

## Seventh spectrum of tungsten (W VII); resonance lines of Hf v†

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Observations of W VII were carried out in the spectral range 100 to 2000 Å utilizing normal- and grazing-incidence spectrographs. The light source was a sliding spark operated at peak currents of 1000 to 3000 A. Eighty-five energy levels of  $4f^{13}nl$  and  $5p^5nl$  configurations were deduced for  $nl = 5d, 6s, 6p, 6d,$  and  $7s$ . These are based on the classification of 310 lines in the range 130 to 1436 Å. Calculations of all observed configurations were carried out with configuration interaction (CI) for the purpose of fitting radial integrals and confirming the analysis. The strong CI between  $p^5nl$  and  $f^{13}nl$  configurations where  $nl = 5d, 6p, 6d$  provided well-defined CI integrals in good agreement with Hartree-Fock values. A value of  $984100 \pm 500 \text{ cm}^{-1}$  was derived for the ionization energy from the  $4f^{13}ns$  series. The resonance lines of Hf v for  $5p^6-5p^55d, 6s$  are given. A revised value for the the ionization energy of W VI is given.

### INTRODUCTION

The resonance transition array  $4f^{14}-4f^{13}5d$  has been observed<sup>1-4</sup> in the isoelectronic sequence Yb III through Ta VI. A new resonance group, the  $5p^6-5p^5(5d, 6s)$  transitions, was discovered for the first time in this sequence<sup>4</sup> in Ta VI. Both types of resonance lines are reported here for W VII, and the latter type are given for Hf V. These excited configurations built on  $5p^5$  and  $4f^{13}$  core states overlap in W VII where the binding energies of the  $4f$  and  $5p$  orbits are nearly equal. The present data permit an empirical prediction of the relative excitation energies of  $4f^{13}5d$  and  $5p^55d$  for other ions in this sequence. In Ref. 4 a plot of their lowest levels showed that Re VIII is the first ion in this sequence for which the lowest excited level belongs to the  $5p^55d$  configuration. A more detailed plot is given in the present paper as well as a correlation with inner-shell x-ray data.

The overlap of these configurations in W VII results in strong interaction between them. The two resonance lines of longest wavelength arise from  $5d$  levels having 38% admixtures of  $5p^5$  or  $4f^{13}$  core states. This mixing results in many normally forbidden transitions (two-electron jumps) and produces quite a complex spectrum.

### OBSERVATIONS

The sliding spark proved to be an excellent light source for distinguishing W VII from lower stages of ionization. The known lines<sup>5</sup> of W VI clearly decrease in intensity relative to W VII as the peak discharge current is raised from 1000 to 3000 A. With voltages in the range of 700 to 1000 V, the variation of the peak currents was produced by

varying the capacitance from 24 to 48  $\mu\text{F}$ . A small amount of resistance (tenths of an ohm) was added to the discharge circuit to suppress ringing, thereby decreasing the presence of lower excitation spectra.

Observations were made in the range of 100 to 2000 Å by means of grazing-incidence and a normal-incidence spectrographs, each of a radius 10.7 m. Exposure times of a few seconds to 10 min with sparking rates of  $\sim 30 \text{ sec}^{-1}$  were sufficient to obtain the spectra with Kodak SWR plates. Longer exposures produce overwhelming numbers of additional lines arising from other ionization stages. The stronger resonance lines of W VII are prominent in all exposures of 500-A sparks and higher.

A list of the classified lines of W VII is given in Table I including vacuum wavelengths, visually estimated relative intensities, wave numbers, and classifications in terms of the  $J, j$ -coupling designations of the levels. The uncertainty in the measured wavelengths is estimated to be  $\pm 0.005 \text{ Å}$ . Impurity lines of C, O, and Si in various stages of ionization served for plate calibration.

### ENERGY LEVELS

Our analyses of the spectra of this sequence have always begun with the interpretation of the lines of the  $4f^{13}6s-4f^{13}6p$  transition array because of the distinct character of this group: a few strong lines that can be readily recognized. Their position decreases in wavelength regularly along the isoelectronic sequence. Lines of the  $5p^56s-5p^56p$  array were found in the same wavelength region as the above group. The relative excitation energies of the  $6s$  and  $6p$  orbits (as well as  $5d$ ) appear to be the same regardless of whether the atomic core is  $4f^{13}$  or  $5p^5$ .

TABLE I. Spectral lines of W VII.

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
1435.863	50	69 644.5	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3$
1421.970	100	70 325.0	$p^5 6s (\frac{3}{2}, \frac{1}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_1$
1380.339	2000	72 446.0	$p^5 6s (\frac{3}{2}, \frac{1}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
1354.341	2000	73 836.6	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_1$
1335.899	500	74 855.9	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3$
1328.575	400	75 268.6	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3$
1322.495	3000	75 614.7	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4$
1321.113	5000	75 693.8	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3$
1317.119	3000	75 923.4	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3$
1316.533	1000	75 957.1	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
1312.109	5000	76 213.2	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
1308.002	2000	76 452.5	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4$
1300.940	1000	76 867.5	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
1262.511	200	79 207.2	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
1256.008	200	79 617.3	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
1252.168	100	79 861.5	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
1245.772	300	80 271.5	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
1232.365	400	81 144.8	$p^5 5d (\frac{1}{2}, \frac{3}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$
1232.009	200	81 168.3	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
1140.533	50	87 678.3	$p^5 6s (\frac{3}{2}, \frac{1}{2})_1^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
1091.704	500	91 599.9	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
1085.143	1000	92 153.7	$p^5 6s (\frac{3}{2}, \frac{1}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_1$
1081.515	100	92 462.9	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3$
1070.580	100	93 407.3	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
1049.333	1000	95 298.6	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_1$
1045.306	20	95 665.7	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_1$
1042.877	2000	95 888.6	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_3$
1037.327	2000	96 401.6	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
1036.662	1000	96 463.4	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_4$
1036.219	3000	96 504.6	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_5$
1032.935	2000	96 811.5	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
1032.078	1000	96 891.9	$p^5 6s (\frac{3}{2}, \frac{1}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$
1026.169	200	97 449.8	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2$
1024.069	500	97 649.7	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
1019.322	1000	98 104.5	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2$
1016.603	1000	98 366.9	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3$
1009.883	1000	99 021.4	$f^{13} 6s (\frac{5}{2}, \frac{1}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3$
1007.742	2000	99 231.7	$f^{13} 6s (\frac{7}{2}, \frac{1}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
995.975	1000	100 404.1	$p^5 6s (\frac{3}{2}, \frac{1}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
989.109	400	101 101.1	$f^{13}6s(\frac{7}{2}, \frac{1}{2})_3^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
980.980	200	101 938.8	$f^{13}6s(\frac{7}{2}, \frac{1}{2})_4^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
967.743	400	103 333.3	$p^56s(\frac{3}{2}, \frac{1}{2})_1^o - p^56p(\frac{3}{2}, \frac{3}{2})_0$
963.199	10	103 820.7	$p^56p(\frac{3}{2}, \frac{3}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_1^o$
923.484	30	108 285.6	$p^56p(\frac{3}{2}, \frac{3}{2})_0 - p^56d(\frac{3}{2}, \frac{5}{2})_1^o$
918.964	30	108 818.2	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_0^o$
918.909	10	108 824.7	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_0^o$
913.052	40	109 522.8	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_0^o$
912.191	10	109 626.2	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_0^o$
907.639	60	110 175.9	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_0^o$
906.825	30	110 274.8	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_1^o$
906.544	20	110 309.0	$p^56p(\frac{3}{2}, \frac{3}{2})_2 - p^56d(\frac{3}{2}, \frac{5}{2})_0^o$
904.688	40	110 535.4	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
903.113	20	110 728.2	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_0^o$
901.276	10	110 953.8	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_0^o$
896.502	200	111 544.7	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_5 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_0^o$
888.699	500	112 524.0	$p^56p(\frac{3}{2}, \frac{3}{2})_2 - p^56d(\frac{3}{2}, \frac{5}{2})_0^o$
886.735	20	112 773.2	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_1^o$
885.720	20	112 902.5	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_5 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_0^o$
885.110	300	112 980.3	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_1^o$
884.696	10	113 033.2	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_1^o$
883.065	30	113 241.9	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
880.787	800	113 534.9	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - p^56d(\frac{3}{2}, \frac{5}{2})_0^o$
879.364	50	113 718.5	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
878.690	100	113 805.8	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_0^o$
877.599	500	113 947.2	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
876.198	500	114 129.4	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
874.289	1000	114 378.6	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_5 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
873.421	1000	114 492.3	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_4 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_0^o$
872.891	400	114 561.9	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
871.667	200	114 722.7	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_0^o$
870.901	100	114 823.6	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - p^56d(\frac{3}{2}, \frac{5}{2})_0^o$ $f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_0^o$
869.210	200	115 046.9	$p^56p(\frac{3}{2}, \frac{3}{2})_1 - p^56d(\frac{3}{2}, \frac{5}{2})_0^o$
865.400	100	115 553.4	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_1^o$
865.213	20	115 578.4	$f^{13}6p(\frac{5}{2}, \frac{3}{2})_1 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_1^o$
864.787	200	115 635.3	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - p^56d(\frac{3}{2}, \frac{3}{2})_0^o$
861.732	50	116 045.3	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_0^o$
860.277	50	116 241.7	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_4 - p^56d(\frac{3}{2}, \frac{5}{2})_1^o$

