Term symbol
1°	0.0	1½	1.967	$5s^2\,5p^3$	$^4S_{1\frac12}$	32	63826.4	0½			
2°	8512.1	1½	0.889	$5s^2\,5p^3$	$^2D_{1\frac12}$	20°	63900.3	0½			
3°	9854.1	2½	1.205	$5s^2\,5p^3$	$^2D_{2\frac12}$	33	64213.8	2½			
4°	16395.6	0½	0.688	$5s^2\,5p^3$	$^2P_{0\frac12}$	34	64221.4	1½			
5°	18464.5	1½	1.277	$5s^2\,5p^3$	$^2P_{1\frac12}$	35	64432.9	0½			
1	43249.4	0½	2.332	$5s^2\,5p^2(^3P_0)6s$	$^4P_{0\frac12}$	21°	64512.3	2½			
2	45945.4	1½	1.713	$5s^2\,5p^2(^3P_1)6s$	$^4P_{1\frac12}$	36	64514.2	2½			
3	46991.1	0½	1.004	$5s^2\,5p^2(^3P_1)6s$	$^2P_{0\frac12}$	37	64769.5	0½			
4	48332.5	2½	1.547	$5s^2\,5p^2(^3P_2)6s$	$^4P_{2\frac12}$	38	64843.2	0½			
5	49391.1	1½	1.277	$5s^2\,5p^2(^3P_2)6s$	$^2P_{1\frac12}$	22°	64878.9	2½			
6°	52612.5	1½				23°	64957.0	3½			
6	53443.3	2½				24°	64984.4	1½			
7	53528.3	1½				39	65144.8	2½			
7°	54196.9	1½				40	65243.0	1½			
8	55120.7	2½				41	65257.8	0½			
8°	55134.4	1½				42	65404.2	1½			
9	55135.2	2½				25°	65460.3	2½			
9°	55168.3					26°	65467.5	3½			
10	55233.2	1½	0.991	$5s^2\,5p^2(^1D_2)6s$	$^2D_{1\frac12}$	27°	65479.6	2½			
10°	55252.4	2½				28°	65568.6	2½			
11	55728.3	2½	1.277	$5s^2\,5p^2(^1D_2)6s$	$^2D_{2\frac12}$	43	65653.2	0½		$5s^2\,5p^2(^1S_0)6s$	$^2S_{0\frac12}$
11°	55864.8	1½				44	66009.5	1½			
12°	55993.8	1½				29°	66029.0	2½			
12	56152.1	1½	1.302			45	66113.0	1½		$5s^2\,5p^2(^3P_1)8s$	$^4P_{1\frac12}$
13	56699.0	0½				46	66354.0	0½			
14	56733.4	1½	(1.311)			47	66536.0	2½			
15	57287.2	0½				48	66743.7	1½			
13°	57410.3	2½				49	66828.6	1½			
16	57597.3	0½		$5s^2\,5p^2(^3P_0)7s$	$^4P_{0\frac12}$	30°	66837.1	2½			
14°	58075.5	1½				50	66967.3	3½			
17	58132.9	0½				51	67052.6	1½			
15°	58589.5	1½				52	67427.7	0½			
16°	58652.9	0½				53	67794.6				
18	58746.6	1½				54	67840.3	1½			
17°	58835.3	2½				55	68045.8				
19	58863.4	2½				31°	68069.9	0½			
20	59737.9	0½				56	68141.5	1½			
21	60404.1	2½				57	68349.0				
22	60580.8	1½				58	68991.0	2½			
23	60964.7	1½		$5s^2\,5p^2(^3P_1)7s$	$^4P_{1\frac12}$	59	69893.3	0½			
18°	61000.0	0½				60	70880.3	2½		$5s^2\,5p^2(^1D_2)7s$	$^2D_{2\frac12}$
24	61386.3	0½		$5s^2\,5p^2(^3P_1)7s$	$^2P_{0\frac12}$		68503			$5s^2\,5p^2(^3P_1)9s$	$^4P_{1\frac12}$
25	61631.2	2½					68652			$5s^2\,5p^2(^3P_2)8s$	$^4P_{2\frac12}$
26	61808.8	1½					71089			$5s^2\,5p^2(^3P_2)9s$	$^4P_{2\frac12}$
27	62502.2	2½									
28	62960.0	0½		$5s^2\,5p^2(^3P_0)8s$	$^4P_{0\frac12}$						
29	63193.3	1½									
30	63516.6	2½		$5s^2\,5p^2(^3P_2)7s$	$^4P_{2\frac12}$						
31	63649.6	2½									
19°	63680.4										

