

New Descriptions and Analyses of the Third and Fourth Spectra of Zirconium, Zr III and Zr IV

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Recent observations of the spectra emitted by ionized zirconium atoms have added many new lines to the descriptions of these spectra and have led to revisions and extensions of their term structures. The low, even terms of Zr III arise in the electron configurations $4d^2$, $4d\ 5s$, and $5s^2$. Excitation of these states leads to higher terms of the $4d\ 5p$, $5s\ 5p$, $4d\ 5d$, $4d\ 6s$, $4d\ 4f$, $5s\ 5d$, $4d\ 6p$, $5s\ 6s$, $5s\ 4f$, and $5s\ 5g$ configurations. Most of the singlet and triplet terms from these configurations have now been established. Zeeman patterns from Massachusetts Institute of Technology plates have confirmed and corrected some of the classifications of earlier work. From the series-forming terms of Zr III the separation of the ground states of Zr III and Zr IV is calculated as 198590 cm^{-1} , corresponding to an ionization potential of 24.6 electron volts for the ion Zr^{2+} . In the doublet spectrum of Zr IV, which arises from the migration of the single electron outside the krypton shell, the terms from the $7s$, $6p$, $6d$, $5f$, $6f$, $5g$, and $6g$ electrons have been added to those already known. A mean value of 276970 cm^{-1} for the separation of the ground states of Zr IV and Zr V has been derived from three accordant values calculated from series of 2S , $^2F^\circ$, and 2G terms. This corresponds to an ionization potential of 34.33 electron volts for Zr^{3+} .

1. Introduction

The new descriptions of the third and fourth spectra of zirconium, presented in this paper, have led to a reexamination of the analyses of their term structures published 25 years ago by Kiess and Lang [1].¹ Recent observations have more than doubled the number of lines known for these spectra at that time, and studies of the Zeeman effect have given unmistakable information about the classification of some of the lines. Preliminary reports [2] on the application of the new results to optical and astrophysical problems have already been made, and a paper has been published [3] with the new additions to and interpretations of the second spectrum, Zr II.

2. Experimental Procedure

Spectra of neutral and ionized zirconium atoms were obtained with a concave-grating spectrograph at the National Bureau of Standards, down to 1920 Å in the ultraviolet. The grating, of 21-ft radius of curvature, was ruled by R. W. Wood [4] with 30,000 lines per inch. It is set up in a Wadsworth mounting and gives uniformly bright spectra throughout the accessible first and second orders, with a dispersion of 2 Å/mm in the first order. The spectra were emitted by arcs and condensed-spark discharges in air between electrodes of the same zirconium metal that was used in the earlier work. Although of high purity this metal was found to contain very small amounts of silicon, titanium, iron, and hafnium. The arcs were operated at about 5 amp from 220-volt d-c mains. The sparks were excited by a battery of condensers, of 0.006- μf capacitance, charged from the high-voltage side of a transformer that stepped-up 110 volts a-c to 30,000 volts. The plates used to record the spectra were

coated with EK 33 and SWR emulsions. Each exposure to a zirconium spectrum was juxtaposed to an exposure of the iron arc or to the spark between copper-silver electrodes to secure the necessary standards for the wavelength calculations.

For the extreme ultraviolet region of the spectra two sets of spectrograms were available for measurement, one obtained with the Carnegie vacuum spectrograph by J. C. Boyce while he was at the Massachusetts Institute of Technology, the other by A. G. Shenstone with the Princeton vacuum spectrograph. Both of these instruments have the same optical dimensions and produce spectra with dispersions of 4.25 Å/mm in the first order from concave gratings ruled with 30,000 lines per inch. The results from these new measurements have confirmed and supplemented the descriptions of the ultraviolet spectra of Zr supplied by R. J. Lang for the Bureau's work of 25 years ago.

The MIT spectrograms were obtained from exposures to an arc operated at 8 amp between Zr-Ag electrodes in an atmosphere of commercial N_2 , and cover the region from 2500 Å down to 1100 Å. The recorded spectra are mixtures of lines of zirconium, silver, nitrogen, carbon, and hafnium. The Princeton plates cover the region from 2200 Å down to 513 Å with exposures to a condensed-spark discharge between Zr electrodes in vacuum. On both sets of spectrograms appear lines of Zr I, Zr II, Zr III, and Zr IV. On the MIT plates the lines all exhibit uniform distributions of illumination along the slit of the spectrograph and differ only in their intensities and qualities of sharpness and diffuseness. On the Princeton plates, however, the lines exhibit distinctive differences of illumination along the slit of the spectrograph that permit them to be grouped according to the degree of ionization of their emitters: those of uniform intensity along the slit belong mostly to Zr I; lines of Zr II generally show illumination along the full length of the slit but are stronger

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

near the electrodes than in the zone midway between them; lines strong at the electrodes and directed like spear-points toward the center of the slit are characteristic of Zr III; while lines strong at the electrodes but tapering outward along the slit belong to Zr IV, and perhaps to Zr V. There are about 50 lines of this latter kind in the region between 900 and 600 Å for which there is no place in Zr IV. It is very likely that they represent the excitation of the Kr-shell of the zirconium atom.

Preliminary values of the wavelengths derived from measurement of the MIT and Princeton plates were based on standards selected from lines of N, O, C, and H that appear as impurities in the spectra. These wavelengths were of sufficient accuracy to allow assignment of many of the lines to their multiplet structures. With more accurate values for energy levels calculated from lines longer than 2000 Å, which were measured against better standards than those in the vacuum region, corrections were derived for the preliminary wavelengths longer than 1200 Å. Nearly all the strong lines with wavelengths shorter than 1200 Å appeared in the second and third orders, overlapping the first order from 2400 to 1000 Å. Their apparent wavelengths, after being corrected as just described, were then divided by the appropriate factor to give the adopted values in the first-order spectrum.

There were also available for measurement plates of the Zeeman effect obtained under the direction of G. R. Harrison at MIT. Although most of the magnetic patterns appearing on these plates are of Zr I and Zr II lines, yet a few of them belong to lines of Zr III. These serve to verify and correct some of the earlier classifications. The results of the measurements are given below.

3. Results

3.1. Spectrum of Trebly Ionized Zirconium, Zr IV

In its unexcited state the neutral zirconium atom has four valence electrons in the configuration $4d^2 5s^2$ outside the krypton shell. The loss of three of these electrons through successive ionizations leaves a single $4d$ -electron to determine the term-structure of Zr IV. The early work on the analysis of Zr IV is summarized in the paper by Kiess and Lang cited above. The terms listed therein account for 12 lines of the spectrum if the term designated there as $7s$, and now known to be incorrect, is excluded. In the present analysis the 39 lines given in table 1 are classified as combinations among the 21 terms recorded in table 2, and include all lines classified in the earlier investigations.

The terms of Zr IV, in table 2, are listed in the order of increasing energy indicated by the relative term-values in the second column and shown graphically in figure 1. In the fourth and fifth columns are given the absolute values of the terms, and the Rydberg denominators that were used in the simple Ritz formula $16R/[m + \alpha + (\beta/m^2)]^2$ to evaluate the running terms and the limits of the several series. Inspection of the table shows that three members have been found for the 2S , 2D , and $^2F^{\circ}$

series, and two members for the $^2P^{\circ}$ and 2G series. The terms of the three-member series are accurately represented by the above formula with the appropriate values of α and β introduced into it. For the two-member series the terms were interpolated from the Princeton table for Rydberg's formula [5]. Table 3 shows that the values for the ground state $4p \ ^2D_{1/2}$ of Zr IV given by the 2S , $^2F^{\circ}$, and the nearly hydrogenic 2G series are in close agreement, whereas the $^2P^{\circ}$ and 2D series give much larger values. It is known from other spectra that series terms from

TABLE 1. Classified lines of Zr IV

Wavelengths longer than 2000 Å, air values; vacuum values shorter than 2000 Å.

