Lawrence Berkeley National Laboratory

Recent Work

Title

ANALYSIS OF 4-IONIZED VANADIUM (V v)

Permalink

<https://escholarship.org/uc/item/1f48j1tq>

Author

Van Deurzen, Cornelius H.H.

Publication Date

1976-08-01

Submitted to Journal of the Optical Society
of America

LBL-5447
Preprint c.1

ANALYSIS OF 4-IONIZED VANADIUM (V v)

Cornelius H.H. Van Deurzen

August 1976

RECEIVED
LAWRENCE
BERKELEY LABORATORY

SEP 19 1976

LIBRARY AND
DOCUMENTS SECTION

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

For Reference

Not to be taken from this room

LBL-5447
c.1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Analysis of 4-Ionized Vanadium (V v)

Cornelius H.H. Van Deurzen*
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

August 1976

ABSTRACT

The spectrum of vanadium V has been observed by using 10-meter grazing- and normal-incidence spectrographs and a vacuum sliding-spark light source to excite the spectrum. The analysis has been extended to include 46 newly classified lines in the region 199 Å to 7600 Å. Five new levels in the $3p^6n\ell$ configuration and two in the $3p^53d4s$ configuration have been identified. The ionization energy is revised to $526532.0 \pm 1.4 \text{ cm}^{-1}$ (65.2822 eV).

* Present address: British Columbia Institute of Technology
Burnaby, B.C.

The Analysis of the V^{4+} ion spectrum (neutral potassium isoelectronic sequence) has been extended beyond earlier work.^{1,2} The wavelength region from 100 Å to 2100 Å was photographed on SWR plates using the 10-meter spectrographs at the National Bureau of Standards (grazing-incidence 0.2 Å/mm; normal incidence 0.8 Å/mm). Previous plates were examined for additional transition lines in the wavelength region from 450 Å to 8500 Å. The spectrum was excited with a vacuum sliding-spark discharge at a peak current of 1000 A, the experimental details were as described previously.¹

OBSERVATIONS AND ANALYSIS

Some of the short-wavelength lines were measured in higher orders ($m = 1, 2, 3, 4$) on the NBS normal-incidence spectrograph ($400 \leq m\lambda \leq 2100$), specifically the 3d-4p triplet and 3d-4f doublet lines. For wavelengths which agreed to better than milliAngstroms in all measured orders, the fourth decimal in the wavelength has been retained. The newly classified lines are listed in Table I together with previously reported lines with or without improved wavelength values for completeness. Intensities are visual estimates of photographic blackening on a scale from 1 to 100.

Seven new levels have been identified and are listed in Table II together with the revised values of previously reported levels. The uncertainty in closed-cycle levels is estimated to be a few units in the second decimal relative to $E(3p^6 4p^2 P_{3/2}^0) = 207660.00 \pm 0.3 \text{ cm}^{-1}$, which reflects the larger uncertainty in the 4p-3d triplet at 483 Å. The uncertainty in the calculated wavelength values (Table I) is in

the last digit shown, specifically $\pm 0.001 \text{ \AA}$ or less for calculated wavelengths shorter than $510 \text{ \AA}$.

Observed inter-configuration transitions indicate appreciable configuration interaction. The most conspicuous mixing and mutual repulsion occurs between the levels:

$$\begin{aligned} 3p^6 4f^2 F_{5/2}^0 & \text{ and } 3p^5 3d^2 ({}^1D) {}^2F_{5/2}^0, \\ 3p^6 5f^2 F_{7/2}^0 & \text{ and } 3p^5 3d^2 ({}^3F) {}^2F_{7/2}^0, \\ 3p^6 9f^2 F_{5/2}^0 & \text{ and } 3p^5 3d ({}^1F) 4s {}^2F_{5/2}^0, \\ 3p^6 7p^2 P_{3/2}^0 & \text{ and } 3p^5 3d^2 ({}^3P) {}^2P_{3/2}^0, \\ 3p^6 7p^2 P_{1/2}^0 & \text{ and } 3p^5 3d ({}^3P) 4s {}^2P_{1/2}^0. \end{aligned}$$