TABLE I. (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
857.091	200	116 673.7	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_5 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_6^o$
854.418	50	117 038.7	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - p^56d(\frac{3}{2}, \frac{5}{2})_3^o$
837.073	30	119 463.9	$p^56p(\frac{3}{2}, \frac{3}{2})_1 - p^56d(\frac{3}{2}, \frac{5}{2})_1^o$
824.221	40	121 326.7	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - p^56d(\frac{3}{2}, \frac{5}{2})_3^o$
788.960	30	126 749.1	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_3^o$
779.617	40	128 268.2	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_1^o$
776.473	3	128 787.4	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_2^o$
773.011	20	129 364.3	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_2^o$
770.978	2	129 705.5	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_3^o$
768.808	10	130 071.5	$p^56p(\frac{3}{2}, \frac{3}{2})_0 - p^57s(\frac{3}{2}, \frac{1}{2})_1^o$
768.549	3	130 115.4	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_3^o$
766.932	200	130 389.6	$p^56p(\frac{3}{2}, \frac{1}{2})_1 - p^56d(\frac{3}{2}, \frac{3}{2})_1^o$
766.466	300	130 468.9	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_3^o$
763.254	3	131 018.0	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_1^o$
761.727	400	131 280.6	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_3^o$
761.412	10	131 334.9	$f^{13}6p(\frac{7}{2}, \frac{3}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_1^o$
759.884	1000	131 599.0	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_6^o$
758.827	200	131 782.3	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_2^o$
758.009	600	131 924.5	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_4^o$
755.837	200	132 303.7	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_3^o$
755.589	200	132 347.1	$p^56p(\frac{3}{2}, \frac{1}{2})_2 - p^56d(\frac{3}{2}, \frac{3}{2})_2^o$
753.428	100	132 726.6	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_2^o$
752.389	40	132 910.0	$p^56p(\frac{3}{2}, \frac{1}{2})_1 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_1^o$
752.124	600	132 956.9	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_4^o$
751.527	400	133 062.5	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_3^o$
751.262	200	133 109.4	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_3^o$
747.854	300	133 715.9	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{3}{2})_4^o$
746.199	20	134 012.5	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_1^o$
745.970	300	134 053.7	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_3^o$
744.442	100	134 328.9	$f^{13}6p(\frac{5}{2}, \frac{1}{2})_2 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_1^o$
743.670	300	134 468.2	$p^56p(\frac{3}{2}, \frac{1}{2})_1 - p^56d(\frac{3}{2}, \frac{3}{2})_2^o$
743.512	60	134 496.8	$p^55d(\frac{3}{2}, \frac{5}{2})_1^o - p^56p(\frac{3}{2}, \frac{1}{2})_1$
739.059	50	135 307.1	$p^56p(\frac{3}{2}, \frac{3}{2})_2 - p^57s(\frac{3}{2}, \frac{1}{2})_2^o$
737.041	20	135 677.7	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_3 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_2^o$
736.583	20	135 762.0	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_4 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_4^o$
732.534	30	136 512.5	$p^56p(\frac{3}{2}, \frac{3}{2})_2 - p^57s(\frac{3}{2}, \frac{1}{2})_1^o$
731.972	5	136 617.3	$p^55d(\frac{3}{2}, \frac{5}{2})_1^o - p^56p(\frac{3}{2}, \frac{1}{2})_2$
731.335	50	136 736.3	$p^56p(\frac{3}{2}, \frac{3}{2})_3 - f^{13}7s(\frac{7}{2}, \frac{1}{2})_4^o$
730.803	5	136 835.8	$f^{13}6p(\frac{7}{2}, \frac{1}{2})_4 - p^56d(\frac{3}{2}, \frac{3}{2})_3^o$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
730.590	100	136 875.6	$p^5 6p (\frac{3}{2}, \frac{1}{2})_1 - p^5 6d (\frac{3}{2}, \frac{5}{2})_2^o$
729.754	5	137 032.5	$p^5 6p (\frac{3}{2}, \frac{3}{2})_3 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
726.774	5	137 594.3	$f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3 - p^5 6d (\frac{3}{2}, \frac{3}{2})_3^o$
717.131	200	139 444.6	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_4^o$
716.010	50	139 662.8	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_2^o$
715.617	100	139 739.6	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
715.191	200	139 822.7	$p^5 6p (\frac{3}{2}, \frac{3}{2})_3 - p^5 7s (\frac{3}{2}, \frac{1}{2})_2^o$
714.896	50	139 880.4	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_2^o$
711.339	70	140 579.9	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_2^o$
710.240	5	140 797.5	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_3^o$
709.085	20	141 026.8	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_4^o$
707.960	50	141 251.0	$p^5 6p (\frac{3}{2}, \frac{3}{2})_1 - p^5 7s (\frac{3}{2}, \frac{1}{2})_1^o$
707.607	100	141 321.3	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
705.562	100	141 731.0	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
705.300	100	141 783.6	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_4 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_3^o$
703.377	200	142 171.3	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_5 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_4^o$
697.423	50	143 384.9	$f^{13} 6p (\frac{5}{2}, \frac{3}{2})_1 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_2^o$
693.909	20	144 111.1	$f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3 - p^5 7s (\frac{3}{2}, \frac{1}{2})_2^o$
673.574	3	148 461.8	$f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3 - p^5 7s (\frac{3}{2}, \frac{1}{2})_2^o$
671.787	40	148 856.8	$p^5 5d (\frac{3}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
658.546	80	151 849.7	$p^5 5d (\frac{3}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
626.843	5	159 529.5	$p^5 5d (\frac{3}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4$
625.961	20	159 754.3	$p^5 6p (\frac{3}{2}, \frac{1}{2})_2 - p^5 7s (\frac{3}{2}, \frac{1}{2})_2^o$
621.280	20	160 958.0	$p^5 6p (\frac{3}{2}, \frac{1}{2})_1 - p^5 7s (\frac{3}{2}, \frac{1}{2})_1^o$
617.765	20	161 873.9	$p^5 6p (\frac{3}{2}, \frac{1}{2})_1 - p^5 7s (\frac{3}{2}, \frac{1}{2})_2^o$
617.156	30	162 033.6	$f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3^o - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_3^o$
616.436	20	162 222.8	$f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_4^o$
615.320	100	162 517.2	$f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
614.402	40	162 759.9	$f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_2^o$
613.571	100	162 980.3	$f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3 - f^{13} 7s (\frac{5}{2}, \frac{1}{2})_3^o$ $f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_4^o$
612.456	5	163 277.0	$f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3 - f^{13} 7s (\frac{7}{2}, \frac{1}{2})_3^o$
605.755	40	165 083.2	$p^5 5d (\frac{3}{2}, \frac{5}{2})_3^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
597.000	200	167 504.2	$p^5 5d (\frac{3}{2}, \frac{5}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_0$
596.679	40	167 594.4	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_3^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
585.390	100	170 826.4	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
577.660	20	173 112.3	$p^5 5d (\frac{3}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_4$
575.475	30	173 769.6	$p^5 5d (\frac{3}{2}, \frac{5}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_1$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
571.331	20	175 029.8	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
568.537	200	175 890.1	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
567.849	3	176 103.2	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
563.939	5	177 324.0	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
563.553	10	177 445.5	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_0^0 - p^56p(\frac{3}{2}, \frac{1}{2})_1$
563.473	10	177 470.8	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
562.713	50	177 710.6	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
562.222	10	177 865.8	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
561.760	5	178 011.9	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_4^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
561.074	60	178 229.6	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
560.318	20	178 469.9	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
559.834	10	178 624.4	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_0^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
559.002	1	178 890.3	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_3^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
557.973	100	179 220.2	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^0 - p^56p(\frac{3}{2}, \frac{1}{2})_1$
556.212	20	179 787.6	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_3^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
551.444	10	181 342.0	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
549.283	500	182 055.5	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - p^56p(\frac{3}{2}, \frac{1}{2})_1$
549.090	1	182 119.5	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
546.649	10	182 932.6	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_4^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
546.260	1	183 062.9	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
544.393	200	183 690.7	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_4^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
543.413	2000	184 022.2	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
542.957	500	184 176.7	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
540.946	100	184 861.4	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
540.496	200	185 015.2	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - p^56p(\frac{3}{2}, \frac{5}{2})_3$
537.516	3	186 041.0	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_1^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
537.351	500	186 098.0	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_3^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
536.918	200	186 248.2	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_1^0 - p^56p(\frac{3}{2}, \frac{1}{2})_1$
535.767	5	186 648.5	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_4^0 - p^56p(\frac{3}{2}, \frac{5}{2})_3$
534.233	2	187 184.2	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
533.877	10	187 309.0	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_0^0 - f^{13}6p(\frac{7}{2}, \frac{3}{2})_5$
533.633	400	187 394.5	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
533.258	30	187 526.4	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_3^0 - p^56p(\frac{3}{2}, \frac{5}{2})_3$
531.551	50	188 128.7	$p^55d(\frac{3}{2}, \frac{5}{2})_2^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
530.956	300	188 339.5	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^0 - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
530.872	5	188 369.5	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_1^0 - p^56p(\frac{3}{2}, \frac{1}{2})_2$
529.003	15	189 034.9	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_1^0 - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
527.625	1000	189 528.5	$p^55d(\frac{3}{2}, \frac{5}{2})_3^0 - p^56p(\frac{3}{2}, \frac{5}{2})_2$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