Wave-lengths	Inten-sities	Wave numbers	Term combinations
A		$K(cm^{-1})$	
2849.19	10	35087.41	$6p \ ^2P_{1/2}^{\circ} - 6d \ ^2D_{1/2}$
2832.82	15	35290.15	$6p \ ^2P_{1/2}^{\circ} - 6d \ ^2D_{3/2}$
2770.44	5	36084.72	$6p \ ^2P_{3/2}^{\circ} - 6d \ ^2D_{1/2}$
2286.68	200	43718.01	$5s \ ^2S_{0/2} - 5p \ ^2P_{1/2}^{\circ}$
2163.63	500	46204.06	$5s \ ^2S_{0/2} - 5p \ ^2P_{3/2}^{\circ}$
2125.29	25	47037.48	$4f \ ^2F_{3/2}^{\circ} - 6d \ ^2D_{3/2}$
2092.40	150	47776.76	$4f \ ^2F_{3/2}^{\circ} - 5g \ ^2G_{4/2}$
2091.49	125	47797.54	$4f \ ^2F_{3/2}^{\circ} - 5g \ ^2G_{3/2}$
1848.06	10	54110.8	$5d \ ^2D_{2/2} - 5f \ ^2F_{3/2}^{\circ}$
1846.42	100	54158.9	$5d \ ^2D_{2/2} - 5f \ ^2F_{5/2}^{\circ}$
1836.14	100	54462.1	$5d \ ^2D_{1/2} - 5f \ ^2F_{3/2}^{\circ}$
1607.99	100	62189.4	$5p \ ^2P_{1/2}^{\circ} - 5d \ ^2D_{1/2}$
1598.98	200	62539.9	$5p \ ^2P_{1/2}^{\circ} - 5d \ ^2D_{2/2}$
1546.19	150	64675.1	$5p \ ^2P_{3/2}^{\circ} - 5d \ ^2D_{1/2}$
1469.50	100	68050.4	$5p \ ^2P_{1/2}^{\circ} - 6s \ ^2S_{0/2}$
1441.11	20	69391.0	$4f \ ^2F_{3/2}^{\circ} - 6g \ ^2G_{4/2}$
1440.68	18	69411.7	$4f \ ^2F_{3/2}^{\circ} - 6g \ ^2G_{3/2}$
1417.73	75	70535.3	$5p \ ^2P_{3/2}^{\circ} - 6s \ ^2S_{0/2}$
1291.77	1	77413.1	$5d \ ^2D_{2/2} - 6f \ ^2F_{3/2}^{\circ}$
1290.60	20	77483.3	$5d \ ^2D_{2/2} - 6f \ ^2F_{5/2}^{\circ}$
1285.94	15	77764.1	$5d \ ^2D_{1/2} - 6f \ ^2F_{3/2}^{\circ}$
1219.85	150	81977.3	$4d \ ^2D_{1/2} - 5p \ ^2P_{1/2}^{\circ}$
1201.77	250	83210.6	$4d \ ^2D_{2/2} - 5p \ ^2P_{1/2}^{\circ}$
1183.96	100	84462.3	$4d \ ^2D_{1/2} - 5p \ ^2P_{3/2}^{\circ}$
864.61	8	115659	$5p \ ^2P_{1/2}^{\circ} - 7s \ ^2S_{0/2}$
846.42	4	118145	$5p \ ^2P_{3/2}^{\circ} - 7s \ ^2S_{0/2}$
823.50	20	121433	$5p \ ^2P_{1/2}^{\circ} - 6d \ ^2D_{1/2}$
822.09	20	121647	$5p \ ^2P_{1/2}^{\circ} - 6d \ ^2D_{2/2}$
806.98	20	123919	$5p \ ^2P_{3/2}^{\circ} - 6d \ ^2D_{1/2}$
760.18	8	131548	$5s \ ^2S_{0/2} - 6p \ ^2P_{1/2}^{\circ}$
754.42	10	132552	$5s \ ^2S_{0/2} - 6p \ ^2P_{3/2}^{\circ}$
633.66	20	157813	$4d \ ^2D_{2/2} - 4f \ ^2F_{3/2}^{\circ}$
633.58	100	157833	$4d \ ^2D_{2/2} - 4f \ ^2F_{5/2}^{\circ}$
628.68	100	159063	$4d \ ^2D_{1/2} - 4f \ ^2F_{3/2}^{\circ}$
589.75			
588.89	25	169563	$4d \ ^2D_{2/2} - 6p \ ^2P_{1/2}^{\circ}$
585.43	20	169811	$4d \ ^2D_{1/2} - 6p \ ^2P_{3/2}^{\circ}$
	5	170815	$4d \ ^2D_{1/2} - 6p \ ^2P_{1/2}^{\circ}$
500.22			
497.12	2	199910	$4d \ ^2D_{2/2} - 5f \ ^2F_{3/2}^{\circ}$
	1	201117	$4d \ ^2D_{1/2} - 5f \ ^2F_{5/2}^{\circ}$

the p and d electrons usually lead to limits that are too large; but the difference of 18000 cm^{-1} between the values for the limit from the 2D and 2S series of $Zr\text{ IV}$ appears to be excessively large. The value adopted, therefore, for the ground state of $Zr\text{ IV}$ is the mean of the three accordant determinations, namely, 276970 cm^{-1} . It yields an ionization potential of 34.33 ev for the Zr^{3+} ion.

TABLE 2. Terms of $Zr\text{ IV}$

Term designations	Relative term values	Term separations	Absolute term values	Rydberg denominators
$4d \begin{cases} {}^2D_{1\frac{1}{2}} \\ {}^2D_{2\frac{1}{2}} \end{cases}$	0 1250	1250	276970 275720	2.5171 2.5228
$5s\ {}^2S_{0\frac{1}{2}}$	38258		238712	2.7113
$5p \begin{cases} {}^2P_{0\frac{1}{2}} \\ {}^2P_{1\frac{1}{2}} \end{cases}$	81977 84461	2484	194993 192509	2.9999 3.0192
$5d \begin{cases} {}^2D_{1\frac{1}{2}} \\ {}^2D_{2\frac{1}{2}} \end{cases}$	146651 147001	350	130319 129969	3.6696 3.6745
$6s\ {}^2S_{0\frac{1}{2}}$	152511		124459	3.7550
$4f \begin{cases} {}^2F_{2\frac{1}{2}} \\ {}^2F_{3\frac{1}{2}} \end{cases}$	159063 159083	20	117907 117887	3.8579 3.8582
$6p \begin{cases} {}^2P_{0\frac{1}{2}} \\ {}^2P_{1\frac{1}{2}} \end{cases}$	169805 170810	1005	107165 106160	4.0466 4.0657
$7s\ {}^2S_{0\frac{1}{2}}$	200121		76849	4.7786
$5f \begin{cases} {}^2F_{2\frac{1}{2}} \\ {}^2F_{3\frac{1}{2}} \end{cases}$	201112 201160	48	75858 75810	4.8097 4.8112
$6d \begin{cases} {}^2D_{1\frac{1}{2}} \\ {}^2D_{2\frac{1}{2}} \end{cases}$	205896 206102	206	71074 70868	4.9689 4.9762
$5g\ {}^2G_{4\frac{1}{2}, 3\frac{1}{2}}$	206860		70110	5.0030
$6f \begin{cases} {}^2F_{2\frac{1}{2}} \\ {}^2F_{3\frac{1}{2}} \end{cases}$	224415 224484	69	52555 52486	5.7785 5.7823
$6g\ {}^2G_{4\frac{1}{2}, 3\frac{1}{2}}$	228474		48496	6.0154