Being based on a more complete, accurate, and homogeneous description of the Sb I spectrum, the present investigation has resulted in the rejection of certain former levels, correction of the values of others, and the establishment of a considerable number of new levels. In addition to the 5 lowest odd levels ($5p^3$), the new ultraviolet data have revealed 60 levels from 43249 to 70880 cm^{-1} above the ground

state. These are even levels from configurations $5s^2\,5p^2\,ns$, $5s^2\,5p^2$ nd, and probably $5s\,5p^4$, but on account of expected large separations of levels and consequent overlapping of terms, it is doubtful if L-values can be assigned to many of these. From the infrared data, we have obtained 31 odd levels with values between 52612 and 66907 cm^{-1}. These undoubtedly arise from the electron configuration $5p^2\,np$ and possibly $5p^2\,nf$, but here again the assignment of L-values probably has little meaning. It will be noticed that these odd levels are completely surrounded and interlaced by the even levels with which they combine to produce infrared radiations. Since the present limit of photographic observation is about 8000 cm^{-1}, only fringe combinations of these even and odd levels have been recorded, and a large number of combinations must exist in the unexplored infrared. The fact that only a portion of these combinations is within reach of present observations makes it impossible to fix unambiguously all the J-values of the established odd levels.

All of the known atomic energy levels of Sb I are collected in table 3 and are based on $^4S^{\circ}{}_{1\frac{1}{2}}=0$. Since it is not possible to assign definite L-values to all of these (for reasons stated above), we have numbered the even and odd levels separately in the order of their magnitude, written the odd values in italics, and added the odd sign (°) to their numerical symbols. Table 3 does not include five provisional odd levels (*63798.1, 64728.0, 66541.3, 67108.0, 67876.6*) appearing in table 1, because each of these is based on only two combinations.

3. SPECTRAL SERIES AND IONIZATION POTENTIAL

The ultraviolet lines of Sb I are of special interest because it is among these that spectral series must be sought for the purposes of determining the spectroscopic ionization potential of Sb atoms and of tracing the convergence of term sequences in one spectrum to limits in the next. Table 4 shows all the combinations given by classified ultraviolet Sb lines, the low odd levels appearing at the head and the even levels at the left margin. The even levels, as stated before, arise from electron configurations $5s^2\,5p^2\,ns$, $5s^2\,5p^2\,nd$, and $5s5p^4$. Terms given by the series s electron ($6s$, $7s$, $8s$, ____) should fit a Ritz formula of the type

$$\nu = L - R \Big/ \left(n + a + \frac{b}{n^2}\right)^2$$

from which determinations of the limits (L) could be obtained. Each configuration of the type $5p^2\,ns$ gives rise to eight levels ($^4P_{0\frac{1}{2}}$, $^4P_{1\frac{1}{2}}$, $^4P_{2\frac{1}{2}}$, $^2P_{0\frac{1}{2}}$, $^2P_{1\frac{1}{2}}$, $^2D_{1\frac{1}{2}}$, $^2D_{2\frac{1}{2}}$, $^2S_{0\frac{1}{2}}$), which converge in an obvious manner toward five limits in the Sb II spectrum ($^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^1S_0$) when the s electron is removed by ionization. The structure of the Sb II spectrum has been partially analyzed by Dhavali [39], Lang and Vestine [40], and Krishnamurty [41]. The low Sb II terms from $5p^2$, according to Lang and Vestine [40], have the following values: $^3P_0=0$, $^3P_1=3055$, $^3P_2=5659$, $^1D_2=12791$, $^1S_0=23906$ cm^{-1}. Guided by these intervals, we have provisionally interpreted the following Sb I levels: $^2D_{1\frac{1}{2}}=55233.1$, $^2D_{2\frac{1}{2}}=55728.4$, and $^2S_{0\frac{1}{2}}=65653.2$, thus completing the assignment of levels to the configuration $5p^2\,6s$.