526.218	3	190 035.3	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_0^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_4$
525.338	500	190 353.7	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
524.847	10	190 531.6	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_2^o - p^56p(\frac{3}{2}, \frac{3}{2})_1$
523.251	1000	191 112.7	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
523.085	40	191 173.6	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_2^o - p^56p(\frac{3}{2}, \frac{1}{2})_2$
522.647	20	191 333.9	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
521.569	200	191 729.2	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_1^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
520.723	20	192 040.8	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_3^o - p^56p(\frac{3}{2}, \frac{3}{2})_2$
520.324	1000	192 187.9	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{1}{2})_3$
519.118	50	192 634.5	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
518.275	300	192 947.9	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
517.698	5	193 162.9	$p^55d(\frac{3}{2}, \frac{5}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_5$
516.779	10	193 506.2	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_1^o - p^56p(\frac{3}{2}, \frac{3}{2})_1$
516.589	200	193 577.7	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
513.553	80	194 722.0	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_1^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
512.621	500	195 075.9	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
511.990	3	195 316.5	$p^55d(\frac{3}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
511.628	2000	195 454.5	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_5^o - f^{13}6p(\frac{7}{2}, \frac{1}{2})_4$
511.262	300	195 594.5	$p^55d(\frac{3}{2}, \frac{5}{2})_2^o - p^56p(\frac{3}{2}, \frac{3}{2})_1$
510.498	100	195 887.2	$p^55d(\frac{3}{2}, \frac{5}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_4$
510.120	2	196 032.2	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
509.526	2	196 260.8	$p^55d(\frac{3}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
509.128	40	196 414.4	$p^55d(\frac{3}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
508.718	3	196 572.4	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
506.606	20	197 392.1	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_3$
504.608	200	198 173.6	$p^55d(\frac{3}{2}, \frac{3}{2})_1^o - p^56p(\frac{3}{2}, \frac{1}{2})_1$
504.194	3	198 336.2	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
503.776	50	198 500.8	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_3^o - p^56p(\frac{3}{2}, \frac{1}{2})_2$
503.621	5	198 561.8	$p^55d(\frac{3}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_2$
503.533	1000	198 596.6	$p^55d(\frac{3}{2}, \frac{5}{2})_4^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
503.335	500	198 675.0	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_5^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_5$
501.996	200	199 204.7	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_4^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_4$
501.866	100	199 256.5	$p^55d(\frac{3}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
501.472	10	199 412.8	$p^55d(\frac{3}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
501.439	200	199 426.0	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_3$
501.310	10	199 477.5	$p^55d(\frac{3}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_3$
500.835	400	199 666.6	$p^55d(\frac{3}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_3$
500.444	3	199 822.6	$p^55d(\frac{3}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_3$
499.787	3	200 085.4	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_4$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
499.261	40	200 296.1	$p^5 5d (\frac{3}{2}, \frac{3}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_2$
499.160	10	200 336.4	$p^5 5d (\frac{3}{2}, \frac{5}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$
498.654	200	200 539.9	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3$
498.480	50	200 609.7	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
497.490	3	201 009.1	$f^{13} 5d (\frac{5}{2}, \frac{3}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
497.338	100	201 070.6	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2$
497.246	500	201 107.9	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3$
496.897	2	201 248.9	$p^5 5d (\frac{3}{2}, \frac{3}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
496.837	10	201 273.4	$f^{13} 5d (\frac{5}{2}, \frac{3}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_3$
496.689	30	201 333.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
496.520	500	201 401.8	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_5^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
496.427	500	201 439.4	$f^{13} 5d (\frac{7}{2}, \frac{3}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{1}{2})_3$
496.293	50	201 493.8	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_1$
495.680	100	201 743.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
495.503	100	201 815.1	$p^5 5d (\frac{3}{2}, \frac{3}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_1$
495.081	100	201 987.1	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3$
493.898	1	202 470.7	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_3$
491.823	50	203 325.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_3^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
491.608	5	203 414.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{1}{2})_2$
491.151	100	203 603.4	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
490.812	1	203 744.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_5$
490.303	1	203 955.6	$p^5 5d (\frac{3}{2}, \frac{3}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_3$
489.931	10	204 110.3	$p^5 5d (\frac{3}{2}, \frac{3}{2})_1^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_3$
489.478	200	204 299.3	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2$
489.064	100	204 472.0	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_1$
488.072	400	204 887.6	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
487.290	7	205 216.6	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_3$
487.095	1000	205 298.9	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_5^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_4$
486.302	4	205 633.6	$f^{13} 5d (\frac{7}{2}, \frac{3}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{1}{2})_1$
485.935	30	205 788.7	$f^{13} 5d (\frac{5}{2}, \frac{3}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$
485.363	100	206 031.4	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_3^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_3$
484.480	400	206 406.9	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_2$
484.334	200	206 469.2	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_4^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_4$
483.912	1000	206 648.9	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_5^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_5$
483.518	100	206 817.7	$f^{13} 5d (\frac{7}{2}, \frac{5}{2})_2^o - f^{13} 6p (\frac{7}{2}, \frac{3}{2})_3$
482.443	30	207 278.4	$f^{13} 5d (\frac{5}{2}, \frac{5}{2})_1^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_2$
479.405	10	208 591.8	$f^{13} 5d (\frac{5}{2}, \frac{3}{2})_3^o - f^{13} 6p (\frac{5}{2}, \frac{3}{2})_4$
479.331	60	208 624.1	$p^5 5d (\frac{3}{2}, \frac{3}{2})_2^o - p^5 6p (\frac{3}{2}, \frac{3}{2})_2$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
478.063	30	209 177.4	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_4^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
477.635	3	209 365.0	$p^55d(\frac{3}{2}, \frac{5}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_2$
477.150	20	209 577.9	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_2$
475.655	50	210 236.3	$f^{13}5d(\frac{5}{2}, \frac{5}{2})_0^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_1$
475.551	1	210 282.4	$p^55d(\frac{3}{2}, \frac{5}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_3$
475.333	10	210 378.9	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_1^o - p^56p(\frac{3}{2}, \frac{3}{2})_0$
475.072	6	210 494.3	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_3$
474.195	3	210 883.8	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_2^o - p^56p(\frac{3}{2}, \frac{3}{2})_1$
473.692	1	211 107.5	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_2^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
473.559	40	211 167.1	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_5$
471.672	2	212 011.8	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_1$
470.511	20	212 534.8	$p^55d(\frac{3}{2}, \frac{3}{2})_1^o - f^{13}6p(\frac{5}{2}, \frac{1}{2})_2$
469.556	1	212 967.3	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_1^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_2$
467.864	2	213 737.3	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
467.521	100	213 894.0	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_4$
464.018	50	215 508.9	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_5^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_5$
463.979	10	215 527.2	$p^55d(\frac{3}{2}, \frac{3}{2})_1^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_2$
463.547	100	215 727.9	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_3^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_4$
462.379	10	216 272.9	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_4$
461.679	60	216 600.8	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_4^o - p^56p(\frac{3}{2}, \frac{3}{2})_3$
461.535	1	216 668.3	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_5^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_4$
458.343	10	218 177.1	$f^{13}5d(\frac{5}{2}, \frac{3}{2})_4^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_3$
458.222	30	218 235.1	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_5^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_4$
454.535	2	220 005.1	$p^55d(\frac{3}{2}, \frac{3}{2})_1^o - p^56p(\frac{3}{2}, \frac{3}{2})_1$
453.527	1	220 494.1	$f^{13}5d(\frac{7}{2}, \frac{5}{2})_3^o - f^{13}6p(\frac{5}{2}, \frac{3}{2})_3$
447.632	20	223 397.9	$f^{13}5d(\frac{7}{2}, \frac{3}{2})_2^o - f^{13}6p(\frac{7}{2}, \frac{3}{2})_3$
444.950	2	224 744.6	$p^55d(\frac{3}{2}, \frac{3}{2})_1^o - p^56p(\frac{3}{2}, \frac{3}{2})_2$
313.573	30	318 905	$f^{14}p^61S_0 - p^55d(\frac{3}{2}, \frac{3}{2})_1^o$
302.272	700	330 827	$f^{14}p^61S_0 - f^{13}5d(\frac{7}{2}, \frac{5}{2})_1^o$
294.376	200	339 701	$f^{14}p^61S_0 - f^{13}5d(\frac{5}{2}, \frac{3}{2})_1^o$
289.526	300	345 392	$f^{14}p^61S_0 - f^{13}5d(\frac{5}{2}, \frac{5}{2})_1^o$
261.387	3000	382 574	$f^{14}p^61S_0 - p^55d(\frac{3}{2}, \frac{5}{2})_1^o$
223.846	300	446 735	$f^{14}p^61S_0 - p^56s(\frac{3}{2}, \frac{1}{2})_1^o$
216.219	500	462 494	$f^{14}p^61S_0 - p^55d(\frac{1}{2}, \frac{3}{2})_1^o$
188.159	800	531 465	$f^{14}p^61S_0 - p^56s(\frac{1}{2}, \frac{1}{2})_1^o$
154.448	1	647 467	$f^{14}p^61S_0 - p^56d(\frac{3}{2}, \frac{3}{2})_1^o$
153.848	20	649 992	$f^{14}p^61S_0 - f^{13}6d(\frac{7}{2}, \frac{5}{2})_1^o$
151.889	20	658 375	$f^{14}p^61S_0 - p^56d(\frac{3}{2}, \frac{5}{2})_1^o$