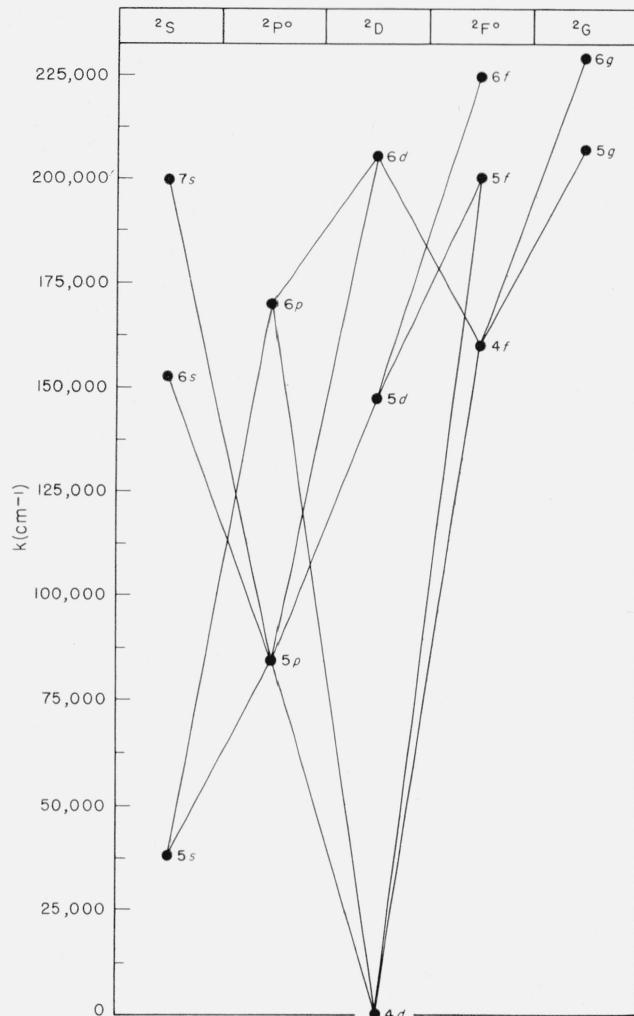


FIGURE 1. Grotrian diagram of the terms and combinations of $Zr\text{ IV}$.

TABLE 3. Series of $Zr\text{ IV}$

Evaluation of limit	Series				
	2S	${}^2P^\circ$	2D	${}^2F^\circ$	2G
Limit term	$5p\ {}^2P^\circ$	$4d\ {}^2D$	$5p\ {}^2P^\circ$	$4d\ {}^2D$	$4f\ {}^2F^\circ$
Value of limit term	194735	281340	212850	276734	118396
Separation of limit term from ground state	81977	0	81977	0	159063
Absolute value of $4p\ {}^2D_{1\frac{1}{2}}$	276712	281340	294827	276734	277459
α	-2.1364		-1.5558	-0.2577	
β	-3.7706		-0.0730	+1.9133	

Adopted mean separation of the ground states of $Zr\text{ V} - Zr\text{ IV} = 276970\text{ cm}^{-1}$.
Ionization potential of $Zr^{3+} = 34.33\text{ ev}$.

TABLE 4. Theoretical terms of Zr III

Electron configurations	Terms										Limit in Zr IV
4d 4d	¹ S	¹ D	¹ G	³ P	³ D	³ F					² D
4d 5s		¹ D									² D
5s 5s	¹ S										² S
4d 5p		¹ P ^o	¹ D ^o	¹ F ^o			³ P ^o	³ D ^o	³ F ^o		² D
5s 5p		¹ P ^o					³ P ^o				² S
4d 5d	¹ S	¹ P	¹ D	¹ F	¹ G		³ S	³ P	³ D	³ F	³ G
4d 6s			¹ D						³ D		² D
4d 4f		¹ P ^o	¹ D ^o	¹ F ^o	¹ G ^o	¹ H ^o	³ P ^o	³ D ^o	³ F ^o	³ G ^o	³ H ^o
5p 5p	¹ S		¹ D				³ P				² P
5s 5d			¹ D					³ D			² S
5s 6s	¹ S						² S				² S
4d 6p		¹ P ^o	¹ D ^o	¹ F ^o			³ P ^o	³ D ^o	³ F ^o		² D
5s 4f				¹ F ^o					³ F ^o		² S
5s 5g					¹ G					³ G	² S

3.2. Spectrum of Doubly Ionized Zirconium, Zr

The term structure of the third spectrum of zirconium presented in the earlier work pertains only to that portion that is derived by addition of *ns*, *np*, *nd*, and *nf* electrons to the ground term 4d²D of Zr IV. However, other terms are to be expected from the addition of similar and also *ng* electrons to the excited states 5s²S and 5p²P^o of Zr IV. All of such theoretical terms that have been found in the present investigation are given in table 4, along with the previously known terms. The level-values of

these terms are given in table 5, and all the lines classified as allowed transitions among the levels are listed in table 6. The relative positions of the Zr III terms are shown in figure 2. For some of the classified lines of Zr III, Zeeman patterns were found on the MIT spectrograms of zirconium. Although few in number these patterns verify some and correct other classifications of lines in the earlier work. They are given in table 7.

Among the terms in table 5 are several pairs that are parts of Rydberg series. No sequence of three or more members of a series has been found in Zr III. Nine such pairs of terms and their absolute values, as interpolated from the Princeton table, are recorded in table 8. By adding to each its distance above the ground state 4d³F₂ of Zr III, a value for the ground state may be derived. Inspection of the table shows that also with Zr III the terms from configurations containing *p*-electrons give higher values for the ground state than do the others. The values for 4d³F₂ from configurations with running *ns* and *nd* electrons are in good agreement, and have been averaged to give a mean value of 198590 cm⁻¹ for the separation of the ground state of Zr III from that of Zr IV. This corresponds to an ionization potential of 24.6 ev.

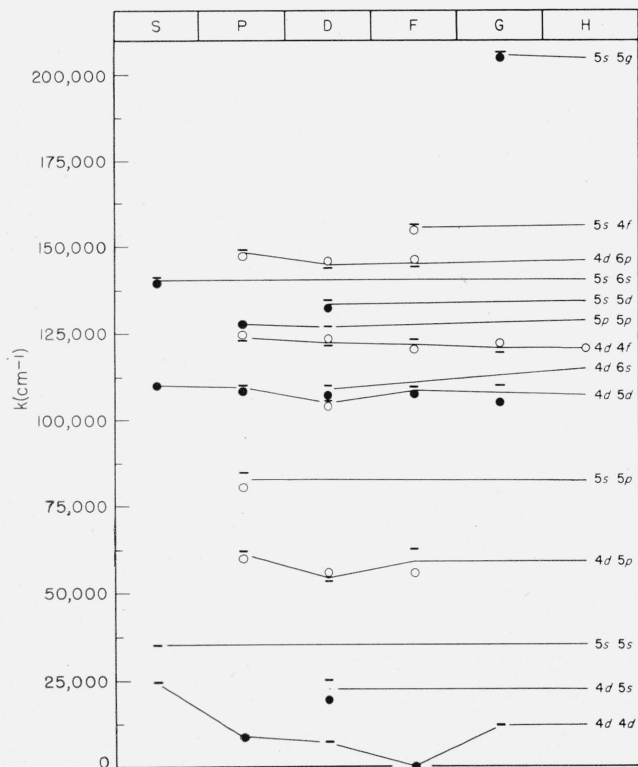


FIGURE 2. Term diagram of Zr III.

●, Even triplet terms; ○, odd triplet terms; —, singlet terms.