These interactions cause respectively the inversion of the $4f$ doublet and the anomalously large fine-structure intervals of the $5f$, $9f$, and $7p$ terms. In addition the mixing and repulsion between the levels:

$$\begin{aligned} 3p^6 10f^2 F_{7/2}^0 & \text{ and } 3p^5 3d ({}^1F) 4s {}^2F_{7/2}^0, \text{ and between} \\ 3p^6 8p^2 P_{3/2}^0 & \text{ and } 3p^5 3d ({}^3P) 4s {}^2P_{3/2}^0 \end{aligned}$$

are expected to cause anomalously large fine-structure intervals of the $10f$ and $8p$ terms respectively.

IONIZATION ENERGY

The ionization energy ($3p^6 {}^1S_0$) of vanadium V has been recalculated using the polarization formula.³ In a multi-electron atom, the deviation of hydrogen-like terms T_n from the corresponding hydrogenic values T_n^0 is attributed to the dipole and quadrupole polarizability of the atomic core in the field of the outer electron, if penetration effects are negligible. The polarization energy of the core's electron-cloud distortion may be expressed⁴

$$T_n - T_n^0 = AR \phi(n\ell) + BR \psi(n\ell)$$

$$\text{where } T_n^0 = R \frac{Z^2}{n^2} \left\{ 1 + \frac{\alpha^2 Z^2}{n^2} \left(\frac{n}{\ell+1/2} - \frac{3}{4} \right) \right\}$$

$$\phi(n\ell) \equiv \frac{a_0^4}{Z^4} \left\langle \frac{1}{r^4} \right\rangle = \frac{3n^2 - \ell(\ell+1)}{2n^5 (\ell-1/2)\ell(\ell+1/2)(\ell+1)(\ell+3/2)} \quad 5$$

$$\psi(n\ell) \equiv \frac{a_0^6}{Z^6} \left\langle \frac{1}{r^6} \right\rangle = \frac{35n^4 - 5n^2 \{6\ell(\ell+1) - 5\} + 3(\ell-1)\ell(\ell+1)(\ell+2)}{8n^7 (\ell-3/2)(\ell-1)(\ell-1/2)\ell(\ell+1/2)(\ell+1)(\ell+3/2)(\ell+2)(\ell+5/2)} \quad 6$$

The calculable functions ϕ and ψ depend only on the $n\ell$ quantum numbers of the excited electron, and the polarizability (dipole α_d and quadrupole α_q) of the remaining core is expressed in the parameters $A \equiv (Z^4/a_0^3)\alpha_d$ and $B \equiv (Z^6/a_0^5)\alpha_q$ which are considered term independent for non-penetrating hydrogen-like levels. The theory neglects fine-structure splitting hence term values are represented by their center of gravity. The term values ($T_n \equiv E_\infty - E_n$) depend on the chosen series limit E_∞ and the known level values E_n resulting in a 3-parameter polarization formula.

The fitting of the data, using equally weighted term values, to the polarization formula yields the values shown in Table III and is graphically illustrated in Figure 2 where the dimensionless polarization-energy quantity $T_n - T_n^0 / R\phi(n\ell)$ is plotted versus $q(n\ell) \equiv \psi/\phi$.

TABLE III. POLARIZATION FORMULA APPLIED TO VANADIUM V.

