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The fifth spectrum of tantalum

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Abstract : The spectrum of the four-times ionised tantalum (Ta V) has been analysed in 478-2504Å spectral region. From the 117 observed lines in this region, a system of 56 energy levels of Ta V was deduced which includes 41 new excited levels found in the present study. The new levels of $4f^{14}nl$ system are with (n) $l=(9,10)s$, $(7,8,9,10)p$, $(7,8,9,10)d$, $(6,7,8,9,10)f$, $(6,7,8,9,10)g$, $(6,7,8,9,10\ 11,12)h$ and $(9,10,11,12)i$; the doublet term system is found for $np(^2P_{1/2,3/2})$, $nd(^2D_{3/2,5/2})$, $nf(^2F_{5/2,7/2})$ except for $9d$ and $10d$. The splitting of ^2G, ^2H and ^2I terms could not be observed.

Keywords : Spectrum, four-times ionized tantalum.

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1. Introduction

The spectrum of four-times ionised tantalum (Ta V) has been investigated earlier by Meijer and Klinkenberg (1973), Sugar and Kaufman (1975, 1979), Kaufman and Sugar (1976). The ground term of Ta V (Ta^{4+}) ion is $5p^6 4f^{14} 5d\,^2D$, obtained by the ionization of both the $6s$ and two $5d$ electrons from tantalum atom. The one-electron spectrum will, therefore, be produced by the excitation of $5d$ electron to one of the optical levels nl. It is expected from the experience of the analogous fifth spectra that some levels of an odd three-electron configuration, like $4f^{13}5d^2$ obtained by the excitation of an internal $4f$ electron, would perturb some of the np or nf levels of the one-electron system.

The isoelectronic sequence of this spectrum starts from the element Tm ($Z=69$) because the $4f$ orbital crushes down from there onwards only. Comparison with the data available on a few lower levels of the sequence has been made by Meijer and Klinkenberg (1973). Despite the additions by Sugar and Kaufman (1975, 1976, 1979), the knowledge of the spectrum of Ta V remained fragmentary. We have, therefore, analysed this spectrum in an extensive manner with the help of spectrograms recorded earlier in Lund University, Sweden.

2. Experiment

For exciting the Ta V spectrum a sliding spark source, under about 8 KV, with an alumina spacer (Rahimullah *et al* 1980) was used. The 3-*m* normal incidence

Table I. Classified lines of Ta V.