TABLE 5. Terms of Zr III

Electron configuration	Term	Relative term value	Term separation
4d(²D)4d	³ F ₂	0.0	
	³ F ₃	680.5	680.5
	³ F ₄	1485.7	805.2
	¹ D	5740.9	
	³ P ₀	8061.50	263.42
	³ P ₁	8324.92	512.53
	³ P ₂	8837.45	
	¹ G ₄	11047.90	
	¹ S ₀	23976.48	

TABLE 5. Terms of Zr III—Continued

Electron configuration	Term	Relative term value	Term separation	Electron configuration	Term	Relative term value	Term separation		
$4d(^2D)5s$	3D_1	18397.85	403.97 730.50	$4d(^2D)5s$	3F_3	120555	234 485		
	3D_2	18801.82			3F_2	120789			
	3D_3	19532.32			3F_1	121274			
$5s(^2S)5s$	1D_2	25065.04	359	$5s(^2S)5s$	3H_4	120660	359		
	1S_0	35500.8			3H_3	121019			
$4d(^2D)5p$	$^3F_2^o$	55554.78	519.46 1606.56	$4d(^2D)4f$	3G_3	122017	584 292		
	$^3F_3^o$	56074.24			3G_4	122601			
	$^3F_4^o$	57680.80			3G_5	122893			
	$^3D_1^o$	55613.40	821.25 911.18		$^3D_1^o$	123336	68 555		
	$^3D_2^o$	56434.65			$^3D_2^o$	123404			
	$^3D_3^o$	57345.83			$^3D_3^o$	123959			
$5s(^2S)5p$	$^3P_0^o$	59944.10	-247.80 659.00	$5p(^2P)5p$	$^3P_0^o$	124800	-221		
	$^3P_1^o$	59696.30			$^3P_1^o$	124683			
	$^3P_2^o$	60355.30			$^3P_2^o$	124462			
	$^1D_3^o$	53646.25	666.3 1450.6		$^1H_3^o$	119791	859 1746		
	$^1P_1^o$	62113.90			$^1G_4^o$	119970			
	$^1F_3^o$	62587.50			$^1D_3^o$	122081			
$4d(^2D)5d$	$^3P_0^o$	79436.7	346.5 772.2	$5p(^2P)5p$	$^1F_3^o$	123303	211 -4		
	$^3P_1^o$	80103.0			$^3P_0^o$	123906			
	$^3P_2^o$	81553.6			$^3P_1^o$	125992			
	$^3D_1^o$	103759.4	556.3 775.8		$^3P_2^o$	126851			
	$^3D_2^o$	104105.9			$^1D_2^o$	128597			
	$^3D_3^o$	104878.1			$^1S_0^o$	126558			
$4d(^2D)5d$	$^3G_3^o$	104632.4	567.1 494.4	$5s(^2S)5d$	$^3D_1^o$	136792	211 -4		
	$^3G_4^o$	105188.7			$^3D_2^o$	137003			
	$^3G_5^o$	105964.5			$^3D_3^o$	136999			
	$^3F_2^o$	107252.5	721.9 911.5		$5s(^2S)6s$	$^1D_2^o$	139441	510 -45	
	$^3F_3^o$	107819.6				$^3S_1^o$	139377		
	$^3F_4^o$	108314.0				$^1S_0^o$	141743		
$4d(^2D)6p$	$^3P_0^o$	107634.6	313.9 980.6	$5s(^2S)4f$		$^3F_2^o$	144846	48 56	
	$^3P_1^o$	108356.5				$^3F_3^o$	145356		
	$^3P_2^o$	109268.0				$^3F_4^o$	145311		
	$^3S_1^o$	109597.7	143945		$^3D_1^o$	146112	281 514		
	$^1D_2^o$	106499.2			$^3D_2^o$	146393			
	$^1F_3^o$	109095.4			$^3D_3^o$	146907			
$4d(^2D)6s$	$^1P_1^o$	109150.9	88 577	$5s(^2S)5g$	$^3P_0^o$	147030	88 577		
	$^1G_4^o$	110627.0			$^3P_1^o$	147118			
	$^1S_0^o$	110134.0			$^3P_2^o$	147695			
	$4d(^2D)6s$	$^3D_1^o$	105006.3		144175	$5s(^2S)5g$	$^1D_3^o$	143945	10 15
		$^3D_2^o$	105320.2				$^1F_3^o$	144175	
		$^3D_3^o$	106300.8				$^1P_1^o$	148082	
$4d(^2D)6s$		$^1D_2^o$	110134.0	156146	$5s(^2S)4f$		$^3F_2^o$	155174	48 56
		$^3D_1^o$	105006.3				$^3F_3^o$	155222	
		$^3D_2^o$	105320.2				$^3F_4^o$	155278	
	$4d(^2D)6s$	$^3D_3^o$	106300.8	205290		$5s(^2S)5g$	$^1F_3^o$	156146	10 15
		$^1D_2^o$	110134.0				$^3G_3^o$	205290	
		$^3D_1^o$	105006.3				$^3G_4^o$	205300	
$4d(^2D)6s$		$^3D_2^o$	105320.2	205315	$5s(^2S)5g$		$^3G_5^o$	205315	10 15
		$^3D_3^o$	106300.8				$^1G_4^o$	206402	
		$^1D_2^o$	110134.0						