Terms used	$E_\infty (\text{cm}^{-1})$	$\alpha_d (a_0^3)$	$\alpha_q (a_0^5)$
5g,6g,7g	526525.3	0.94	2.1
6h,7h,7i,8i	526532.0 $\pm$ 1	1.01 $\pm$.08	1.4 $\pm$ 1.1
5g,6g,7g,6h,7h,7i,8i	526530.3 $\pm$ 2	0.93 $\pm$.05	2.3 $\pm$ 0.3

The indicated uncertainty in a parameter corresponds to the increment (when the two remaining parameters are least-squares fitted) which doubles the mean square deviation of the best least-squares fit to the term values. Values of series limits were also calculated by fitting an extended Ritz-like formula to all observed members of an $n\ell$ series: $E_{\infty}(4-8^2S_{1/2}) = 526524 \text{ cm}^{-1}$ and $E_{\infty}(5-7^2G) = 526523 \text{ cm}^{-1}$; the n^2P^0 and n^2F^0 series yield anomalous values due to the mentioned perturbations as does the n^2D series due to core effects.

The difference (6.7 cm^{-1}) in ionization energies obtained from the $ng(^2G)$ series and from higher angular momentum series is possibly due to the slight difference in the penetration effects which have been neglected in the polarization theory. We calculate similar smaller differences from the Ti IV data⁷ (3.7 cm^{-1}) and the Sc III data⁸ ($< 1 \text{ cm}^{-1}$). A larger difference observed in Cr VI is attributed⁹ to configuration interaction between $3p^66g(^2G)$ and $3p^53d4p(^2G)$ levels; the latter lie increasingly higher above the observed ng members and the $3p^6^1S_0$ limit in vanadium V and all lower members of the isoelectronic sequence. The well-established relative energy differences between members of the ng , nh , ni series coupled with the expected smaller penetration effects, lower quadrupole polarizability, and lesser if any perturbation of the members of the nh , ni series, leads us to adopt the value

$$E_{\text{ion}} = 526532.0 \pm 1.4 \text{ cm}^{-1}$$

where the additional uncertainty in the $6h$ to $3d$ ground term has been taken into account. This value of the ionization energy yields

effective quantum number changes: $\delta n_h^* = n_{7h}^* - n_{6h}^* = 0.999622$ and $\delta n_i^* = n_{8i}^* - n_{7i}^* = 0.999808$ which fit appropriately into the isoelectronic sequence.

ACKNOWLEDGEMENTS

We wish to thank Professor Sumner P. Davis of the University of California who assisted in taking the NBS plates and in measuring the grazing incidence plates and George V. Shalimoff of LBL who also assisted in taking the NBS plates. We wish to thank Dr. W. C. Martin and the spectroscopy group at the National Bureau of Standards in Washington for making their high-resolution spectrographs available.

This work was done with support from the U. S. Energy Research and Development Administration.

REFERENCES

1. C.H.H. Van Deurzen, J.G. Conway, and S.P. Davis, J. Opt. Soc. Am. 64, 498 (1974).
2. J.O. Ekberg, Physica Scripta 9, 96 (1974).
3. K. Bockasten, Ark. Fys. 10, 567 (1956).
4. R.M. Sternheimer, Phys. Rev. 96, 951 (1954).
5. I. Waller, Z. Phys. 38, 635 (1926).
6. J.H. Van Vleck, Proc. Roy. Soc. London A143, 679 (1934).
7. J.W. Swensson, and B. Edlén, Physica Scripta 9, 335 (1974).
8. C.H.H. Van Deurzen, S.P. Davis, and J.G. Conway, J. Opt. Soc. Am. 63, 158 (1973).
9. J.O. Ekberg, Physica Scripta 8 35 (1973).

FIGURE CAPTIONS

FIGURE 1 Energy-level diagram for vanadium V. The wavelengths ($\text{\AA}$) refer to the strongest transition line in each multiplet.

FIGURE 2 Illustration of the polarization formula applied to vanadium V. The error bars correspond to one rms deviation $\pm \frac{1}{4} \text{ cm}^{-1}$. The dashed line illustrates the least-squares fit to the set of seven terms combined (rms deviation $\pm \frac{3}{4} \text{ cm}^{-1}$).

Fig. 1.