TABLE 4.—Sb I combinations, $5s^2\,5p^3 - 5s^2\,5p^2$ (ns, nd)

Level number Value		1° 0.0	2° 8512.1	3° 9854.1	4° 16395.6	5° 18464.5
Level number	Value					
1	43249.4	43249.2(2500R)	34737.2(1000R)		26854.0(200R)	24785.1(200)
2	45945.4	45945.4(1500R)	37433.1(300r)	36091.1(400R)	29549.8(100)	27481.1(250)
3	46991.1	46991.0(100R)	38478.9(1500R)		30595.6(700r)	28526.8(50)
4	48332.5	48332.7(1000R)	39820.1(100)	38478.3(500R)		29868.0(5)
5	49391.1	49391.1(50)	40878.9(400r)	39536.9(2000R)	32995.6(500r)	30926.7(600r)
6	53443.3	53443.1(300R)	44931.2(120r)	43589.2(150r)		34978.9(20)
7	53528.3	53528.3(50r)	45016.2(150r)	43674.1(120)	37132.7(120)	35063.8(100)
8	55120.7	55120.7(80r)	46608.4(100R)	45266.5(300r)		36656.4(80)
9	55135.2		46623.2(10)	45281.2(20)		36670.3(4)
10	55233.2	55233.4(50r)	46721.0(100R)	45379.0(10)	38837.5(150)	36768.7(150r)
11	55728.3		47216.1(40)	45874.2(250r)		37264.0(200r)
12	56152.1	56152.3(100r)	47639.9(50r)	46298.0(40)	39756.4(40)	37687.7(200r)
13	56699.0	56699.3(40r)	48186.6(4)		40303.3(150)	38234.5(30)
14	56733.4	56731.8?(40r)[a]	48221.3(40)	46879.3(2)	40337.7(400)	38268.9(300r)
15	57287.2	57287.2(9)	48775.0(150R)			38822.9(5)
16	57597.3	57597.4(100r)	49085.1(9)		41201.7(250)	39132.7(80)
17	58132.9	58133.1(4)	49620.8(20)		41737.1(100)	39668.4(50)
18	58746.6	58746.8(20)	50234.3(40)	48892.8(25)	42350.9(80)	40282.1(40)
19	58863.4	58863.4(50)	50351.2(60)	49009.3(70r)[a]		40398.9(80)
20	59737.9	59737.9(10)	51225.6(10)		43343.1(300)[a]	41273.4(150)
21	60404.1	60403.9(10r)	51892.0(100r)	50550.2(30)		41939.8(300h)
22	60580.8	60580.4(3)	52069.0(10)	50726.9(20)	44185.0(300r)	42116.0(400h)
23	60964.7	60963.7(15)	52453.0(7)	51110.6(20)		42500.2(50)
24	61386.3	61386.2(10)	52874.2(70)		44990.9(100)	42921.8(50)
25	61631.2	61631.4(8)	53119.2(150r)	51777.0(40)		43166.6(150)
26	61808.8	61808.5(10)	53296.7(20)	51955.1(8)	45413.1(200r)	43343.1(300)[a]
27	62502.2	62501.6(80R)	53990.4(20)	52648.5(70)		44037.8(80)
28	62960.0	62959.6(8)	54448.1(20)		46564.5(15)	
29	63193.3	63192.8(40R)	54681.3(10)	53339.0(40)	46798.4(5)	44728.8(4)
30	63516.6	63515.9(30R)	55004.9(3)	53662.5(30)		45052.1(5)
31	63649.6	63649.7(15)	55137.4(20)	53795.5(60)		45185.2(20)
32	63826.4	63826.0(15r)	55314.6(8)		47430.9(20)	45361.8(10)
33	64213.8	64214.1(30)	55701.6(10)	54359.9(4)		45749.1(20)
34	64221.4	64220.7(10)	55709.4(3)	54367.6(7)	47825.9(30)	45758 (5)
35	64432.9	64432.6(3)	55920.9(100r)	54578.9(40)	48037.3(10)	45968.5(10)
36	64514.2		56002.3(15)	54659.7(100)		46049.8(15)
37	64769.5	64768.5(20r)	56258.8(20)[a]		48373.8(7)	46305.1(50)
38	64843.2		56331.4(20)		48447.4(50)	46378.7(20)
39	65144.8	65144.0(80R)	56632.8(100)	55290.8(25)		46680.4(20)
40	65243.0	66242.6(120R)	56731.8(40r)[a]	55389.4(30)	48846.5 (20)	46778.7(50r)
41	65257.8	65258.0(15r)	56746.0(20)		48861.8(2)	46793 (3)
42	65404.2			55550.0(150)	49009.3(70r)[a]	
43	65653.2	65653.4(4)	57140.9(15)		49257.5(60r)	47188.7(80r)
44	66009.5		57497.4(20)		49613.9(3)	
45	66113.0	66112.6(50R)		56258.8(20)[a]		47649.0(10)
46	66354.0		57841.6(15)	56681.9(15)	49958.5(3)	47889.6(25)
47	66536.0		58023.8(150r)	56889.6(50)		48071.7(100)
48	66743.3			56889.6(50)		
49	66828.6		58316.5(2)	56974.2(10)	50433.2(15h)	
50	66967.3			57113.2(15)		
51	67052.6	67052.9(40)		57198.4(6h)	50656.8(5)	48590.3?(8h)
52	67427.7	67427.7(5)	58915.7(2)		51032.1(2)	
53	67794.6	67794.8(R10)	59282.4(20h)			
54	67840.3	67840.3(R3)		57985.8(2)	51445.1(10)	
55	68045.8	68045.7(R5)	59533.7(R5)			
56	68141.5	68141.2(R10)		58287.3(2)		49677.5(20h)
57	68349.0	68349.0(R10)	59836.9(5)			
58	68991.0	68991.0(R5)		59135.9(30h)		50526.7(20h)
59	69893.3	69892.9(10)	61380.9(10)		53498.0(5)	51429.2(3)
60	70880.3	70880.8(R5)		61025.8(8)		52415.8(5h)