TABLE 6. Classified lines of Zr III

Wavelength	Intensity	Wave number	Term combination	Wavelength	Intensity	Wave number	Term combination
<i>A</i>		<i>K (cm⁻¹)</i>		<i>A</i>		<i>K (cm⁻¹)</i>	
3497. 78	15	28581. 41	4d 5s ¹ D ₂ —4d 5p ¹ D _{3/2}	2220. 25	18	45025. 91	4d 4d ¹ G ₄ —4d 5p ³ F ₃
3278. 86	40	30489. 65	4d 5s ¹ D ₂ —4d 5p ³ F _{3/2}	2218. 48	15	45061. 83	4d 5p ³ P ₀ —4d 6s ³ D ₁
3223. 95	20	31008. 92	4d 5s ¹ D ₂ —4d 5p ³ F _{3/2}	2206. 97	40	45296. 82	5s 5p ³ P _{3/2} —5p 5p ³ P ₁
3160. 00	7	31636. 44	4d 4d ¹ S ₀ —4d 5p ³ D ₁	2206. 33	60	45309. 96	4d 5p ³ P ₁ —4d 6s ³ D ₁
3096. 95	5	32280. 50	4d 5s ¹ D ₂ —4d 5p ³ D _{3/2}	2192. 05	35	45605. 09	
2978. 72	5	35720. 11	4d 4d ¹ S ₀ —4d 5p ³ P ₁	2191. 15	100	45623. 83	4d 5p ³ P ₁ —4d 6s ³ D ₂
2886. 70	15	34631. 50	4d 5s ¹ D ₂ —4d 5p ³ P ₁	2186. 20	1	45727. 12	4d 5p ¹ F ₃ —4d 5d ³ F ₄
2869. 06	20	34844. 42	4d 5s ³ D _{3/2} —4d 5p ¹ D _{3/2}	2180. 12	22	45854. 61	
2836. 18	40	35248. 35	4d 5s ³ D _{1/2} —4d 5p ¹ D _{3/2}	2178. 49	20	45888. 93	5s 5p ³ P ₁ —5p 5p ³ P ₀
2832. 81	20	35290. 28	4d 5s ¹ D ₂ —4d 5p ³ P ₂	2175. 80	100	45945. 66	4d 5p ³ P _{3/2} —4d 6s ³ D ₃
2775. 23	25	36022. 43	4d 5s ³ D _{3/2} —4d 5p ³ F _{3/2}	2166. 38	22	46145. 42	4d 5p ³ P _{3/2} —4d 5d ¹ D ₂
2735. 76	75	36542. 12	4d 5s ³ D _{3/2} —4d 5p ³ F _{3/2}	2162. 20	40	46234. 62	
2720. 07	40	36752. 89	4d 5s ³ D _{3/2} —4d 5p ³ F _{3/2}	2159. 24	40	46297. 99	4d 4d ¹ G ₄ —4d 5p ³ D _{3/2}
2715. 76	45	36811. 22	4d 5s ³ D _{2/2} —4d 5p ³ D ₁	2151. 98	15	46454. 17	5s 5p ³ P ₁ —5p 5p ¹ D ₂
2709. 05	50	36902. 39	4d 5s ³ D _{3/2} —4d 5p ³ D _{3/2}	2149. 45	10	46508. 94	4d 5p ¹ F ₃ —4d 5d ¹ F ₃
2698. 31	60	37049. 26	4d 5s ¹ D ₂ —4d 5p ¹ P ₁	2143. 72	12	46633. 13	4d 4d ¹ G ₄ —4d 5p ³ F ₄
2690. 49	70	37156. 94	4d 5s ³ D _{1/2} —4d 5p ³ F _{3/2}	2139. 85	25	46717. 47	4d 4d ³ P ₂ —4d 5p ³ F ₃
2686. 28	75	37215. 17	4d 5s ³ D _{1/2} —4d 5p ³ D ₁	2138. 45	35	46748. 05	5s 5p ³ P ₁ —5p 5p ³ P ₁
2682. 16	100	37272. 47	4d 5s ³ D _{2/2} —4d 5p ³ F _{3/2}	2137. 90	35	46760. 07	4d 5p ³ D _{3/2} —4d 5d ³ D ₂
2664. 26	150	37522. 73	4d 5s ¹ D ₂ —4d 5p ¹ F ₃	2135. 92	10	46803. 41	4d 5p ³ P ₁ —4d 5d ¹ D ₂
2656. 46	100	37632. 90	4d 5s ³ D _{2/2} —4d 5p ³ D _{3/2}	2131. 61	4	46898. 03	4d 5p ³ P _{3/2} —4d 5d ³ F ₂
2643. 79	200	37813. 24	4d 5s ³ D _{3/2} —4d 5p ³ D _{3/2}	2125. 29	15	47037. 48	4d 5p ¹ P ₁ —4d 5d ¹ P ₁
2628. 26	60	38036. 65	4d 5s ³ D _{1/2} —4d 5p ³ D _{3/2}	2125. 06	40	47042. 57	5s 5p ³ P _{3/2} —5p 5p ³ P ₂
2621. 28	50	38137. 93	4d 4d ¹ S ₀ —4d 5p ¹ P ₁	2120. 05	4	47153. 72	4d 5p ¹ P ₁ —4d 5d ³ P ₂
2620. 56	250	38148. 41	4d 5s ³ D _{3/2} —4d 5p ³ F ₄	2116. 63	18	47229. 90	4d 4d ³ P ₁ —4d 5p ³ F ₂
2593. 64	100	38544. 33	4d 5s ³ D _{2/2} —4d 5p ³ D _{3/2}	2116. 30	18	47237. 27	4d 4d ³ P ₂ —4d 5p ³ F ₃
2448. 86	100	40822. 96	4d 5s ³ D _{3/2} —4d 5p ³ P ₂	2114. 10	35	47286. 42	4d 5p ³ D _{3/2} —4d 5d ³ G ₃
2444. 58	50	40894. 42	4d 5s ³ D _{2/2} —4d 5p ³ P ₁	2113. 98	40	47289. 10	4d 4d ³ P ₁ —4d 5p ³ D ₁
2438. 70	25	40993. 02		2112. 40	5	47324. 47	4d 5p ³ D _{3/2} —4d 5d ³ D ₁
2420. 65	75	41298. 67	4d 5s ³ D _{1/2} —4d 5p ³ P ₁	2108. 37	7	47414. 90	5s 5p ³ P ₀ —5p 5p ³ P ₁
2406. 21	40	41546. 48	4d 5s ³ D _{1/2} —4d 5p ³ P ₀	2106. 18	3, Hf?	47464. 21	4d 5p ³ P _{3/2} —4d 5d ³ F ₃
2405. 81	35	41553. 39	4d 5s ³ D _{2/2} —4d 5p ³ P ₂	2105. 33	1	47483. 37	4d 5p ¹ F ₃ —4d 5d ³ S ₁
2389. 32	10	41840. 15		2104. 23	25	47508. 19	4d 5p ³ F ₄ —4d 5d ³ G ₄
2382. 65	10	41957. 26	4d 5s ³ D _{1/2} —4d 5p ³ P ₂	2103. 16	50	47532. 36	4d 5p ³ D _{3/2} —4d 5d ³ D ₃
2336. 50	10	42785. 92	5s 5p ¹ P ₁ —5p 5p ¹ D ₂	2102. 30	40	47551. 80	4d 4d ³ P ₀ —4d 5p ³ D ₁
2321. 89	7	43055. 11	4d 5s ³ D _{3/2} —4d 5p ¹ F ₃	2100. 29	10	47597. 30	4d 4d ³ P ₂ —4d 5p ³ D _{3/2}
2308. 12	75	43311. 95	4d 5s ³ D _{2/2} —4d 5p ¹ P ₁	2097. 03	40	47671. 28	4d 5p ³ D _{3/2} —4d 5d ³ D ₂
2301. 60	100	43434. 64		2089. 50	40	47843. 06	4d 5p ³ D _{3/2} —4d 5d ³ G ₄
2286. 78	20	43716. 05	4d 5s ³ D _{1/2} —4d 5p ¹ P ₁	2086. 78	200	47905. 41	4d 4d ¹ D ₂ —4d 5p ¹ D _{3/2}
2283. 15	20	43785. 59	4d 5s ³ D _{2/2} —4d 5p ¹ F ₃	2085. 35	25	47938. 25	4d 5p ³ P ₁ —4d 5d ³ P ₀
2281. 60	20	43815. 34	4d 5p ³ P ₀ —4d 5d ³ D ₁	2083. 77	7, Hf?	47974. 60	4d 5p ³ D _{3/2} —4d 6s ³ D ₂
2281. 43	30	43818. 60		2082. 61	20	48001. 32	4d 5p ³ P _{3/2} —4d 5d ³ P ₁
2280. 07	8	43844. 74		2081. 81	30	48019. 76	4d 5p ¹ P ₁ —4d 6s ¹ D ₂
2276. 66	15	43910. 40	4d 5p ¹ F ₃ —4d 5d ¹ D ₂	2080. 99	100	48038. 68	4d 5p ¹ F ₃ —4d 5d ¹ G ₄
2257. 83	40	44276. 57	4d 5p ³ P _{3/2} —4d 5d ³ G ₃	2077. 92	100	48109. 64	4d 4d ³ P ₁ —4d 5p ³ D _{3/2}
2254. 26	15	44346. 68		2076. 37	10	48145. 55	4d 5p ³ D ₁ —4d 5d ³ D ₁
2252. 37	20	44383. 89	4d 5p ¹ P ₁ —4d 5d ¹ D ₂	2074. 12	50	48197. 77	4d 5p ³ D _{3/2} —4d 5d ³ G ₃
2251. 14	25	44408. 14	4d 5p ³ P ₁ —4d 5d ³ D ₂	2073. 81	?	48207. 00	4d 5p ³ F ₃ —4d 5d ³ D ₁
2245. 36	50	44522. 44	4d 5p ³ P ₂ —4d 5d ³ D ₃	2070. 96	45, Hf?	48271. 31	5s 5s ¹ S ₀ —5s 5p ¹ P ₁
2241. 33	2	44602. 48	5s 5s ¹ S ₀ —5s 5p ³ P ₁	2070. 43	125	48283. 66	4d 5p ³ F ₄ —4d 5d ³ G ₅
2238. 26	5	44663. 65		2064. 93	10	48412. 25	4d 5p ³ P ₀ —4d 5d ³ P ₁
2231. 00	30	44808. 98	4d 4d ³ P ₂ —4d 5p ¹ D _{3/2}	2061. 47	50	48493. 49	5s 5p ³ P ₁ —5p 5p ³ P ₂
2228. 10	20	44867. 30		2060. 83	75	48508. 55	4d 5p ³ D ₁ —4d 5d ³ D ₂
2223. 31	10	44963. 95	4d 5p ³ P _{3/2} —4d 6s ³ D ₂				4d 4d ³ P ₂ —4d 5p ³ D _{3/2}
2221. 36	20	45003. 42	5s 5p ³ P _{3/2} —5p 5p ¹ D ₂				