Fig. 2

XBL 768-3894

Table I. Classified lines of vanadium V.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination		
	Obs.	Calc.		Even		Odd
1	8457.555	0.51	11820.50	3p ⁶ 6s	² S _{1/2} - 3p ⁶ 6p	² P _{3/2}
3	7595.511		13162.05	8i	² I - 7h	² H
4	6635.164	0.171	15067.06	6d	² D _{3/2} - 6f	² F _{5/2}
7	6628.796	0.788	15081.53		² D _{5/2} -	² F _{7/2}
3	6541.429	0.437	15282.96	6d	² D _{3/2} - 7p	² P _{1/2}
6	6478.300	0.306	15431.88		² D _{5/2} -	² P _{3/2}
1	6462.734	0.748	15469.05		² D _{3/2} -	² P _{3/2}
5	6188.907	0.916	16153.47	6d	² D _{5/2} - 5f	² F _{7/2}
2	6135.907	0.907	16293.00	8s	² S _{1/2} - 7p	² P _{3/2}
1	6066.620	0.620	16479.08		² S _{1/2} -	² P _{1/2}
3	6020.741	0.735	16604.65	6d	² D _{3/2} - 5f	² F _{5/2}
3	5442.704	0.703	18368.12	5g	² G _{9/2} - 3p ⁵ 3d ² (² F)	² F _{7/2}
1	5366.750	0.747	18628.07	6d	² D _{3/2} - 6p	² P _{3/2}
8	5356.070	0.066	18665.21		² D _{5/2} -	² P _{3/2}
4	5294.115	0.108	18883.64		² D _{3/2} -	² P _{1/2}
1	5079.413		19681.83	6g	² G _{7/2} - 7f	² F _{5/2}
15w	4930.533		20276.12	7i	² I - 6h	² H
7w	4885.299		20463.86	6g	² G - 7h	² H
3	4780.787	0.771	20911.21	7g	² G _{9/2} - 6f	² F _{7/2}
1	4769.064	0.081	20962.61		² G _{7/2} -	² F _{5/2}
10	4293.735	0.732	23283.20	5s	² S _{1/2} - 5p	² P _{1/2}
20	4200.322	0.314	23800.99		² S _{1/2} -	² P _{3/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination	
	Obs.	Calc.		Even	Odd
1	3989.471	0.462	25058.89	3p ⁶ 4d ² D _{5/2}	3p ⁵ 3d ² (¹ G) ² F _{5/2}
5	3966.598	0.607	25203.39	² D _{3/2}	(¹ G) ² F _{5/2}
12b	3746.36	0.449	26685.0	² D _{5/2}	(¹ G) ² F _{7/2}
4	3648.724	0.725	27399.03	7s ² S _{1/2}	6p ² P _{3/2}
8	3642.887	0.874	27442.94	5d ² D _{3/2}	6p ² P _{1/2}
15	3617.966	0.961	27631.96	² D _{5/2}	² P _{3/2}
2h	3615.039	0.001	27654.33	7s ² S _{1/2}	6p ² P _{1/2}
2	3609.269	0.259	27698.54	5d ² D _{3/2}	6p ² P _{3/2}
1	3371.089	0.098	29655.48	5d ² D _{5/2}	5f ² F _{5/2}
6	3363.517	0.541	29722.24	² D _{3/2}	² F _{5/2}
10	3316.470	0.480	30143.86	² D _{5/2}	² F _{7/2}
8b	3139.94	0.018	31838.5	6g ² G _{9/2}	5f ² F _{7/2}
4	3092.641	0.641	32325.44	² G _{7/2}	² F _{5/2}
8w	2950.134		33886.87	5g ² G	6h ² H
3	2780.959*	0.966	35958.82	5d ² D _{3/2}	5p ² P _{3/2}
15	2775.816*	0.823	36025.44	² D _{5/2}	² P _{3/2}
10	2741.480*	0.487	36476.65	² D _{3/2}	² P _{1/2}
10	2610.881*	0.864	38301.25	5d ² D _{3/2}	4f ² F _{5/2}
4h	2606.30 *	0.330	38368.6	² D _{5/2}	² F _{5/2}
20	2577.899*	0.898	38791.27	² D _{5/2}	² F _{7/2}
1	2374.183*		42119.75	6g ² G _{7/2}	9f ² F _{5/2}
3	2370.984*		42176.59	² G _{9/2}	² F _{7/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination	