[a] Doubly classified.

Reference to Rydberg's interpolation table indicated that the lines with wave numbers 43249, 57597, and 62960 cm^{-1} might represent the series $5s^2\ 5p^3\ {}^4S^\circ{}_{1\frac{1}{2}} - 5s^2\ 5p^2\ ({}^3P_0)ns\ {}^4P_{0\frac{1}{2}}$. The Ritz formula

$$\nu = 70064 - 109737 / \left(n - 4.18902 + \frac{7.63201}{n^2} \right)^2,\ n=6, 7, 8$$

represents these three lines without error, but no line is observed for $n=9$, probably because the intensity decrement (2500, 100, 8) is too great in this series. This same series was arrived at independently by Professor Russell, who employed the method of comparison with spectra of neighboring elements. Good series are known for all the spectra from Ag I to Cs I, except Sb I and I I. For these spectra, table 5 gives the effective quantum numbers, $n^* = \sqrt{R/T}$, corresponding to terms of highest L- and J-values converging to the lowest limit in the second spectrum.

TABLE 5.—*Effective quantum numbers n^* in spectra Ag I to Cs I*

Spectrum	Ag I	Cd I	In I	Sn I	Sb I	Te I	I I	Xe I	Cs I
Term	${}^2S_{0\frac{1}{2}}$	${}^3S_1$	${}^2S_{0\frac{1}{2}}$	${}^3P_1$	${}^4P_{0\frac{1}{2}}$	${}^5S_2$	${}^4P_{2\frac{1}{2}}$	${}^3P_2$	${}^2S_{0\frac{1}{2}}$
Electron ↓									
6s	2.432	2.283	2.219	2.128		1.965		1.889	1.869
7s	3.450	3.317	3.254	3.168					2.920
8s	4.457	4.328	4.266	4.229		4.036		3.951	3.935
9s	5.460	5.334	5.271	5.239		5.050		4.974	4.941
10s	6.464	6.337	6.274	6.299		6.051		5.975	5.944
11s	7.467	7.339	7.283	7.299		7.055		6.975	6.947

By interpolation, the $6s$ value of n^* for Sb I is found to be about 2.036. The corresponding term, $T=R/n^{*2}$, has a numerical value of $109737/(2.036)^2=26473$, and if this is added to the wave number 43249 cm^{-1}, representing the resonance line, a value of 69722 is obtained for the limit (${}^3P_0$ of Sb II). This differs by less than 0.5 percent from the limit contained in the Ritz formula given above. Further series assignments were then suggested by the various limits in the Sb II spectrum to which such series are expected to converge. Complete data for the proposed series of Sb I are shown in table 6.