TABLE I (continued)

Wavelength (Å)	Intensity	Wave number (cm <sup>-1</sup> )	Classification
150.275	40	665 446	$f^{14}p^6 6^1S_0 - f^{13}6d(\frac{5}{2}, \frac{5}{2})_1^o$
150.203	40	665 765	$f^{14}p^6 6^1S_0 - f^{13}6d(\frac{5}{2}, \frac{3}{2})_1^o$
147.025	40	680 156	$f^{14}p^6 6^1S_0 - p^5 7s(\frac{3}{2}, \frac{1}{2})_1^o$
134.959	20	740 965	$f^{14}p^6 6^1S_0 - p^5 6d(\frac{1}{2}, \frac{3}{2})_1^o$
130.416	2	766 777	$f^{14}p^6 6^1S_0 - p^5 7s(\frac{1}{2}, \frac{1}{2})_1^o$

Because of the simplicity of these configurations, the repeating intervals found among the lines were readily correlated with calculations of the energy levels made with extrapolated interaction parameter values. The analysis was extended to other configurations above and below the  $6p$  levels with the aid of their calculated level structures and the anticipated selection rules of  $J_1 j$  coupling.

The experimentally derived energy levels of W VII are given in Table II. Their values were derived from a least-squares fit of the measured wave numbers of the spectral lines. The relative standard errors of the  $6s$  and  $6p$  levels are approximately  $0.5 \text{ cm}^{-1}$ , while the rest are generally  $1 \text{ cm}^{-1}$ . The levels at 531 465, 740 964, and 766 776  $\text{cm}^{-1}$  are each defined only by one low-wavelength resonance line with an uncertainty of  $\pm 25 \text{ cm}^{-1}$ . The uncertainty of all levels relative to the ground level is  $\pm 3 \text{ cm}^{-1}$ .

As in Ta VI we were unable to find levels of the  $5p^5 nl$  system based on the  $J_1 = \frac{1}{2}$  core state except for those giving rise to resonance lines. These are the  $J = 1$  levels of the  $5p^5 nd$  and  $5p^5 ns$  configurations. The  $5p^5 6d$  and  $5p^5 7s$  configurations were detected in W VII for the first time in this sequence with the latter lying only  $2791 \text{ cm}^{-1}$  above  $4f^{13} 7s$ . This leaves the question of the ground state of W VII somewhat uncertain.

Figure 1 shows the energy range occupied by all the presently known configurations of W VII. The lowest levels of each pair of configurations having the same outer electron but different core are seen to be nearly coincident. A similar diagram in Ref. 4 for Ta VI shows the configurations built on the  $5p^5$  core starting about  $60\,000 \text{ cm}^{-1}$  higher than those built on  $4f^{13}$ . In Re VIII the arrangement will be approximately the reverse of this, as deduced from the observed resonance lines of this ion.

#### INTERPRETATION OF ENERGY LEVELS

At the start of the analysis of the spectrum we carried out calculations of the level structure of the anticipated low-lying configurations, using extrapolated values for the radial integrals or scaled Hartree-Fock values. The latter were particularly useful for the  $5p^5 nl$  configurations, which were known previously only for Ta VI. The analysis began with the discovery of the splitting between the two levels of  $4f^{13}(^2F_{7/2})6s$ , which appears among the few strong lines of the  $4f^{13}(6s-6p)$  transition array. As new levels were found the calculations were improved by adjusting the values for the radial energy integrals.

Since most of the configurations of this ion having either the  $4f^{13}$  or  $5p^5$  core and the same outer electron are completely overlapped and are strongly mixed, single-configuration calculations were inadequate for interpreting a number of the levels. It would have been much more difficult to carry out the interpretation without the data provided by the earlier ions in the sequence.

The low configurations mixing strongly are  $4f^{13} 5d$  and  $5p^5 5d$ . The observed levels are shown in Fig. 2 with designations in  $J_1 j$  coupling. Although the  $4f^{13} 6s$  and  $5p^5 6s$  configurations lie within the upper energy range included, there is no apparent interaction with the levels shown. Configuration interaction in Ta VI is quite different.<sup>4</sup> There the  $5p^5 5d$  occurs at higher energy, overlapping and interacting strongly with  $4f^{13} 6s$ .

We have already reported<sup>3</sup> five resonance lines of W VII and identified them as transitions from the  $5p^5(5d+6s)$  system to the ground level. It appeared at that time that the resonance lines of the  $4f^{13} 5d$  configuration were absent. In the final interpretation the reported resonance line at  $302.272 \text{ Å}$  was found to arise from a level that is 62%  $4f^{13} 5d$ .

TABLE II. Energy levels of W VII.

Configuration	Designation	<i>J</i>	Level (cm <sup>-1</sup> )	Configuration	Designation	<i>J</i>	Level (cm <sup>-1</sup> )
$4f^{14}5p^6$	$^1S_0$		0.0	$5p^5(^2P_{3/2})6p$	$(\frac{3}{2}, \frac{3}{2})$	1	538 902.7
$4f^{13}(^2F_{7/2})5d$	$(\frac{7}{2}, \frac{3}{2})^o$	2	311 441.0			3	539 126.5
		5	318 185.2			2	543 641.1
		3	320 692.7			0	550 081.6
		4	322 527.0	$4f^{13}(^2F_{5/2})6p$	$(\frac{5}{2}, \frac{3}{2})$	1	549 865.3
$5p^5(^2P_{3/2})5d$	$(\frac{3}{2}, \frac{3}{2})^o$	0	315 259			4	551 684.3
		1	318 899.0			2	552 670.8
		2	335 016.9			3	553 588.0
		3	335 171.5	$4f^{13}(^2F_{7/2})6d$	$(\frac{7}{2}, \frac{3}{2})^o$	2	
$4f^{13}(^2F_{7/2})5d$	$(\frac{7}{2}, \frac{5}{2})^o$	6	327 044			5	645 238.4
		2	328 019.8			3	645 943.5
		4	329 949.6			4	646 596.4
		1	330 824.9	$5p^5(^2P_{3/2})6d$	$(\frac{3}{2}, \frac{3}{2})^o$	0	
		3	333 095.4			1	647 462.0
		5	335 017.1			3	650 474.3
$4f^{13}(^2F_{5/2})5d$	$(\frac{5}{2}, \frac{3}{2})^o$	4	335 411.4			2	651 541.7
		2	337 853.6	$4f^{13}(^2F_{7/2})6d$	$(\frac{7}{2}, \frac{5}{2})^o$	6	648 071.9
		1	339 704.6			2	648 557.6
		3	343 093.3			4	649 400.8
$4f^{13}(^2F_{5/2})5d$	$(\frac{5}{2}, \frac{5}{2})^o$	0	339 628.6			3	649 662.1
		1	345 393.5			1	649 982.2
		5	346 384.7			5	650 367.2
		2	348 370.2	$5p^5(^2P_{3/2})6d$	$(\frac{3}{2}, \frac{5}{2})^o$	4	652 661.6
		3	351 599.8			2	653 949.9
		4	352 478.4			3	656 165.0
$5p^5(^2P_{3/2})5d$	$(\frac{3}{2}, \frac{5}{2})^o$	4	340 530.0			1	658 366.6
		2	343 305.1	$4f^{13}(^2F_{5/2})6d$	$(\frac{5}{2}, \frac{3}{2})^o$	4	662 412.7
		3	354 110.8			2	663 215.0
		1	382 577.2			3	664 542.6
$5p^5(^2P_{1/2})5d$	$(\frac{1}{2}, \frac{3}{2})^o$	2	462 496.3			1	665 762.5
		1	462 496.3	$4f^{13}(^2F_{5/2})6d$	$(\frac{5}{2}, \frac{5}{2})^o$	0	
$4f^{13}(^2F_{7/2})6s$	$(\frac{7}{2}, \frac{1}{2})^o$	4	437 188.1			1	665 444.6
		3	438 026.0			5	666 176.6
$5p^5(^2P_{3/2})6s$	$(\frac{3}{2}, \frac{1}{2})^o$	2	443 237.3			2	
		1	446 748.9			3	667 393.6
$4f^{13}(^2F_{5/2})6s$	$(\frac{5}{2}, \frac{1}{2})^o$	2	454 566.3			4	
		3	455 220.6	$4f^{13}(^2F_{7/2})7s$	$(\frac{7}{2}, \frac{1}{2})^o$	4	675 863.8
$4f^{13}(^2F_{7/2})6p$	$(\frac{7}{2}, \frac{1}{2})$	3	512 881.8			3	676 159.0
		4	513 640.4	$5p^5(^2P_{3/2})7s$	$(\frac{3}{2}, \frac{1}{2})^o$	2	678 949.0
$5p^5(^2P_{3/2})6p$	$(\frac{3}{2}, \frac{1}{2})$	1	517 073.8			1	680 153.4
		2	519 194.4	$4f^{13}(^2F_{5/2})7s$	$(\frac{5}{2}, \frac{1}{2})^o$	2	693 250.3
$5p^5(^2P_{1/2})6s$	$(\frac{1}{2}, \frac{1}{2})^o$	0	531 465			3	693 468.2
		1	531 465	$5p^5(^2P_{1/2})6d$	$(\frac{1}{2}, \frac{3}{2})^o$	2	
$4f^{13}(^2F_{5/2})6p$	$(\frac{5}{2}, \frac{1}{2})$	3	530 488.9			1	740 964
		2	531 433.6	$5p^5(^2P_{1/2})7s$	$(\frac{1}{2}, \frac{1}{2})^o$	0	
$4f^{13}(^2F_{7/2})6p$	$(\frac{7}{2}, \frac{3}{2})$	5	533 693.3			1	766 776
		2	534 427.8				
		3	534 837.9				
		4	536 420.1				