TABLE 6. Classified lines of Zr III—Continued

Wavelength	Intensity	Wave number	Term combination	Wavelength	Intensity	Wave number	Term combination
<i>A</i>				<i>A</i>			
2059.01	12	48551.42	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3D_2$	1940.25	200	51539.8	$4d\ 4d\ ^1G_4-4d\ 5p\ ^1F_3$
2058.73	40	48558.03	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3G_3$	1937.81	12	51604.6	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3D_3$
2058.14	20	48571.94	$4d\ 5p\ ^3D_3-4d\ 6s\ ^3D_1$	1937.27	80	51619.0	$4d\ 4d\ ^3P_1-4d\ 5p\ ^3P_0$
2056.13	75	48619.42	$4d\ 5p\ ^3F_4-4d\ 6s\ ^3D_3$	1936.67	75	51635.0	$4d\ 4d\ ^3P_0-4d\ 5p\ ^3P_1$
2048.40	3	48802.87	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3D_3$	1936.48	75	51640.1	$4d\ 5p\ ^3D_1-4d\ 5d\ ^3F_2$
2043.79	20	48912.94	$4d\ 5p\ ^3P_2-4d\ 5d\ ^3P_2$	1935.20	40	51674.2	$4d\ 5p\ ^1D_2-4d\ 6s\ ^3D_2$
2042.04	20	48954.85	$4d\ 5p\ ^3D_3-4d\ 6s\ ^3D_3$	1934.32	50	51697.8	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3F_2$
2036.92	50	49077.88	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3G_3$	1932.54	75	51745.4	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3F_3$
2035.42	100	49114.04	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3G_4$	1925.98	15	51921.6	$4d\ 5p\ ^3D_2-4d\ 5d\ ^3P_1$
2033.76	12	49154.12	$\begin{cases} 5s\ 4f\ ^1F_3-5s\ 5g\ ^3G_4 \\ 4d\ 5p\ ^3D_3-4d\ 5d\ ^1D_2 \end{cases}$	1925.88	12	51924.3	$4d\ 5p\ ^3D_3-4d\ 5d\ ^3P_2$
2030.12	8	49242.25	$4d\ 5p\ ^3P_2-4d\ 5d\ ^3S_1$	1922.26	6	52022.1	$4d\ 5p\ ^3D_1-4d\ 5d\ ^3P_0$
2029.94	10	49246.61	$4d\ 5p\ ^3F_3-4d\ 6s\ ^3D_2$	1921.96	75	52030.2	$4d\ 4d\ ^3P_1-4d\ 5p\ ^3P_2$
2026.78	60	49323.38	$4d\ 5p\ ^3F_2-4d\ 5d\ ^3D_3$	1914.25	65	52239.8	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3F_4$
2023.88	7	49394.05	$4d\ 5p\ ^3D_1-4d\ 6s\ ^3D_1$	1913.34	18	52264.6	$4d\ 5p\ ^3F_2-4d\ 5d\ ^3F_3$
2021.52	30	49451.70	$4d\ 5p\ ^3F_2-4d\ 6s\ ^3D_1$	1894.36	20	52788.3	$4d\ 5p\ ^3D_3-4d\ 6s\ ^1D_2$
2016.63	35	49571.60	$4d\ 5p\ ^3P_1-4d\ 5d\ ^3P_2$	1892.07	50	52852.2	$4d\ 5p\ ^1D_2-4d\ 5d\ ^1D_2$
2013.30	30	49653.58	$4d\ 5p\ ^3P_0-4d\ 5d\ ^3S_1$	1888.70	2	52946.5	$4d\ 5p\ ^3F_4-4d\ 5d\ ^1G_4$
2011.13	2	49707.14	$4d\ 5p\ ^3D_1-4d\ 6s\ ^3D_2$	1881.02	20	53162.6	$4d\ 5p\ ^3D_3-4d\ 5d\ ^3S_1$
2008.26	12	49778.17	$4d\ 5p\ ^3P_2-4d\ 6s\ ^1D_2$	1879.92	10	53193.8	$4d\ 5p\ ^3F_2-4d\ 5d\ ^3P_2$
2006.82	100	49813.88	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3F_2$	1878.56	10	53232.3	$5s\ 5p\ ^1P_1-5s\ 5d\ ^3D_2$
2004.69	8	49866.80	$4d\ 5p\ ^3D_2-4d\ 6s\ ^3D_3$	1877.00	35	53276.5	$4d\ 4d\ ^3P_2-4d\ 5p\ ^1P_1$
2004.45	7	49872.77	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3D_1$	1867.76	15	53540.1	$4d\ 5p\ ^3F_3-4d\ 5d\ ^1F_3$
2003.26	8	49902.40	$4d\ 5p\ ^3P_1-4d\ 5d\ ^3S_1$	1865.83	18	53595.4	$4d\ 5p\ ^3F_2-4d\ 5d\ ^1P_1$
2002.00	55, Hf?	49933.80		1865.45	30	53606.4	$4d\ 5p\ ^1D_2-4d\ 5d\ ^3F_2$
2001.96	20	49935.80		1864.06	75	53646.3	$4d\ 4d\ ^3F_2-4d\ 5p\ ^1D_2$
2000.23	45	49994.25		1861.77	25	53712.3	$4d\ 5p\ ^3F_2-4d\ 5d\ ^3P_2$
1999.09	3	50022.8	$5s\ 4f\ ^3F_4-5s\ 5g\ ^3G_4$	1860.47	25	53749.9	$4d\ 4d\ ^3P_2-4d\ 5p\ ^1F_3$
1998.51	6	50037.3	$5s\ 4f\ ^3F_4-5s\ 5g\ ^3G_3$	1859.12	30	53788.9	$4d\ 4d\ ^3P_1-4d\ 5p\ ^1P_1$
1997.30	3	50067.6	$5s\ 4f\ ^3F_3-5s\ 5g\ ^3G_3$	1853.38	40	53955.5	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3P_1$
1996.92	15	50077.1	$5s\ 4f\ ^3F_3-5s\ 5g\ ^3G_4$	1850.35	12	54043.8	$4d\ 5p\ ^3F_2-4d\ 5d\ ^3S_1$
1995.36	15	50116.3	$5s\ 4f\ ^3F_2-5s\ 5g\ ^3G_3$	1850.06	40	54052.3	$4d\ 4d\ ^3P_0-4d\ 5p\ ^1P_1$
1994.46	30	50138.9	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3F_3$	1849.84	1	54058.7	$4d\ 5p\ ^3F_3-4d\ 6s\ ^1D_2$
1990.95	30	50227.3	$4d\ 5p\ ^3F_3-4d\ 6s\ ^3D_3$	1833.09	15	54552.7	$4d\ 5p\ ^3F_3-4d\ 5d\ ^1G_4$
1989.83	50	50255.5	$5s\ 4f\ ^1F_3-5s\ 5g\ ^1G_4$	1832.16	22	54580.4	$4d\ 5p\ ^3F_2-4d\ 5d\ ^1D_2$
1986.75	20	50333.5	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3F_3$	1831.89	35	54588.4	$4d\ 4d\ ^3F_4-4d\ 5p\ ^3F_3$
1983.14	40	50425.1	$4d\ 5p\ ^3F_3-4d\ 5d\ ^1D_2$	1822.35	10	54874.2	$4d\ 4d\ ^3F_3-4d\ 5p\ ^3F_2$
1982.61	12	50438.6	$4d\ 5p\ ^3P_1-4d\ 6s\ ^1D_2$	1805.26	100	55393.7	$4d\ 4d\ ^3F_3-4d\ 5p\ ^3F_3$
1981.67	20	50462.5	$4d\ 5p\ ^1D_2-4d\ 5d\ ^3D_2$	1803.57	18	55445.6	$5s\ 5p\ ^3P_2-5s\ 5d\ ^3D_3$
1981.21	20	50474.2	$4d\ 5p\ ^3D_3-4d\ 5d\ ^3F_3$	1803.46	12	55449.0	$\begin{cases} 5s\ 5p\ ^3P_2-5s\ 5d\ ^3D_2 \\ 4d\ 5p\ ^1D_2-4d\ 5d\ ^1F_3 \end{cases}$
1974.99	60	50633.2	$4d\ 5p\ ^3F_1-4d\ 5d\ ^3F_4$	1801.67	25	55504.1	$4d\ 5p\ ^1D_2-4d\ 5d\ ^1P_1$
1972.63	22	50693.7	$4d\ 4d\ ^1D_2-4d\ 5p\ ^3D_2$	1800.03	75	55554.6	$4d\ 4d\ ^3F_2-4d\ 5p\ ^3F_2$
1967.81	25	50817.9	$4d\ 5p\ ^3D_2-4d\ 5d\ ^3F_2$	1798.36	18	55606.2	$5s\ 5p\ ^1P_1-5s\ 6s\ ^3S_1$
1966.22	85	50859.0	$4d\ 4d\ ^3P_2-4d\ 5p\ ^3P_1$	1798.13	125	55613.3	$4d\ 4d\ ^3F_2-4d\ 5p\ ^3D_1$
1965.18	20	50885.9	$4d\ 5p\ ^3D_1-4d\ 5d\ ^1D_2$	1796.36	15	55668.1	$5s\ 5p\ ^1P_1-5s\ 5d\ ^1D_2$
1962.92	40	50944.5	$4d\ 5p\ ^3F_2-4d\ 5d\ ^1D_2$	1793.59	150	55754.1	$4d\ 4d\ ^3F_3-4d\ 5p\ ^3D_2$
1962.01	100	50968.1	$4d\ 5p\ ^3D_3-4d\ 5d\ ^3F_4$	1790.19	200	55860.0	$4d\ 4d\ ^3F_4-4d\ 5p\ ^3D_3$
1961.32	50	50986.1	$4d\ 5p\ ^1D_2-4d\ 5d\ ^3G_3$	1783.35	40	56074.2	$4d\ 4d\ ^3F_2-4d\ 5p\ ^3F_3$
1956.03	10	51124.0	$5s\ 4f\ ^3F_4-5s\ 5g\ ^1G_4$	1779.51	100	56195.2	$4d\ 4d\ ^3F_4-4d\ 5p\ ^3F_4$
1953.95	100	51178.4	$4d\ 5p\ ^3F_3-4d\ 5d\ ^3F_2$	1773.90	40	56373.0	$4d\ 4d\ ^1D_2-4d\ 5p\ ^1P_1$
1951.86	8	51233.2	$4d\ 5p\ ^1D_2-4d\ 5d\ ^3D_3$	1771.96	30	56434.7	$4d\ 4d\ ^3F_2-4d\ 5p\ ^3D_2$
1946.99	50	51361.3	$4d\ 4d\ ^3P_1-4d\ 5p\ ^3P_1$	1770.35	4	56486.0	$4d\ 5s\ ^1D_2-5s\ 5p\ ^3P_2$
1946.61	80	51371.4	$4d\ 5p\ ^3D_2-4d\ 5d\ ^3F_3$	1770.28	20	56488.2	$4d\ 5p\ ^1D_2-4d\ 6s\ ^1D_2$
1946.12	25	51384.3	$4d\ 5p\ ^3F_4-4d\ 5d\ ^1F_3$	1764.75	30	56665.2	$4d\ 4d\ ^3F_3-4d\ 5p\ ^3D_3$
1945.00	20	51413.9	$4d\ 4d\ ^3P_2-4d\ 5p\ ^3P_2$	1763.99	20	56689.7	$5s\ 5p\ ^3P_1-5s\ 5d\ ^3D_1$