The Ritz formula,

$$\nu = 72721 - 109737 / \left(n - 3.85951 - \frac{4.17719}{n^2} \right),\ n=6, 7, 8, 9,$$

reproduces the series $5s^2\ 5p^3\ {}^4S^\circ{}_{1\frac{1}{2}} - 5s^2\ 5p^2({}^3P_1)ns\ {}^4P_{1\frac{1}{2}}$ perfectly for three members but gives an observed-calculated residual of 20 cm^{+1} for $n=9$. If the Sb II interval, ${}^3P_0 - {}^3P_1 = 3055$ cm^{-1}, is subtracted from the limit, 69666 cm^{-1} is derived as a value of ${}^3P_0$. Similarly, the formula

$$\nu = 75206 - 109737 / \left(n - 3.81637 - \frac{5.86271}{n^2} \right),\ n-6, 7, 8, 9,$$

represents without error the first three members of the $5s^2\ 5p^3\ {}^4S^\circ{}_{1\frac{1}{2}} - 5s^2\ 5p^2({}^3P_2)ns\ {}^4P_{2\frac{1}{2}}$ series, but gives a residual of 84 cm^{-1} for $n=9$. Subtraction of the Sb II interval, ${}^3P_0 - {}^3P_2 = 5659$ cm^{-1}, from the limit, gives a value of 69547 cm^{-1} for ${}^3P_0$.

TABLE 6.—Sb I *series and effective quantum numbers*

Limits	Electron	Lines	Terms	Effective quantum numbers $n^* = \sqrt{R/T}$
cm^{-1} $^3P_0=69700$	$6s$	cm^{-1} 43249	cm^{-1} $^4P_{0\frac{1}{2}}=26451$	2.0368
	$7s$	57597	$=12103$	3.0112
	$8s$	62960	$=6740$	4.0350
$^3P_1=72755$	$6s$	45945	$^4P_{1\frac{1}{2}}=26810$	2.0232
	$7s$	60965	$=11790$	3.0508
	$8s$	66113	$=6642$	4.0647
	$9s$	68503	$=4252$	5.0802
	$6s$	46991	$^2P_{0\frac{1}{2}}=25764$	2.0638
	$7s$	61386	$=11369$	3.1068
$^3P_2=75359$	$6s$	48332	$^4P_{2\frac{1}{2}}=27027$	2.0150
	$7s$	63517	$=11842$	3.0442
	$8s$	68652	$=6707$	4.0450
	$9s$	71089	$=4270$	5.0695
	$6s$	49391	$^2P_{1\frac{1}{2}}=25968$	2.0557
$^1D_2=82491$	$6s$	55233	$^2D_{1\frac{1}{2}}=27258$	2.0065
	$6s$	55728	$^2D_{2\frac{1}{2}}=26763$	2.0250
	$7s$	70880?	$=11611?$	3.0742?
$^1S_0=93606$	$6s$	65653	$^2S_{0\frac{1}{2}}=65653$	1.9814

The average of the three values of $^3P_0$ indicated by the above series is 69759 cm^{-1}. However, the second series appears to be least perturbed, and its value of $^3P_0$ ($=69666$) agrees very closely with 69722 obtained from the resonance line and interpolated n^*. We have, therefore, adopted the rounded mean of these two values as the most probable magnitude of $^3P_0=69700$ cm^{-1}. The *principal ionization potential* of antimony is then $69700 \times 1.2395 \times 10^{-4}=8.64$ volts. This is a measure of the energy required to move a valence electron from its normal state in a neutral Sb atom to the lowest energy state ($^3P_0$) of the Sb$^+$ ion. Ionization to the higher (metastable) states will require greater energy, the maximum being $(69700+23906) \times 1.2395 \times 10^{-4}=11.60$ volts, which is necessary for transferring a valence electron from the normal state of Sb to the $^1S_0$ state of Sb$^+$. In fact, the only levels of Sb I which, according to Hund's theory, go to the $^3P_0$ state of Sb II are $^4P_{0\frac{1}{2}}$ with an s-electron and $^4F_{1\frac{1}{2}.2\frac{1}{2}}$ with a d-electron. All other types of Sb I terms seek metastable states in Sb$^+$ ions, and this accounts for the fact that Sb I lines have actually been observed with wave numbers exceeding 69700 cm^{-1}, the principal ionization limit.