Three weaker resonance lines were found that complete the set of eight for the two low systems.

Four parameters of configuration interaction between  $4f^{13}5d$  and  $5p^55d$  are allowed. They are all well defined by the least-squares fit of the radial coefficients to the levels, and take values nearly equal to those predicted by a Hartree-Fock (HF) calculation.<sup>5</sup> The strong configuration interaction caused some difficulty in correctly assigning the observed levels. A satisfactory fit was realized only when all interaction parameters acquired well-defined values nearly equal to the HF results. In contrast to the earlier sequence members, only one of the "effective" electrostatic parameters,<sup>2</sup> the  $X^2$  for  $4f^{13}5d$ , was defined by the least-squares calculation rather than the accustomed three ( $D^1$ ,  $X^2$ , and  $X^4$ ). Perhaps the undefined ones take into account the interaction with  $5p^55d$  when it is a "far configuration."

A very similar overlap of configurations occurs for the second series members, the  $4f^{13}6d$  and  $5p^56d$  whose levels are given in Fig. 3. The  $5p^56d$  is seen in this sequence for the first time in W VII. The parameters of configuration interaction are considerably reduced from those of the lower series members, but all four remain well defined and near the HF values. The largest mixture again appears in the  $J = 1$  file where it is as much as 25% compared with 38% for the corresponding

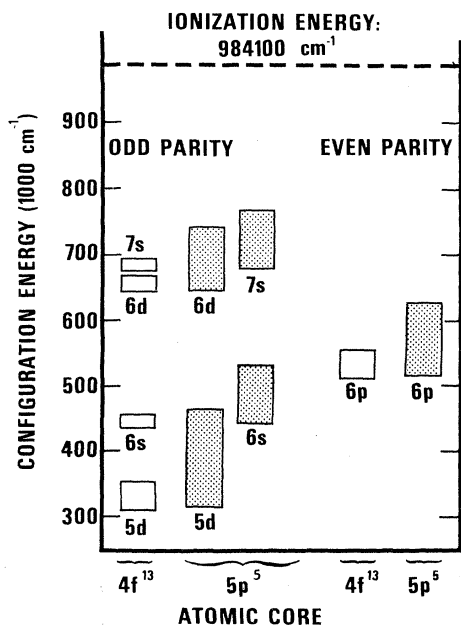


FIG. 1. Relative positions of all known configurations of W VII.

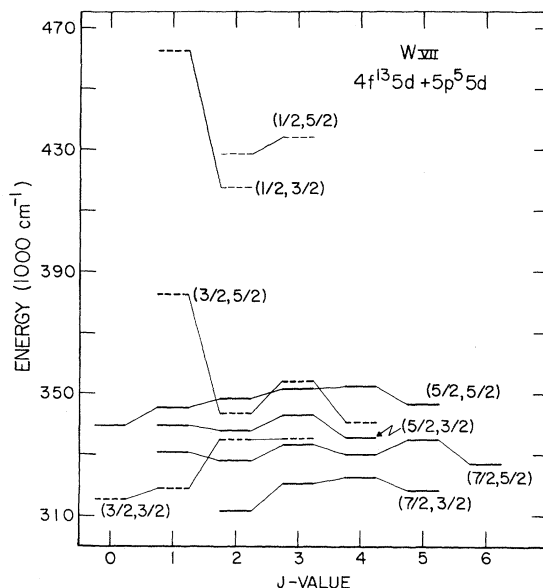


FIG. 2. Energy levels of the mixed  $4f^{13}5d$  (solid bars) and  $5p^55d$  (dashed bars) configurations of W VII. Undetected levels are drawn as thin lines at their calculated positions. The levels are connected in  $J_1 j$ -coupling terms.

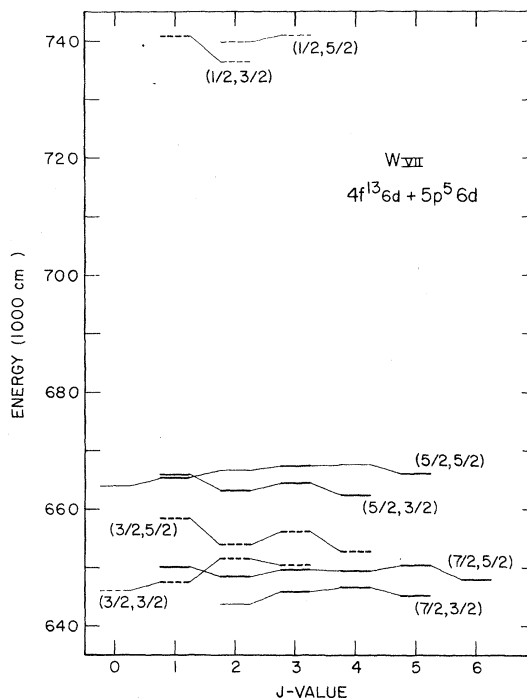


FIG. 3. Energy levels of the mixed  $4f^{13}6d$  (solid bars) and  $5p^56d$  (dashed bars) configurations of W VII. Undetected levels are drawn as thin lines at their calculated positions. The levels are connected in  $J_1 j$ -coupling terms.

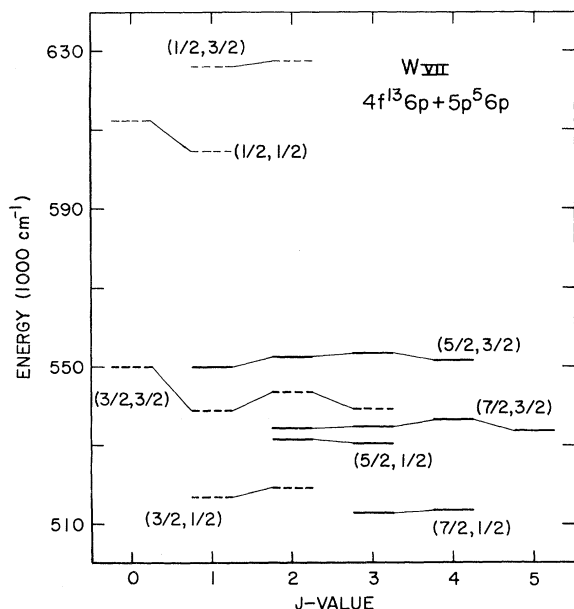


FIG. 4. Energy levels of the mixed  $4f^{13}6p$  (solid bars) and  $5p^56p$  (dashed bars) configurations of  $W_{VII}$ . Undetected levels are drawn as thin lines at their calculated positions. The levels are connected in  $J_1 j$ -coupling terms.

lower group. Also located in this energy range were the  $4f^{13}7s$  and  $5p^57s$  configurations. All eight resonance lines of the second-series group were plainly visible on the spectral plates with no interference from other lines.

A third pair of strongly mixed configurations are  $4p^{13}6p$  and  $5p^56p$ . Two parameters of interaction are allowed between them, but only one was defined in the least-squares fit and a low rms error was achieved. The effective parameter  $D^1$  for  $4f^{13}6p$  was not very well defined, but it took a value similar to that found in Ta VI and was therefore kept. A diagram of the levels of these two configurations appears in Fig. 4.