Wave length (Å)[a]	Intensity[b]	Wave number (cm^{-1})	Classification
478.307 (MK)	6	209071	$5d\ ^2D_{3/2} - 5f\ ^2F_{5/2}$
493.074 (MK)	6	202809	$5d\ ^2D_{5/2} - 5f\ ^2F_{7/2}$
493.884 (MK)	4	202477	$5d\ ^2D_{5/2} - 5f\ ^2F_{5/2}$
645.970	4	154806	$6p\ ^2P_{3/2} - 7d\ ^2D_{5/2}$
762.426	2	131160	$7s\ ^2S_{1/2} - 10p\ ^2P_{3/2}$
782.403	2	127811	$6d\ ^2D_{3/2} - 8f\ ^2F_{5/2}$
797.652	3	125368	$6d\ ^2D_{5/2} - 8f\ ^2F_{7/2}$
808.898	1	123625	$7g\ ^2G_{7/2,9/2} - 5f\ ^2F_{5/2}$
811.130	3	123285	$7g\ ^2G_{7/2,9/2} - 5f\ ^2F_{7/2}$
819.532	d	122021	$9d\ ^2D_{3/2,5/2} - 5f\ ^2F_{7/2}$
829.259	1	120590	$9p\ ^2P_{3/2} - 6d\ ^2D_{3/2}$
841.315 (MK)	6	118862	$6p\ ^2P_{3/2} - 5d\ ^2D_{3/2}$
842.902	d	118638	$9p\ ^2P_{3/2} - 6d\ ^2D_{5/2}$
864.688	2	115649	$6d\ ^2D_{3/2} - 7f\ ^2F_{5/2}$
879.052	1	113759	$6d\ ^2D_{5/2} - 7f\ ^2F_{7/2}$
879.552	1	113694	$6d\ ^2D_{5/2} - 7f\ ^2F_{5/2}$
882.150	d	113359	$7s\ ^2S_{1/2} - 9p\ ^2P_{3/2}$
887.494	5	112677	$7s\ ^2S_{1/2} - 9p\ ^2P_{1/2}$
890.874 (MK)	18	112249	$6p\ ^2P_{3/2} - 5d\ ^2D_{5/2}$
891.324	3.5	112193	$7p\ ^2P_{1/2} - 10d\ ^2D_{3/2,5/2}$
947.302 (MK)	21	105563	$6p\ ^2P_{1/2} - 5d\ ^2D_{3/2}$
968.784 (SK)	3	103222	$6g\ ^2G_{7/2} - 5f\ ^2F_{5/2}$
972.084 (SK)	3.5	102872	$6g\ ^2G_{9/2} - 5f\ ^2F_{7/2}$
989.612	3	101050	$8d\ ^2D_{5/2} - 5f\ ^2F_{5/2}$
990.324 (MK)	12	100977	$7s\ ^2S_{1/2} - 6p\ ^2P_{1/2}$
991.910	d	100816	$8d\ ^2D_{3/2} - 5f\ ^2F_{5/2}$
992.993	2	100706	$8d\ ^2D_{5/2} - 5f\ ^2F_{7/2}$
1012.278	d	98787.1	$10s\ ^2S_{1/2} - 7p\ ^2P_{1/2}$
1016.379 *1	3 5	98388.5	$7p\ ^2P_{1/2} - 9d\ ^2D_{3/2,5/2}$
1066.665 (MK)	21	93750.1	$6p\ ^2P_{1/2} - 6d\ ^2D_{3/2}$
1093.676	2	91434.8	$8p\ ^2P_{3/2} - 6d\ ^2D_{3/2}$
1113.272	1	89825.3	$8p\ ^2P_{1/2} - 6d\ ^2D_{3/2}$
1117.648	1	89473.6	$8p\ ^2P_{3/2} - 6d\ ^2D_{5/2}$
1133.364	4.5	88232.9	$5g\ ^2G_{9/2} - 11h\ ^2H_{9/2,11/2}$
1140.498 (MK)	13.5	87681.0	$7s\ ^2S_{1/2} - 6p\ ^2P_{3/2}$
1185.214	3.5	84372.9	$10g\ ^2G_{7/2,9/2} - 6f\ ^2F_{5/2}$

Table I. (Contd.)