	Obs.	Calc.		Even	Odd
6	2327.463*	0.457	42965.23	3p ⁶ 4d ² D _{5/2} - 3p ⁵ 3d ² (¹ D)	² F _{5/2}
20b	2319.66 *	0.662	43109.7	² D _{3/2} - (¹ D)	² F _{5/2}
1	1962.154	0.151	50964.41	5d ² D _{3/2} - 3p ⁵ 3d ² (¹ D)	² F _{5/2}
9	1929.138	0.132	51836.63	6s ² S _{1/2} - 5p	² P _{3/2}
1	1921.915	0.911	52031.43	6g ² G _{9/2} - 3p ⁵ 3d ² (³ F)	² F _{7/2}
1	1917.686	0.682	52146.17	7g ² G _{9/2} - 5f	² F _{7/2}
4	1910.062	0.052	52354.33	6s ² S _{1/2} - 5p	² P _{1/2}
30	1811.425	0.425	55205.15	4d ² D _{5/2} - 4f	² F _{7/2}
6	1797.646	0.645	55628.31	² D _{5/2} -	² F _{5/2}
25	1792.992	0.992	55772.71	² D _{3/2} -	² F _{5/2}
10	1736.182	0.182	57597.66	4d ² D _{3/2} - 5p	² P _{1/2}
15	1724.994	0.998	57971.23	² D _{5/2} -	² P _{3/2}
4	1720.712	0.712	58115.48	² D _{3/2} -	² P _{3/2}
50	1716.725	0.727	58250.43	4s ² S _{1/2} - 4p	² P _{1/2}
100	1680.204	0.202	59516.56	² S _{1/2} -	² P _{3/2}
10	1499.596	0.594	66684.63	5g ² G _{7/2} - 4f	² F _{5/2}
20	1490.107	0.105	67109.29	² G _{9/2} -	² F _{7/2}
1	1260.278	0.276	79347.57	5g ² G _{7/2} - 3p ⁵ 3d ² (¹ D)	² F _{5/2}
6	1159.516	0.516	86242.87	4d ² D _{3/2} - 4p	² P _{3/2}
25	1157.575	0.578	86387.48	² D _{5/2} -	² P _{3/2}
1	1143.395	0.401	87458.84	5s ² S _{1/2} - 6p	² P _{3/2}
15	1142.737	0.738	87509.18	4d ² D _{3/2} - 4p	² P _{1/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination	
	Obs.	Calc.		Even	Odd
2	1098.222	0.221	91056.27	3p ⁶ 7s ² S _{1/2} -	5p ² P _{3/2}
1h	1092.00	0.011	91575.0	² S _{1/2} -	² P _{1/2}
2	1045.711	0.771	95628.71	5g ² G _{7/2} - 3p ⁵ 3d ² (¹ G)	² F _{7/2}
5	996.521	0.522	100349.1	6g ² G _{7/2} -	4f ² F _{5/2}
10	992.330	0.331	100773.0	² G _{9/2} -	² F _{7/2}
1	979.547	0.547	102088.1	4d ² D _{5/2} - 3p ⁵ 3d ² (³ F)	² F _{5/2}
10	978.166	0.164	102232.2	² D _{3/2} -	(³ F) ² F _{5/2}
15	962.031	0.034	103946.7	² D _{5/2} -	(³ F) ² F _{7/2}
2	897.124		111467.3	7d ² D _{5/2} -	4f ² F _{7/2}
30	829.483	0.481	120557.0	5s ² S _{1/2} -	4p ² P _{3/2}
1	828.791	0.790	120657.7	7g ² G _{7/2} -	4f ² F _{5/2}
2	825.891	0.891	121081.3	² G _{9/2} -	² F _{7/2}
3	822.927	0.928	121517.4	4d ² D _{3/2} -	6p ² P _{1/2}
1	822.668	0.670	121555.7	5s ² S _{1/2} -	7p ² P _{3/2}
6	822.176	0.176	121628.5	4d ² D _{5/2} -	6p ² P _{3/2}
1	821.202	0.201	121772.7	² D _{3/2} -	² P _{3/2}
20	820.859	0.859	121823.5	5s ² S _{1/2} -	4p ² P _{1/2}
1	643.603	0.603	155375.3	4d ² D _{5/2} -	6f ² F _{7/2}
2	509.697	0.6967	196195.1	6s ² S _{1/2} -	4p ² P _{3/2}
1	506.429	0.4281	197461.0	² S _{1/2} -	4p ² P _{1/2}
2	491.746	0.7457	203357.2	4s ² S _{1/2} -	5p ² P _{1/2}