Final parameter values for all configurations observed are collected in Tables III, IV and V. They are defined as follows: the parameter  $A$  is the coefficient of a unit matrix which represents the position of the total configuration;  $F^k$  and  $G^k$  are the Slater parameters;  $D^k$  and  $X^k$  are the effective electrostatic parameters<sup>2</sup> representing interactions with far configurations;  $\zeta(nl)$  are the spin-orbit parameters;  $R^k$  are the parameters of near configuration interaction. The standard errors for the parameters obtained by their least-squares adjustment are given in parentheses, and the rms fit of the observed to predicted levels are included

TABLE III. Values for radial energy integrals (parameters) of the  $4f^{13}nl$  configurations of  $W_{VII}$  derived by least-squares fitting of calculated to experimental levels. Units are  $cm^{-1}$ .

Parameter	$4f^{13}5d$	$4f^{13}6d$	$4f^{13}6p$	$4f^{13}6s$	$4f^{13}7s$
$A$	344 850(340)	657 893(130)	536 750(96)	445 381(12)	683 572(4)
$F^2(fd)$	34 958(380)	97 69(190)			
$F^4(fd)$	21 012(980)	54 67(440)			
$G^1(fd)$	14 697(270)	33 56(82)			
$G^3(fd)$	14 861(1100)	26 86(500)			
$G^5(fd)$	11 184(870)	37 57(360)			
$D^1(fd)$	0(fixed)				
$D^3(fd)$	0(fixed)				
$X^2(fd)$	-1394(700)				
$X^4(fd)$	0(fixed)				
$F^2(fp)$			12 397(240)		
$G^2(fp)$			4374(180)		
$G^4(fp)$			3988(540)		
$D^1(fp)$			-293(240)		
$X^3(fp)$			0(fixed)		
$G^3(fs)$				5230(120)	1800(38)
$\zeta(6p)$			14 167(31)		
$\zeta(d)$	4257(32)	1382(12)			
$\zeta(4f)$	4937(22)	4993(10)	4956(14)	4961(5)	4966(2)
rms error				17	5

TABLE IV. Values for radial energy integrals (parameters) of the  $5p^5nl$  configurations of W VII derived by least-squares fitting of calculated to experimental levels. Units are  $\text{cm}^{-1}$ .

Parameter	$5p^55d$	$5p^56d$	$5p^56p$	$5p^56s$	$5p^57s$
$A$	427 496(520)	690 039(240)	568 767(400)	474 713(0)	708 928(0)
$F^2(dp)$	63 981(1100)	18 044(470)			
$G^1(dp)$	61 071(330)	9075(160)			
$G^3(dp)$	51 564(1400)	7628(590)			
$F^2(pp')$			21 463(1900)		
$G^0(pp')$			3849(87)		
$G^2(pp')$			9719(1400)		
$G^1(sp)$				8070(0)	2728(0)
$\zeta(5p)$	57 000(fixed)	57 926(66)	57 600(fixed)	57 572(0)	58 142(0)
$\zeta(d)$	4089(120)	1334(30)			
$\zeta(6p)$			14 226(150)		

in the parameter lists. Where configuration interaction is present, the rms error is given in the table of  $R^k$  parameters (Table V).

The spin-orbit parameter  $\zeta(5p)$  of the  $5p^5$  core is determined by only one upper core ( $J_1 = \frac{1}{2}$ ) level of  $J = 1$  in the  $5p^56s$ ,  $6d$  and  $7s$  configurations. The fitted values for this parameter approach an upper limit for configurations with successively more external outer orbits, as expected. For  $5p^55d$  a level of the upper core is known, but there is so much configuration interaction affecting it that  $\zeta(5p)$  cannot be freely adjusted. It was therefore fixed at an estimated value somewhat lower than the fitted value for  $5p^56s$ . In the case of  $5p^56p$  no levels built on the upper core state are known, and an estimated value equal to that of  $5p^56s$  was used in the calculation. The standard error of the fitted parameters of  $5p^56s$  and  $5p^57s$  is undefined because the number of known levels equals the number of parameters.

Values for the effective interaction parameters  $D^k$  and  $X^k$  were fixed at zero when they were not

well defined in the least-squares calculations.

This was also done for the configuration-interaction parameter  $R^2(pp', p'f)$  in Table V.

Tables VI, VII, and VIII contain the calculated levels and leading components of the eigenvectors of all the known configurations of W VII with the exception of the  $4f^{13}ns$  and  $5p^5ns$ . These latter configurations are 100% pure in  $J_1j$  coupling and the calculation is nearly exact due to the almost equal number of levels and parameters. The strong configuration interaction (CI) present in all the other configurations is evident from the eigenvector mixtures.

#### IONIZATION ENERGIES OF W VI AND W VII

The two-member series  $4f^{13}6s$  and  $4f^{13}7s$  may be used to calculate the ionization energy if a value for the change in effective quantum number  $\Delta n^*$  is known. In Table XI of Ref. 4 the variation of  $\Delta n^*(7s-6s)$  along the Lu III isoelectronic sequence

TABLE V. Values for parameters of configuration interaction derived by least-squares fitting of calculated to experimental levels. Units are  $\text{cm}^{-1}$ .

Parameter	$5p^55d + 4f^{13}5d$	$5p^56d + 4f^{13}6d$	$5p^56p + 4f^{13}6p$
$R^2(pd, fd)$	-26 471(660)	-6314(380)	
$R^4(pd, fd)$	-19 953(620)	-4468(640)	
$R^1(pd, df)$	-23 322(360)	-3580(170)	
$R^3(pd, df)$	-20 242(1100)	-3174(410)	
$R^2(pp', fp')$			8298(500)
$R^2(pp', p'f)$			0(fixed)
rms error	122	45	68

TABLE VI. Calculated energy levels and percentage composition in  $J, j$  coupling of the  $4f^{13}5d + 5p^55d$  configurations of W VII. Levels of  $5p^55d$  are preceded by an asterisk. The first two components of the eigenvectors are given. Units for the levels are  $\text{cm}^{-1}$ .

$J$	Calculated	Levels Observed	Calculated minus observed	Composition (%)	
0	315 353	315 259	94	* $(\frac{3}{2}, \frac{3}{2})$ 92	$(\frac{5}{2}, \frac{5}{2})$ 8
	339 539	339 629	-90	$(\frac{5}{2}, \frac{5}{2})$ 92	* $(\frac{3}{2}, \frac{3}{2})$ 8
1	318 816	318 899	-83	* $(\frac{3}{2}, \frac{3}{2})$ 49	$(\frac{7}{2}, \frac{5}{2})$ 22
	330 944	330 825	119	$(\frac{7}{2}, \frac{5}{2})$ 46	* $(\frac{3}{2}, \frac{3}{2})$ 36
	339 700	339 705	-5	$(\frac{5}{2}, \frac{5}{2})$ 68	* $(\frac{3}{2}, \frac{5}{2})$ 17
	345 357	345 393	-36	$(\frac{5}{2}, \frac{5}{2})$ 89	$(\frac{7}{2}, \frac{5}{2})$ 7
	382 565	382 577	-12	* $(\frac{3}{2}, \frac{5}{2})$ 49	* $(\frac{1}{2}, \frac{3}{2})$ 23
	462 504	462 496	8	* $(\frac{1}{2}, \frac{3}{2})$ 76	* $(\frac{3}{2}, \frac{5}{2})$ 17
2	311 596	311 441	155	$(\frac{7}{2}, \frac{3}{2})$ 84	$(\frac{7}{2}, \frac{5}{2})$ 9
	328 079	328 020	59	$(\frac{7}{2}, \frac{5}{2})$ 82	$(\frac{7}{2}, \frac{3}{2})$ 10
	334 873	335 017	-144	* $(\frac{3}{2}, \frac{3}{2})$ 59	$(\frac{5}{2}, \frac{3}{2})$ 20
	337 824	337 854	-30	$(\frac{5}{2}, \frac{3}{2})$ 73	* $(\frac{3}{2}, \frac{5}{2})$ 14
	343 424	343 305	119	* $(\frac{3}{2}, \frac{5}{2})$ 58	* $(\frac{3}{2}, \frac{3}{2})$ 23
	348 374	348 370	4	$(\frac{5}{2}, \frac{5}{2})$ 88	* $(\frac{3}{2}, \frac{3}{2})$ 4
	416 641			* $(\frac{1}{2}, \frac{3}{2})$ 99	
	427 768			* $(\frac{1}{2}, \frac{5}{2})$ 98	* $(\frac{3}{2}, \frac{5}{2})$ 2
3	320 662	320 693	-31	$(\frac{7}{2}, \frac{3}{2})$ 90	* $(\frac{3}{2}, \frac{3}{2})$ 7
	333 059	333 095	-36	$(\frac{7}{2}, \frac{5}{2})$ 53	* $(\frac{3}{2}, \frac{3}{2})$ 38
	335 145	335 171	-26	* $(\frac{3}{2}, \frac{3}{2})$ 48	$(\frac{7}{2}, \frac{5}{2})$ 42
	343 068	343 093	-25	$(\frac{5}{2}, \frac{3}{2})$ 97	$(\frac{7}{2}, \frac{5}{2})$ 2
	351 696	351 600	96	$(\frac{5}{2}, \frac{5}{2})$ 86	* $(\frac{3}{2}, \frac{5}{2})$ 10
	354 131	354 111	20	* $(\frac{3}{2}, \frac{5}{2})$ 87	$(\frac{5}{2}, \frac{5}{2})$ 9
	433 083			* $(\frac{1}{2}, \frac{5}{2})$ 99	* $(\frac{3}{2}, \frac{3}{2})$ 1
4	322 444	322 527	-83	$(\frac{7}{2}, \frac{3}{2})$ 84	* $(\frac{3}{2}, \frac{5}{2})$ 9
	329 960	329 950	10	$(\frac{7}{2}, \frac{5}{2})$ 55	* $(\frac{3}{2}, \frac{5}{2})$ 21
	335 398	335 411	-13	$(\frac{5}{2}, \frac{3}{2})$ 84	$(\frac{7}{2}, \frac{5}{2})$ 6
	340 442	340 530	-88	* $(\frac{3}{2}, \frac{5}{2})$ 65	$(\frac{7}{2}, \frac{5}{2})$ 33
	352 610	352 478	132	$(\frac{5}{2}, \frac{5}{2})$ 96	$(\frac{5}{2}, \frac{3}{2})$ 2
5	318 230	318 185	45	$(\frac{7}{2}, \frac{3}{2})$ 98	$(\frac{7}{2}, \frac{5}{2})$ 1
	335 016	335 017	-1	$(\frac{7}{2}, \frac{5}{2})$ 97	$(\frac{5}{2}, \frac{5}{2})$ 1
	346 344	346 385	-41	$(\frac{5}{2}, \frac{5}{2})$ 98	$(\frac{7}{2}, \frac{5}{2})$ 1
6	326 930	327 044	-114	$(\frac{7}{2}, \frac{5}{2})$ 100	