IV. REFERENCES

[1] H. Kayser, Handbuch der Spectroscopie **6**, 426 (S. Hirzel Leipzig, 1912).
[2] H. Kayser and C. Runge, Abhandl. Berlin Akad. (1893); Weidem. Ann. **52**, 93 (1894).
[3] H. Schippers, Z. wiss. Phot. **11**, 235 (1912).
[4] F. M. Walters, Jr., BS Sci. Pap. **17**, 161 (1921) S411.
[5] H. M. Randall, Astrophys. J. **34**, 1. (1911).
[6] H. Lehmann, Ann. Physik **39**, 53 (1912).
[7] T. Takamine and S. Nitta, Mem. Coll. Sci. Kyoto Imp. Univ. **2**, 117 (1917).
[8] J. C. McLennan, J. F. T. Young, and H. J. C. Ireton, Proc. Roy. Soc. (London) [A] **98**, 95 (1920).
[9] L. and E. Bloch, J. phys. radium **8**, 217 (1937).
[10] J. C. Dobbie and J. J. Fox, Proc. Roy. Soc. (London) [A] **98**, 147 (1920).
[11] W. Grotrian, Z. Physik **18**, 169 (1923).
[12] A. E. Ruark, F. L. Mohler, P. D. Foote, and R. L. Chenault, BS Sci. Pap. **19**, 463 (1920) S490.
[13] A. L. Narayan and K. R. Rao, Phil. Mag. [6] **50**, 645 (1925).
[14] J. C. McLennan and A. B. McLay, Trans. Roy. Soc. Can. **19**, 89 (1925).
[15] J. G. Frayne and A. W. Smith, Phil. Mag. [7] **1**, 732 (1926).
[16] R. V. Zumstein, Phys. Rev. **29**, 209 (1927).
[17] F. Charola, Physik. Z. **31**, 457 (1930).
[18] E. O. Hulburt, Phys. Rev. **24**, 129 (1924).
[19] M. C. W. Buffam and H. J. C. Ireton, Trans. Roy. Soc. Can. **19**, 113 (1925).
[20] P. A. van der Harst, Proc. Acad. Sci. Amsterdam. **22**, 300 (1920).
[21] H. Löwenthal, Z. Physik, **57**, 822 (1929).
[22] A. G. Shenstone, Trans. Roy. Soc. (London) [A] **237**, 453 (1938).
[23] W. F. Meggers and K. Burns, BS Sci. Pap. **18**, 185 (1922) S442.
[24] Eastman Kodak Co., Photographic Plates for use in Spectroscopy and Astronomy (1940).
[25] Proc. Sixth Summer Conference on Spectroscopy, p. 114, (John Wiley & Sons, New York, N. Y., 1939).
[26] K. Burns and F. M. Walters, Jr., Pub. Allegheny Observatory, Univ. Pittsburgh, **6**, 159 (1929); **8**, 39 (1931); **8**, 27 (1931).
[27] J. C. Boyce and H. A. Robinson, J. Opt. Soc. Am. **26**, 133 (1936).
[28] W. F. Meggers, J. Research NBS **14**, 33 (1935) RP755; W. F. Meggers and C. J. Humphreys, J. Research NBS **18**, 543 (1937) RP992.
[29] H. Kayser, Tabelle der Schwingungszahlen (Julius Springer, Berlin, 1927).
[30] W. F. Meggers and C. G. Peters, Bul. BS **14**, 697 (1918) S327.
[31] Trans. Int. Astron. Union **6**, 100 (1938).
[32] W. F. Meggers and B. F. Scribner, J. Research NBS **13**, 657 (1934) RP732.
[33] W. F. Meggers, J. Opt. Soc. Am. **31**, 44 (1941).
[34] F. Hund, Linienspektren und Periodisches System der Elemente (Julius Springer, Berlin, 1927).
[35] I. S. Bowen, Phys. Rev. **29**, 231 (1927).
[36] T. van Lohuizen, Z. wiss. Phot. **11**, 397 (1913).
[37] J. C. McLennan and A. B. McLay, Trans. Roy. Soc. Can. **21**, 63 (1927).
[38] S. L. Malurkar, Proc. Cambr. Phil. Soc. **24**, 85 (1927).
[39] D. G. Dhavali, Proc. Roy. Soc. (London) [A] **131**, 109 (1931).
[40] R. J. Lang and E. H. Vestine, Phys. Rev. **42**, 233 (1932).
[41] S. G. Krishnamurty, Indian J. Phys. **10**, 83 (1936).

WASHINGTON, January 19, 1942.