Wave length (Å)[a]	Intensity[b]	Wave number (cm^{-1})	Classification
1187.119 *2	4.5	84237.6	10g $^2G_{7/2,9/2}$ – 6f $^2F_{7/2}$
1187.642	3	84200.5	7s $^2S_{1/2}$ – 8p $^2P_{3/2}$
1197.997	d	83472.7	5g $^2G_{9/2}$ – 10h $^2H_{9/2,11/2}$
1210.814	d	82589.1	7s $^2S_{1/2}$ – 8p $^2P_{1/2}$
1213.424 (MK)	11.5	82411.4	6p $^2P_{3/2}$ – 6d $^2D_{5/2}$
1216.022	1	82235.4	7d $^2D_{3/2}$ – 10f $^2F_{5/2}$
1226.030	1	81564.1	7d $^2D_{5/2}$ – 10f $^2F_{5/2}$
1232.193	3	81156.1	7d $^2D_{5/2}$ – 10f $^2F_{7/2}$
1243.003 (MK)	10.5	80450.3	6p $^2P_{3/2}$ – 6d $^2D_{3/2}$
1283.682	9	77900.91	6d $^2D_{3/2}$ – 6f $^2F_{5/2}$
1284.274	d	77865.0	9g $^2G_{7/2,9/2}$ – 6f $^2F_{5/2}$
1286 429	1	77734.6	9g $^2G_{7/2,9/2}$ – 6f $^2F_{7/2}$
1289.029	1	77577.8	9s $^2S_{1/2}$ – 7p $^2P_{1/2}$
1301.494	5	76834.8	7p $^2P_{1/2}$ – 8d $^2D_{3/2}$
1302.235	4.5	76791.1	5g $^2G_{7/2}$ – 10f $^2F_{5/2}$
1309.145	9	76385.7	5g $^2G_{9/2}$ – 10f $^2F_{7/2}$
1309.233	6	76380.6	5g $^2G_{7/2}$ – 10f $^2F_{7/2}$
1314.474	4	76076.1	6d $^2D_{5/2}$ – 6f $^2F_{7/2}$
1316.775	2	75943.1	6d $^2D_{5/2}$ – 6f $^2F_{5/2}$
1369.510	3.5	73018.8	9s $^2S_{1/2}$ – 7p $^2P_{3/2}$
1379.066	2	72512.8	7p $^2P_{3/2}$ – 8d $^2D_{5/2}$
1383.566	2	72277.0	7p $^2P_{3/2}$ – 8d $^2D_{3/2}$
1392.545 (MK)	18.5	71811.0	6s $^2S_{1/2}$ – 6p $^2P_{3/2}$
1422.006	3	70323.2	7d $^2D_{3/2}$ – 9f $^2F_{5/2}$
1435.716	3	69651.7	7d $^2D_{5/2}$ – 9f $^2F_{5/2}$
1441.612 *3 (SK)	7	69366.8	5g $^2G_{7/2}$ – 5f $^2F_{5/2}$
1447.565	3	69081.5	7d $^2D_{5/2}$ – 9f $^2F_{7/2}$
1448.919 (SK)	10.5	69017.0	5g $^2G_{7/2}$ – 5f $^2F_{7/2}$
1448.995 (SK)	15	69013.5	5g $^2G_{9/2}$ – 5f $^2F_{7/2}$
1454.036	2	68774.1	8g $^2G_{7/2,9/2}$ – 6f $^2F_{5/2}$
1456.813	13.5	68643.0	8g $^2G_{7/2,9/2}$ – 6f $^2F_{7/2}$
1469.641	3.5	68043.8	5g $^2G_{9/2}$ – 8h $^2H_{9/2,11/2}$
1469.802 *3	16	68036.4	10d $^2D_{3/2,5/2}$ – 6f $^2F_{5/2}$
1472.668	3	67904.0	10d $^2D_{5/2,5/2}$ – 6f $^2F_{7/2}$
1541.473	5	64873.0	5g $^2G_{7/2}$ – 9f $^2F_{5/2}$
1545.502	1	64703.9	10p $^2P_{3/2}$ – 7d $^2D_{3/2}$

Table I. (Contd.)