TABLE VII. Calculated energy levels and percentage composition in  $J_1j$  coupling of the  $4f^{13}6d + 5p^56d$  configurations of W<sub>VII</sub>. Levels of  $5p^56d$  are preceded by an asterisk. The first two components of the eigenvectors are given. Units for the levels are  $\text{cm}^{-1}$ .

$J$	Calculated	Levels Observed	Calculated minus observed	Composition (%)	
0	646 023			$*(\frac{3}{2}, \frac{3}{2})$ 99	$(\frac{5}{2}, \frac{5}{2})$ 1
	663 869			$(\frac{5}{2}, \frac{5}{2})$ 99	$*(\frac{3}{2}, \frac{3}{2})$ 1
1	647 456	647 462	-6	$*(\frac{3}{2}, \frac{3}{2})$ 57	$(\frac{7}{2}, \frac{5}{2})$ 23
	649 985	649 982	3	$(\frac{7}{2}, \frac{5}{2})$ 69	$*(\frac{3}{2}, \frac{3}{2})$ 30
	658 367	658 367	0	$*(\frac{3}{2}, \frac{5}{2})$ 70	$(\frac{5}{2}, \frac{3}{2})$ 18
	665 435	665 445	-10	$(\frac{5}{2}, \frac{5}{2})$ 78	$(\frac{5}{2}, \frac{3}{2})$ 14
	665 767	665 762	5	$(\frac{5}{2}, \frac{3}{2})$ 67	$(\frac{5}{2}, \frac{5}{2})$ 21
	740 963	740 964	-1	$*(\frac{1}{2}, \frac{3}{2})$ 100	
2	643 620			$(\frac{7}{2}, \frac{3}{2})$ 91	$(\frac{7}{2}, \frac{5}{2})$ 7
	648 538	648 558	-20	$(\frac{7}{2}, \frac{5}{2})$ 90	$(\frac{7}{2}, \frac{3}{2})$ 7
	651 515	651 542	-27	$*(\frac{3}{2}, \frac{3}{2})$ 79	$*(\frac{3}{2}, \frac{5}{2})$ 18
	654 001	653 950	51	$*(\frac{3}{2}, \frac{5}{2})$ 79	$*(\frac{3}{2}, \frac{3}{2})$ 18
	663 256	663 215	41	$(\frac{5}{2}, \frac{3}{2})$ 99	$(\frac{5}{2}, \frac{5}{2})$ 1
	666 585			$(\frac{5}{2}, \frac{5}{2})$ 99	$(\frac{5}{2}, \frac{3}{2})$ 1
	736 719			$*(\frac{1}{2}, \frac{3}{2})$ 100	
740 139			$*(\frac{1}{2}, \frac{5}{2})$ 100		
3	645 919	645 943	-24	$(\frac{7}{2}, \frac{3}{2})$ 95	$*(\frac{3}{2}, \frac{3}{2})$ 4
	649 681	649 662	19	$(\frac{7}{2}, \frac{5}{2})$ 76	$*(\frac{3}{2}, \frac{5}{2})$ 24
	650 488	650 474	14	$*(\frac{3}{2}, \frac{3}{2})$ 72	$(\frac{7}{2}, \frac{5}{2})$ 23
	656 143	656 165	-22	$*(\frac{3}{2}, \frac{5}{2})$ 99	
	664 522	664 543	-21	$(\frac{5}{2}, \frac{3}{2})$ 100	
	667 405	667 394	11	$(\frac{5}{2}, \frac{5}{2})$ 99	
	740 968			$*(\frac{1}{2}, \frac{5}{2})$ 100	
4	646 571	646 596	-25	$(\frac{7}{2}, \frac{3}{2})$ 94	$*(\frac{3}{2}, \frac{5}{2})$ 3
	649 432	649 401	31	$(\frac{7}{2}, \frac{5}{2})$ 82	$*(\frac{3}{2}, \frac{5}{2})$ 13
	652 644	652 662	-18	$*(\frac{3}{2}, \frac{5}{2})$ 84	$(\frac{7}{2}, \frac{5}{2})$ 15
	662 414	662 413	1	$(\frac{5}{2}, \frac{3}{2})$ 98	$(\frac{5}{2}, \frac{5}{2})$ 2
	667 816			$(\frac{5}{2}, \frac{5}{2})$ 98	$(\frac{5}{2}, \frac{3}{2})$ 2
5	645 258	645 238	20	$(\frac{7}{2}, \frac{3}{2})$ 99	$(\frac{7}{2}, \frac{5}{2})$ 1
	650 369	650 367	2	$(\frac{7}{2}, \frac{5}{2})$ 99	$(\frac{7}{2}, \frac{3}{2})$ 1
	666 156	666 177	-21	$(\frac{5}{2}, \frac{5}{2})$ 100	
6	648 068	648 072	-4	$(\frac{7}{2}, \frac{5}{2})$ 100	

TABLE VIII. Calculated energy levels and percentage composition in  $J_1 j$  coupling of the  $4f^{13}6p + 5p^5 6p$  configurations of W VII. Levels of  $5p^5 6p$  are preceded by an asterisk. The first two components of the eigenvectors are given. Units for the levels are  $\text{cm}^{-1}$ .

$J$	Calculated	Levels Observed	Calculated minus observed	Composition (%)	
0	550 073	550 082	-9	* $(\frac{3}{2}, \frac{3}{2})$ 99	* $(\frac{1}{2}, \frac{1}{2})$ 1
	612 476			* $(\frac{1}{2}, \frac{1}{2})$ 99	* $(\frac{3}{2}, \frac{3}{2})$ 1
1	517 071	517 074	-3	* $(\frac{3}{2}, \frac{1}{2})$ 96	* $(\frac{3}{2}, \frac{3}{2})$ 3
	538 902	538 903	-1	* $(\frac{3}{2}, \frac{3}{2})$ 96	* $(\frac{3}{2}, \frac{1}{2})$ 3
	549 818	549 865	-47	$(\frac{5}{2}, \frac{3}{2})$ 99	* $(\frac{3}{2}, \frac{3}{2})$ 1
	604 594			* $(\frac{1}{2}, \frac{1}{2})$ 100	
	626 077			* $(\frac{1}{2}, \frac{3}{2})$ 100	
2	519 194	519 194	0	* $(\frac{3}{2}, \frac{1}{2})$ 98	$(\frac{5}{2}, \frac{1}{2})$ 2
	531 505	531 434	-29	$(\frac{5}{2}, \frac{1}{2})$ 91	$(\frac{7}{2}, \frac{3}{2})$ 6
	534 403	534 428	-25	$(\frac{7}{2}, \frac{3}{2})$ 92	$(\frac{5}{2}, \frac{1}{2})$ 6
	543 639	543 641	-2	* $(\frac{3}{2}, \frac{3}{2})$ 98	$(\frac{7}{2}, \frac{3}{2})$ 1
	552 715	552 671	44	$(\frac{5}{2}, \frac{3}{2})$ 99	$(\frac{7}{2}, \frac{3}{2})$ 1
	627 406			* $(\frac{1}{2}, \frac{3}{2})$ 100	
3	512 871	512 882	-11	$(\frac{7}{2}, \frac{1}{2})$ 98	$(\frac{7}{2}, \frac{3}{2})$ 1
	530 447	530 490	-43	$(\frac{5}{2}, \frac{1}{2})$ 97	$(\frac{7}{2}, \frac{3}{2})$ 2
	534 890	534 838	52	$(\frac{7}{2}, \frac{3}{2})$ 85	* $(\frac{3}{2}, \frac{3}{2})$ 11
	539 119	539 126	-7	* $(\frac{3}{2}, \frac{3}{2})$ 88	$(\frac{7}{2}, \frac{3}{2})$ 12
	553 519	553 588	-69	$(\frac{5}{2}, \frac{3}{2})$ 100	
4	513 622	513 640	-18	$(\frac{7}{2}, \frac{1}{2})$ 100	
	536 379	536 420	-41	$(\frac{7}{2}, \frac{3}{2})$ 100	
	551 713	551 684	29	$(\frac{5}{2}, \frac{3}{2})$ 100	
5	533 728	553 693	35	$(\frac{7}{2}, \frac{3}{2})$ 100	