TABLE 6. *Classified lines of Zr III—Continued*

Wavelength	Intensity	Wave number	Term combination	Wavelength	Intensity	Wave number	Term combination
<i>A</i>		<i>K (cm⁻¹)</i>		<i>A</i>		<i>K (cm⁻¹)</i>	
823. 69	35	121405	4d 4d ³ F ₄ —4d 4f ³ G ₅	719. 16	1	139051	4d 4d ³ P ₀ —4d 6p ³ P ₁
820. 91	8	121816	4d 4d ³ F ₄ —4d 4f ¹ F ₃	717. 53	3	139367	4d 4d ³ P ₁ —4d 6p ³ P ₂
820. 21	30	121920	4d 4d ³ F ₃ —4d 4f ³ G ₄	716. 28	7	139610	4d 4d ¹ D ₂ —4d 6p ³ F ₃
819. 59	25	122012	4d 4d ³ F ₂ —4d 4f ³ G ₃	715. 53	7	139756	4d 4d ³ P ₁ —4d 6p ¹ P ₁
819. 14	1	122079	4d 4d ³ F ₂ —4d 4f ¹ D ₂	714. 18	6	140020	4d 4d ³ P ₀ —4d 6p ¹ P ₁
816. 53	6	122470	4d 4d ³ F ₄ —4d 4f ³ D ₃	710. 98	10	140651	4d 4d ¹ D ₂ —4d 6p ³ D ₃
815. 53	5	122620	4d 4d ³ F ₃ —4d 4f ¹ F ₃	708. 40	8	141163	4d 4d ¹ D ₂ —4d 6p ³ D ₃
814. 89	12	122716	4d 4d ³ F ₃ —4d 4f ³ D ₂	700. 80	2	142694	4d 4d ³ F ₄ —4d 6p ¹ F ₃
811. 00	6	123305	4d 4d ³ F ₂ —4d 4f ¹ F ₃	696. 91	4	143491	4d 4d ³ F ₃ —4d 6p ¹ F ₃
810. 80	6	123335	4d 4d ³ F ₂ —4d 4f ³ D ₁	695. 29	12	143825	4d 4d ³ F ₄ —4d 6p ³ F ₄
807. 88	2	123781	4d 4d ³ F ₃ —4d 4f ³ P ₃	695. 06	10	143872	4d 4d ³ F ₄ —4d 6p ³ F ₃
802. 00	4	124688	4d 4d ³ F ₂ —4d 4f ³ P ₁	694. 69	8	143949	4d 4d ³ F ₂ —4d 6p ¹ D ₃
762. 90	20	131079	4d 5s ¹ D ₂ —5s 4f ¹ F ₃	693. 65	2	144165	4d 4d ³ F ₃ —4d 6p ³ F ₃
751. 16	5	133127	4d 4d ¹ G ₄ —4d 6p ¹ F ₃	691. 42	15	144630	4d 4d ³ F ₃ —4d 6p ³ F ₄
744. 58	4	134304	4d 4d ¹ G ₄ —4d 6p ³ F ₃	691. 19	10	144678	4d 4d ³ F ₃ —4d 6p ³ F ₃
736. 97	4	135691	4d 5s ³ D ₃ —5s 4f ³ F ₃	690. 39	50	144846	4d 4d ³ F ₂ —4d 6p ³ F ₃
736. 67	20	135746	4d 5s ³ D ₃ —5s 4f ³ F ₄	687. 95	12	145359	4d 4d ³ F ₂ —4d 6p ³ F ₃
733. 29	4	136372	4d 5s ³ D ₂ —5s 4f ³ F ₃	687. 64	25	145425	4d 4d ³ F ₄ —4d 6p ³ D ₃
733. 03	18	136420	4d 5s ³ D ₂ —5s 4f ³ F ₃	686. 28	4	145713	4d 4d ³ F ₃ —4d 6p ³ D ₃
731. 98	2	136616	4d 5s ³ D ₃ —5s 4f ¹ F ₃	684. 38	2	146118	4d 4d ³ F ₂ —4d 6p ³ D ₁
731. 12	10	136776	4d 5s ³ D ₁ —5s 4f ³ F ₃	683. 09	5	146394	4d 4d ³ F ₂ —4d 6p ³ D ₃
726. 99	5	137554	4d 4d ³ P ₂ —4d 6p ³ D ₂	680. 69	3	146910	4d 4d ³ F ₂ —4d 6p ³ D ₃
724. 40	12	138045	4d 4d ³ P ₀ —4d 6p ³ D ₁				
724. 30	15	138064	{ 4d 4d ³ P ₂ —4d 6p ³ D ₃ 4d 4d ³ P ₁ —4d 6p ³ D ₂				
723. 59	15	138200	4d 4d ¹ D ₂ —4d 6p ¹ D ₃				
723. 13	4	138288	4d 4d ³ P ₂ —4d 6p ³ P ₁				
720. 96	2	138704	4d 4d ³ P ₁ —4d 6p ³ P ₀				
720. 50	5	138792	4d 4d ³ P ₁ —4d 6p ³ P ₁				
720. 15	3	138860	4d 4d ³ P ₂ —4d 6p ³ P ₂				

TABLE 7. *Zeeman patterns of Zr III lines*

A=shaded outward /| \; *B*=shaded inward \ | /.