4	490.496	0.4966	203875.1	² S _{1/2} -	² P _{3/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination	
	Obs.	Calc.		Even	Odd
25	484.5108		206393.74	3p ⁶ 3d ² D _{3/2} -	4p ² P _{1/2}
35	483.0098		207035.13	² D _{5/2} -	² P _{3/2}
8	481.5564		207660.00	² D _{3/2} -	² P _{3/2}
1	424.782	0.7823	235415.1	7s ² S _{1/2} -	4p ² P _{3/2}
10	313.993	0.9902	318478	3d ² D _{5/2} -	3p ⁵ 4d ² (¹ G) ² F _{5/2}
14	313.376	0.3753	319105	² D _{3/2} -	(¹ G) ² F _{5/2}
17	312.394	0.3958	320109	² D _{5/2} -	(¹ G) ² F _{7/2}
10b	301.604		331561	3d ² D _{5/2} -	3p ⁵ 3d ² (¹ D) ² F _{7/2}
2	297.276	0.2760	336387.3	² D _{5/2} -	(¹ D) ² F _{5/2}
5	296.724	0.7248	337013.6	² D _{3/2} -	(¹ D) ² F _{5/2}
20	286.8395	0.8391	348627.0	3d ² D _{5/2} -	4f ² F _{7/2}
5	286.490	0.4913	349052.6	² D _{5/2} -	² F _{5/2}
18	285.9791	0.9794	349676.0	² D _{3/2} -	² F _{5/2}
11	284.581	0.5813	351393.4	3d ² D _{5/2} -	5p ² P _{3/2}
8	284.494	0.4946	351500.8	² D _{3/2} -	² P _{1/2}
2	284.075	0.0761	352019.8	² D _{3/2} -	² P _{3/2}
8	252.838	0.8379	395509.7	3d ² D _{5/2} -	3p ⁵ 3d ² (³ F) ² F _{5/2}
18	252.440	0.4390	396133.2	² D _{3/2} -	(³ F) ² F _{5/2}
20	251.655	0.6554	397369.4	² D _{5/2} -	(³ F) ² F _{7/2}
7	240.933	0.9343	415052.8	3d ² D _{5/2} -	6p ² P _{3/2}
4	240.719	0.7202	415422.5	² D _{3/2} -	² P _{1/2}
1	240.572	0.5722	415676.2	² D _{3/2} -	² P _{3/2}
7	239.765	0.7655	417075.7	3d ² D _{5/2} -	5f ² F _{5/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination			
	Obs.	Calc.		Even		Odd	
19	239.485	0.4850	417562.2	3p ⁶	² D _{5/2} -	5f	² F _{7/2}
16	239.407	0.4068	417698.1		² D _{3/2} -		² F _{5/2}
14	228.301		438018.3	3p	² D _{3/2} -	3p ⁵ 3d ² (³ P)	² P _{1/2}
17	227.885		438817.2		² D _{5/2} -	(³ P)	² P _{3/2}
10	227.561		439443.4		² D _{3/2} -	(³ P)	² P _{3/2}
20	225.465		443527.6	3d	² D _{5/2} -	3p ⁵ 3d ² (³ F)	² D _{5/2}
13	225.225		444000.5		² D _{5/2} -	(³ F)	² D _{3/2}
13	225.146		444154.8		² D _{3/2} -	(³ F)	² D _{5/2}
18	224.913		444616.3		² D _{3/2} -	(³ F)	² D _{3/2}
3	222.842	0.8432	448748.0	3d	² D _{5/2} -	6f	² F _{5/2}
13	222.818	0.8176	448796.8		² D _{5/2} -		² F _{7/2}
10	222.533	0.5334	449371.1		² D _{3/2} -		² F _{5/2}
9	213.178		469092	3d	² D _{5/2} -	7f	² F _{7/2}
7	212.901		469702		² D _{3/2} -		² F _{5/2}
12	210.568		474906	3d	² D _{5/2} -	3p ⁵ 3d (³ F) 4s	² F _{7/2}
1	209.230		477942		² D _{5/2} -	(³ F)	² F _{5/2}
10	208.958		478565		² D _{3/2} -	(³ F)	² F _{5/2}
6	207.291		482414	3d	² D _{5/2} -	8f	² F _{7/2}
4	207.031		483019		² D _{3/2} -		² F _{5/2}
5	203.428		491574	3d	² D _{5/2} -	9f	² F _{7/2}
2	203.194		492141		² D _{3/2} -		² F _{5/2}