Wave length (Å)[a]	Intensity[b]	Wave number (cm^{-1})	Classification
1548.259	1	64588.7	$7d\ ^2D_{5/2}-5f\ ^2F_{5/2}$
1552.122	1	64427.9	$10p\ ^2P_{1/2}-7d\ ^2D_{3/2}$
1555.009 *3	9	64308.3	$5g\ ^2G_{9/2}-9f\ ^2F_{7/2}$
1555.128	2	64303.4	$5g\ ^2G_{7/2}-9f\ ^2F_{7/2}$
1556 553	4	64244 5	$7d\ ^2D_{5/2}-5f\ ^2F_{7/2}$
1561.770	2	64029.9	$10p\ ^2P_{3/2}-7d\ ^2D_{5/2}$
1564.498	3	63918.3	$7d\ ^2D_{3/2}-5f\ ^2F_{5/2}$
1585.295	3	63079.8	$8s\ ^2S_{1/2}-10p\ ^2F_{3/2}$
1592.221	d	62805.4	$8s\ ^2S_{1/2}-10p\ ^2P_{1/2}$
1709.139 (MK)	24	58509.0	$6s\ ^2S_{1/2}-6p\ ^2P_{1/2}$
1724.275	3.5	57995.4	$6g\ ^2G_{9/2}\ \ 12h\ ^2H_{9/2,11/2}$
1749.326	1	57164.9	$6h\ ^2H_{9/2,11/2}-12i\ ^2I_{11/2,13/2}$
1782.106	1	56113.4	$8p\ ^2P_{1/2}-10d\ ^2D_{3/2,5/2}$
1802.098	4.5	55490.9	$7g\ ^2G_{7/2,9/2}-6f\ ^2F_{5/2}$
1806.414	7.5	55358.3	$7g\ ^2G_{7/2,9/2}-6f\ ^2F_{7/2}$
1820.848	3.5	54919.5	$5g\ ^2G_{9/2}-7h\ ^2H_{9/2,11/2}$
1834.761	3	54503.0	$8p\ ^2P_{3/2}-10d\ ^2D_{3/2,5/2}$
1839.035	3.5	54376.4	$6g\ ^2G_{9/2}-11h\ ^2H_{9/2,11/2}$
1843.956	3	54231.2	$9d\ ^2D_{3/2,5/2}-6f\ ^2F_{5/2}$
1847.330	9	54132.2	$7d\ ^2D_{3/2}-8f\ ^2F_{5/2}$
1848.561	3.5	54096.1	$9d\ ^2D_{5/2,5/2}-6f\ ^2F_{7/2}$
1869.087	7	53502.0	$6h\ ^2H_{9/2,11/2}-11i\ ^2I_{11/2,13/2}$
1870.628	3	53458.0	$7d\ ^2D_{5/2}-8f\ ^2F_{5/2}$
1887.728	15.5	52973.7	$7d\ ^2D_{5/2}-8f\ ^2F_{7/2}$
2015.640	3	49612.0	$6g\ ^2G_{9/2}-10h\ ^2H_{9/2,11/2}$
2050.081	7	48778.6	$6h\ ^2H_{9/2,11/2}-10i\ ^2I_{11/2,13/2}$
2054.076	11	48683.7	$5g\ ^2G_{7/2}-8f\ ^2F_{5/2}$
2074.553	20	48203.2	$5g\ ^2G_{9/2}-8f\ ^2F_{7/2}$
2074.758	19	48198.4	$5g\ ^2G_{7/2}-8f\ ^2F_{7/2}$
2131.686	4	46911.2	$9p\ ^2P_{3/2}-7d\ ^2D_{3/2}$
2144.899	3.5	46622.2	$10g\ ^2G_{7/2,9/2}-7f\ ^2F_{5/2}$
2148.129	13	46552.1	$10g\ ^2G_{7/2,9/2}-7f\ ^2F_{7/2}$
2162.671	4.5	46239.1	$9p\ ^2P_{3/2}-7d\ ^2D_{5/2}$
2163.276	8	46226.2	$9p\ ^2P_{1/2}-7d\ ^2D_{3/2}$
2205.349	3.5	45344.3	$8d\ ^2D_{3/2}-10f\ ^2F_{5/2}$
2207.943	13	45291.0	$8s\ ^2S_{1/2}-9p\ ^2P_{3/2}$

Table I. (Contd.)

Wave length (Å)[a]	Intensity[b]	Wave number (cm^{-1})	Classification
2237.407	3.5	44694.6	$8d\ ^2D_{5/2}-10f\ ^2F_{7/2}$
2241.869	3	44605.6	$8s\ ^2S_{1/2}-9p\ ^2P_{1/2}$
2316.020	3	43177.5	$6g\ ^2G_{9/2}-9h\ ^2H_{9/2,11/2}$
2341.342	7	42710.5	$10s\ ^2S_{1/2}-8p\ ^2P_{1/2}$
2361.346	9	42348.7	$6h\ ^2H_{9/2,11/2}-9i\ ^2I_{11/2,13/2}$
2432.954	9	41102.3	$10s\ ^2S_{1/2}-8p\ ^2P_{3/2}$
2492.710	3.5	40117.0	$9g\ ^2G_{7/2,9/2}-7f\ ^2F_{5/2}$
2496.978	3.5	40048.4	$9g\ ^2G_{7/2,9/2}-7f\ ^2F_{7/2}$
2503.808	6	39939.2	$7p\ ^2P_{1/2}-7d\ ^2D_{3/2}$