is given. The trend of values shows a decrease of 0.001 for each succeeding ionization stage. By extrapolation, Re VII would have  $\Delta n^*(7s-6s) = 1.041$ . We assume, as in Ref. 4, that  $\Delta n^*$  is constant for the same stage of ionization, and therefore take this value for W VII with an estimated uncertainty of 0.002. For the series we use the center of gravity of the pair of levels built on the  $4f^{13} {}^2F_{7/2}$  core state. The limit is then the ground state of W VIII, with the assumption that  $5p^5$  is at a higher energy. By applying the Rydberg-Ritz series formula, we obtain the value  $984\,100 \pm 500 \text{ cm}^{-1}$  for the ionization energy, where the uncertainty is attributed to

the uncertainty in  $\Delta n^*$ .

A similar calculation utilizing the  $5p^5({}^2P_{3/2})6s$  and  $5p^5({}^2P_{3/2})7s$  series and the same value for  $\Delta n^*$  leads to an ionization energy of  $984\,900 \pm 500 \text{ cm}^{-1}$ . These results indicate that both the  ${}^2P_{3/2}$  and  ${}^2F_{7/2}$  levels are close to the ground state of W VIII but that the latter may be several hundred  $\text{cm}^{-1}$  lower and is more probably the ground state. However the uncertainties in these calculations preclude a positive choice. The W VIII ion is the only known case of  $p$  and  $f$  orbits competing for the ground state.

Meijer<sup>5</sup> has found the  $6s$  and  $7s$  levels of W VI

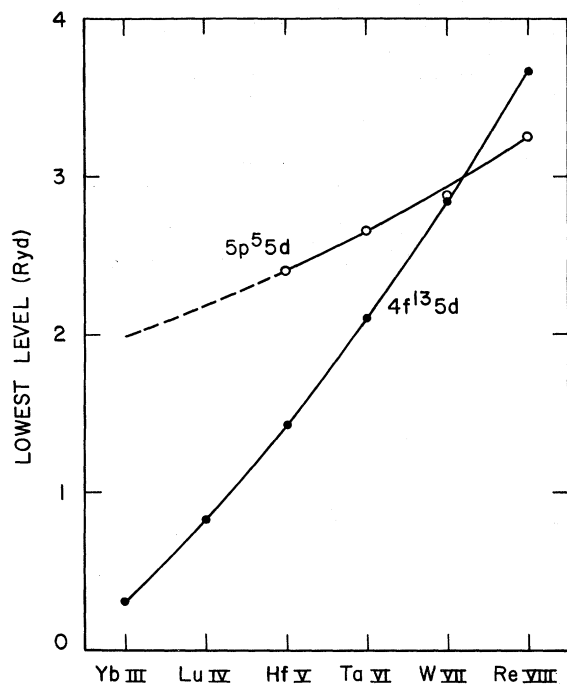


FIG. 5. Trend of lowest levels of  $4f^{13}5d$  and  $5p^55d$  configurations along the isoelectronic sequence.

and derived a value for the ionization energy of  $523\,500 \pm 500 \text{ cm}^{-1}$  with the assumption that  $\Delta n^* = 1.0365$ . Our extrapolated value of 1.042 for  $\Delta n^*$  of W VI given in Ref. 4 leads to a value of  $522\,300 \pm 500 \text{ cm}^{-1}$  ( $64.76 + 0.06 \text{ eV}$ ) for this ionization energy.

#### THE $4f^{13}5d$ AND $5p^55d$ ISOELECTRONIC SEQUENCES

In Ref. 4 we plotted the lowest levels of these configurations from Lu IV through Re VIII, extrapolating linearly from the known points. Newly observed data permit the more accurate curves of Fig. 5 to be drawn. The  $4f^{13}5d$  now includes the experimental point for W VII and a semiempirical

TABLE IX. Resonance lines of Hf v  $5p^6-5p^5(5d, 6s)$ .

Wavelength (Å)	Wave number		Classification
	Int.	( $\text{cm}^{-1}$ )	
372.249	100	268 637	$5p^6 \ ^1S_0-5p^55d(\frac{3}{2}, \frac{3}{2})_1^o$
321.557	300	310 987	$5p^6 \ ^1S_0-5p^55d(\frac{3}{2}, \frac{5}{2})_1^o$
307.432	300	325 275	$5p^6 \ ^1S_0-5p^56s(\frac{3}{2}, \frac{1}{2})_1^o$
262.03	200	381 630	$5p^6 \ ^1S_0-5p^55d(\frac{1}{2}, \frac{3}{2})_1^o$
257.04	100	389 040	$5p^6 \ ^1S_0-5p^56s(\frac{1}{2}, \frac{1}{2})_1^o$

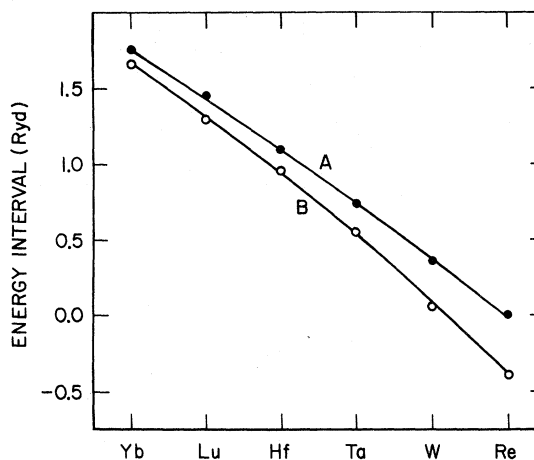


FIG. 6. Curve A: Energy interval between  $5p^{5^2}P_{3/2}$  and  $4f^{13^2}F_{7/2}$  in the singly ionized atom, as obtained from x-ray transitions (Ref. 7). Curve B: Energy interval between lowest levels of  $4f^{13}5d$  and  $5p^55d$  configurations in Yb III isoelectronic sequence (see Fig. 5).

point for Re VIII, which was obtained by fitting a calculation to the observed resonance lines.

We have identified the five resonance lines of HF V (given in Table IX) arising from the  $5p^55d$  and  $5p^56s$  configurations. The three lines due to  $5p^55d$  were used to calculate the position of the lowest level of this configuration. The W VII point for  $5p^55d$  is low because of configuration mixing which shifts the lowest level by several thousand  $\text{cm}^{-1}$ . The figure shows clearly that  $5p^55d$  becomes the lowest system of excited levels in Re VIII.

The crossing of these configurations exhibited by the isoelectronic sequences closely follows the difference in energies of the  $5p^5$  and  $4f^{13}$  configurations observed by means of x-ray transitions in the singly ionized atoms. A comparison of these trends is made in Fig. 6. Curve B shows the difference between the two curves of Fig. 5, the difference in the excitation energies of lowest levels of  $4f^{13}5d$  and  $5p^55d$ . Curve A gives the difference in energies of the  $5p^{5^2}P_{3/2}$  and  $4f^{13^2}F_{7/2}$  hole states, or  $O_3$  minus  $N_7$ , derived from x-ray emission data by Lotz.<sup>7</sup> The zero of curve A occurs at Re VIII, showing a slight shift to higher  $Z$  for the singly ionized atoms due to screening by the  $5d$  and  $6s$  electrons. The somewhat greater slope of curve B arises from the more rapid increase of effective nuclear charge as electrons are stripped away in succeeding ions. However, the near coincidence of these two curves shows that the  $5d$  and  $6s$  electrons have little influence on the deep-lying  $4f$  and  $5p$  shells. This was also seen in the high purity of the eigenvectors of  $4f^{13}5d$  and  $5p^55d$  in the  $J_1j$  coupling scheme.

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<sup>1</sup>B. W. Bryant, *J. Opt. Soc. Am.* 55, 771 (1965).

<sup>2</sup>J. Sugar and V. Kaufman, *J. Opt. Soc. Am.* 62, 562 (1972).

<sup>3</sup>V. Kaufman and J. Sugar, *J. Opt. Soc. Am.* 64, 1370A (1974).

<sup>4</sup>V. Kaufman and J. Sugar, *J. Opt. Soc. Am.* 65, 302 (1975).

<sup>5</sup>F. G. Meijer, *Physica* 73, 415 (1974).

<sup>6</sup>The Hartree-Fock program written by Charlotte Froese was used for these calculations. See C. Froese, *Can. J. Phys.* 41, 1895 (1963).

<sup>7</sup>W. Lotz, *J. Opt. Soc. Am.* 60, 206 (1970).