Table I. Continued.

Int. ^a	Wavelength ^b (Å)		Wave Number (cm ⁻¹)	Level Combination	
	Obs.	Calc.		Even	Odd
2	201.746		495673	3p ⁶ 3d ² D _{5/2}	- 3p ⁵ 3d (¹ F) 4s ² F _{5/2}
1	201.493		496295	² D _{3/2}	- (¹ F) ² F _{5/2}
4	201.235		496931	² D _{5/2}	- (¹ F) ² F _{7/2}
1	200.202		499495	3d ² D _{5/2}	- 3p ⁵ 3d (³ D) 4s ² D _{5/2}
5	200.050		499876	² D _{5/2}	- (³ D) ² D _{3/2}
5	199.955		500113	² D _{3/2}	- (³ D) ² D _{5/2}
1	199.799		500503	² D _{3/2}	- (³ D) ² D _{3/2}

^a Intensities are visual estimates of photographic blackening on a scale from 1 to 100. w = wide, b = blend, h = hazy.

^b Estimated uncertainties in the observed wavelengths are:
 $\lambda < 222$, $\pm 0.004\text{\AA}$; $222 < \lambda < 2100$, $\pm 0.002\text{\AA}$; $\lambda > 2100$, $\pm 0.008\text{\AA}$.

* Wavelength in vacuum as measured.

Table II. Energy levels of vanadium V.