Wavelengths	Term combinations	Observed Zeeman patterns	Derived <i>g</i> -values
<i>A</i>			
3497. 78	5s ¹ D ₂ —5p ¹ D ₂	(0.128) 0.993	1. 070; 0. 914
2836. 18	5s ³ D ₁ —5p ¹ D ₂	(0.000 , 0.422) . . . 1.336	0. 495; 0. 914
2735. 76	5s ³ D ₃ —5p ³ F ₃	(0.438, 0.684) 0.878, 1.104 , 1.345, 1.552	1. 345; 1. 104
2715. 76	5s ³ D ₂ —5p ³ D ₁	(0.000) 1.824	1. 162; 0. 500
2698. 31	5s ¹ D ₂ —5p ¹ P ₁	(0.000) 0.972	1, 070; 1. 266
2690. 49	5s ³ D ₁ —5p ³ F ₃	(0.000 , 0.281) 0.791, 1.074	0. 495; 0. 792
2686. 28	5s ³ D ₁ —5p ³ D ₁	(0.000) 0.506	0. 495; 0. 500
2682. 16	5s ³ D ₂ —5p ³ F ₃	(0.000) 1.040 <i>A</i>	1. 162; 1. 104
2664. 26	5s ¹ D ₂ —5p ¹ F ₃	(0.000) 1.020	1. 070; 1. 045
2656. 46	5s ³ D ₂ —5p ³ D ₂	(0.000) 1.166	1. 162; 1. 136
2643. 79	5s ³ D ₃ —5p ³ D ₃	(0.000) 1.341	1. 345; 1. 364
2628. 26	5s ³ D ₁ —5p ³ D ₂	(0.000 , 0.666) 1.150, 1.788	0. 495; 1. 136
2620. 56	5s ³ D ₃ —5p ³ F ₄	(0.000) 1.042 <i>A</i>	1. 345; 1. 224
2593. 64	5s ³ D ₂ —5p ³ D ₃	(0.000 <i>w</i>) 1.566 <i>B</i>	1. 162; 1. 364

TABLE 8. Series terms of Zr III

Terms	Limits in Zr IV	Relative term-values	Term separations	Distances to limits	Distances to ground state of Zr III	Distances between ground states of Zr III-Zr IV
4d 4d ¹ G ₄ 4d 5d ¹ G ₄	4d ² D _{3/2}	11048 110627	<i>cm</i> ⁻¹ 99579	<i>cm</i> ⁻¹ 192085 92505	<i>cm</i> ⁻¹ +9798	201883
4d 4d ³ F ₂ 4d 5d ³ F ₂	4d ² D _{1/2}	0 107252	107252	203530 96278	0	203530
4d 5s ¹ D ₂ 4d 6s ¹ D ₂	4d ² D _{3/2}	25065 110134	85069	169981 84912	+23815	193796
4d 5s ³ D ₁ 4d 6s ³ D ₁	4d ² D _{1/2}	18398 105006	86608	172357 85749	+18398	190755
4d 5p ¹ D _{3/2} 4d 6p ¹ D _{3/2}	4d ² D _{3/2}	53646 143945	90299	178028 87725	+52396	230424 ^a
4d 5p ³ F _{3/2} 4d 6p ³ F _{3/2}	4d ² D _{1/2}	55555 144846	89291	176479 87188	+55555	230034 ^a
5s 5s ¹ S ₀ 5s 6s ¹ S ₀	5s ² S _{0/2}	35501 141743	106242	202031 95789	-2757	199274
5s 4d ¹ D ₂ 5s 5d ¹ D ₂	5s ² S _{0/2}	25065 139441	114376	214028 99652	-13193	200835
5s 4d ³ D ₁ 5s 5d ³ D ₁	5s ² S _{0/2}	18398 136792	118394	219902 101507	-19860	200043
Mean Zr III-Zr IV=198590						
Ionization potential=198590×1.2395×10 ⁻⁴ =24.6 ev						

^a Not included in the mean.

4. Discussion

The terms of Zr IV and Zr III recorded in tables 2 and 5 conform almost without exception to those required theoretically for atoms with 1 and 2 valence electrons. It is usually difficult to establish singlet terms with certainty if Zeeman patterns and inter-system combinations are missing. This is particularly true of the ¹S₀ terms of Zr III for which, at most, only a few combinations can occur in the spectrum. It is always possible to find, in a complex spectrum, pairs of lines that exhibit wave-number separations in approximate agreement with the separations of established levels. If any such pairs are physically real, they should satisfy further requirements relative to the intensities of the lines and the way in which they fit into series. The ¹S₀ terms in table 5 have been selected on the basis of such tests in the absence of the more convincing testimony of Zeeman observations.

A singlet term of Zr III that should be accepted with reserve is the one in table 5 designated as 4d 4f ¹H_{5/2}. It combines with the same levels as does 4d 4f ¹G₄ from which it is separated by only 180 *cm*⁻¹. Thus, it would violate the selection rule for inner quantum numbers if the assigned designation

is correct. However, in the theoretical term-structure of the 4d 4f electron-configuration there is no room for an additional term with *J*=4. Careful combing of the spectrum for another term with *J*=5 has proved fruitless. We are left, therefore, with a choice of one of three possibilities: (1) the term labeled ¹H_{5/2} is correctly designated and violates the ΔJ rule; (2) it should be accepted as an unexplained level ¹X₄; (3) the line at 839.55 Å designated as 4d ³F₃-4f ¹H_{5/2} should be regarded as fortuitously and not physically represented by this designation. If interpretation (3) is correct this line, with appearance similar to that of nearby lines of the 4d-4f group, would be left unexplained. Choice (2) does not seem warranted. In favor of the first choice is the fact that violations of the ΔJ rule are not unknown in other spectra as, for example, Paschen [6] pointed out in the case of the Hg II line at 2814.9 Å.

Of the isoelectronic spectra Sr I, Y II, Zr III, Nb IV, and Mo V, the first is the only one in which series of three or more members have been found. In the other spectra of this sequence not more than two members of a series are known. The series limits that have been reported for the spectra following Sr I have been determined either with the Rydberg formula or with the irregular-doublet law. The

values of the limits thus derived with the one method are likely to be too high, and too low with the other. Although the limits of Zr III given in table 8 are undoubtedly too large, the amount by which they should be reduced can, at present, be only a matter of conjecture. Therefore, it is deemed preferable to offer these values only as provisional ones subject to revision when future data become available.

In the isoelectronic sequence of spectra from Rb I to Mo VI the only one with series of more than two members, following Rb I and Sr II, is Zr IV. As stated above the 2S , $^2F^{\circ}$, and 2G series give concordant results in placing the ground state $4p\ ^2D_{1\frac{1}{2}}$ of Zr IV 276970 cm^{-1} from the ground state 1S_0 of Zr V, whereas the 2D series gives a value about 18000 cm^{-1} greater. The series of Y III, Nb V, and Mo VI each consist of only two members. Although these series terms can be accurately represented with a simple Rydberg formula yet the limits calculated by this method are greater than those derived from application of the irregular-doublet rule to similar series of Rb I, Sr II, and Zr IV. It seems reasonable, therefore, to adopt for the limits provisional values that are means between the extreme values given by the different methods. When this is done and the results are compared with limits derived from the 2D series, as in table 9, the differences between the convergences of the series are clearly revealed. These findings confirm Russell's statement that "Series involving changes in a d electron are usually very regular, except for the lowest term, when this involves the binding of the electron as part of an incomplete shell. In this case the energy of binding is considerably increased, and the application of a single Rydberg formula puts the limit a great deal too high."

The results presented in this paper could not have been achieved without the observational material supplied by Professors A. G. Shenstone, J. C. Boyce,

TABLE 9. Absolute term values of $^2D_{1\frac{1}{2}}$

Spectrum	From 2S or $^2F^{\circ}$ series	From 2D series	Differences
Rb I	14336	{ 14310 ^a 19780 ^b }	{ -26 +5440}
Sr II	74408	{ 74428 ^a 76970 ^b }	{ +20 +2560}
Y III	168400	175080	+6680
Zr IV	276970	294850	+17880
Nb V	407700	433730	+26030
Mo VI	549000	589630	+40630

^a Calculated with high series members (Rydberg formula).

^b Calculated with first two series members (Rydberg formula).

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