Designation	Energy (cm ⁻¹)	Interval (cm ⁻¹)	n *	10 ⁶ Δn *
3p ⁶ 4s ² S _{1/2}	148143.35		2.692624	
5s ² S _{1/2}	328217.30		3.719353	
6s ² S _{1/2}	403855.12		4.728937	
7s ² S _{1/2}	443074.72		5.733406	
8s ² S _{1/2}	466065.79		6.735789	
9s ² S _{1/2}	(480704.7) ^a			
4p ² P _{1/2} ^o	206393.72	1266.28	2.927359	5806
² P _{3/2} ^o	207660.00		2.933166	
5p ² P _{1/2} ^o	351500.51	517.83	3.959011	5869
² P _{3/2} ^o	352018.34		3.964881	
6p ² P _{1/2} ^o	415420.10	255.59	4.968949	5724
² P _{3/2} ^o	415675.69		4.974674	
7p ² P _{1/2} ^o	449586.71	186.08	5.971093	7233
² P _{3/2} ^o	449772.79		5.978326	
3d ² D _{3/2}	0.00	624.87	2.282614	1355
² D _{5/2}	624.87		2.283969	
4d ² D _{3/2}	293902.86	144.38	3.434099	1066
² D _{5/2}	294047.24		3.435165	
5d ² D _{3/2}	387977.07	66.62	4.449732	1070
² D _{5/2}	388043.69		4.450802	
6d ² D _{3/2}	434303.77	37.15	5.453972	1098
² D _{5/2}	434340.92		5.455071	
7d ² D _{3/2}	(460696.8)	(22.9)		
² D _{5/2}	460719.7		6.456413	

Table II. Continued.

Designation	Energy (cm ⁻¹)	Interval (cm ⁻¹)	n [*]	10 ⁶ Δn [*]
4f ² F _{5/2} ^o	349675.57	-423.17	3.938532	-4703
² F _{7/2} ^o	349252.40		3.933829	
5f ² F _{5/2} ^o	417699.10	488.37	5.020705	11302
² F _{7/2} ^o	418187.47		5.032008	
6f ² F _{5/2} ^o	449370.81	51.66	5.962733	1997
² F _{7/2} ^o	449422.47		5.964730	
7f ² F _{5/2} ^o	469706.4	15	6.948208	892
² F _{7/2} ^o	469721		6.949101	
8f ² F _{5/2} ^o	483019	20	7.940271	1825
² F _{7/2} ^o	483039		7.942096	
9f ² F _{5/2} ^o	492144.3	57.5	8.931886	7476
² F _{7/2} ^o	492201.8		8.939363	
5g ² G _{7/2}	416360.29	1.49	4.990106	33
² G _{9/2}	416361.78		4.990140	
6g ² G _{7/2}	450024.54	0.66	5.988154	25
² G _{9/2}	450025.20		5.988179	
7g ² G _{7/2}	470333.35	0.40	6.986857	24
² G _{9/2}	470333.75		6.986882	
8g ² G	(483515.7)			
6h ² H ^o	450247.99		5.996917	
7h ² H ^o	470488.77		6.996539	
8h ² H ^o	(483626.4)			

Table II. Continued.

Designation	Energy (cm ⁻¹)	Interval (cm ⁻¹)	n [*]	10 ⁶ Δn [*]
7i ² I	470524.11		6.998746	
8i ² I	483650.82		7.998554	
9i ² I	(492651.5)			
Limit 3p ⁶ ¹ S ₀	526532.0			
3p ⁵ 3d ² (¹ G) ² F _{5/2} ^o	319106.19	1625.41		
² F _{7/2} ^o	320731.60			
(¹ D) ² F _{5/2} ^o	337012.59	-4814.5		
² F _{7/2} ^o	332198.10			
(³ F) ² F _{5/2} ^o	396135.24	1858.42		
² F _{7/2} ^o	397993.66			
(³ P) ² P _{1/2} ^o	438018.3	1424.4		
² P _{3/2} ^o	439442.7			
(³ F) ² D _{3/2} ^o	444620.8	-467.1		
² D _{5/2} ^o	444153.7			
3p ⁵ 3d (³ F) 4s ² F _{5/2} ^o	478566	-3035		
² F _{7/2} ^o	475531			
(¹ F) 4s ² F _{5/2} ^o	496296	1260		
² F _{7/2} ^o	497556			
(³ D) 4s ² D _{3/2} ^o	500502	-385		
² D _{5/2} ^o	500117			
^a Predicted levels.				

This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720