[a]Transition originally assigned by—
SK : Sugar and Kaufman (1975, 1976, 1979).
MK : Meijer and Klinkenberg (1973).
Coincident with a line of
*1 OIIIX2
*2 Ta VI
*3 Ta IV
d-doubtful line.
[b]Intensities are visual estimates of photographic blackening

spectrograph used for recording the spectrum employed an aluminium coated grating. Efficiency of the grating declined for wavelengths shorter than 600A. We could, however, prepare a line list for the region 400-2540Å using the standard procedure described by Rahimullah *et al* (1980).

Lines of the spectra Ta II-VIII are expected to be present on the photographic plate and separation of the ionisation stages is always necessary. We used the wellknown technique of introducing extra inductance through copper coils in the discharge circuit to vary the excitation conditions. The capacitance in the circuit was about 0.5 μF and the turns of copper coil used were 0, 2, 4, 5, 10 and 20. A careful study of the intensity variation of individual lines with different inductance values led us to separate the ionization stages involved.

3. Results and discussion

The observed transitions which formed the basis of the present analysis are given in Table 1. Intensity of these transitions are given in column 2 and represent visual estimates of the photographic blackening. Lines of intensity 1 are so weak that they can admit errors upto 0.03Å in their measurement, while the rest of the lines are expected to be good to ± 0.001Å. Lines marked *d* are still fainter and are considered doubtful.

We started our analysis with the skeleton of 15 levels of Ta V established earlier by Meijer and Klinkenberg (1973) and Sugar and Kaufman (1975, 1976, 1979) and found consistent. As the *ns*, *nd* and *ng* Rydberg series had to be

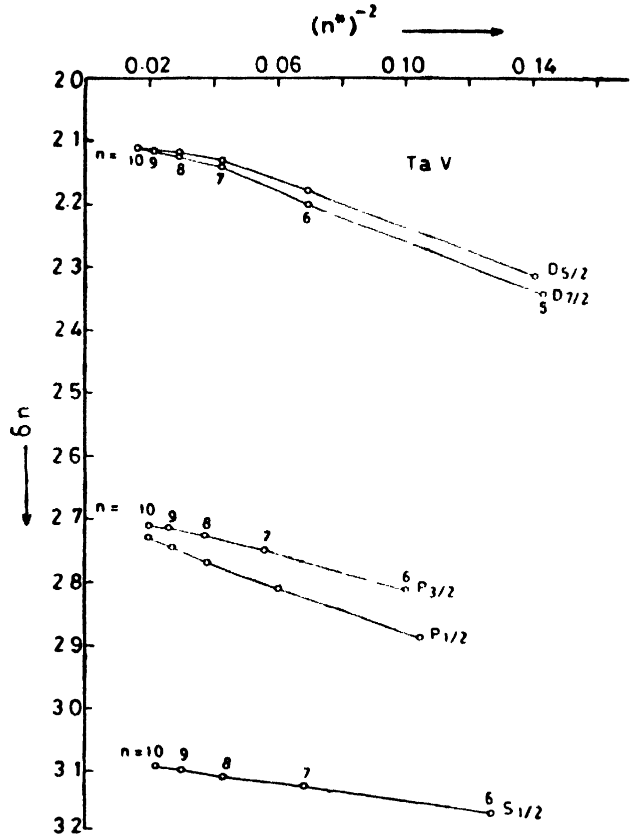

Figure 1(a). Ritz diagram for *S*, *P* and D term series of Ta V. δ_n is quantum defect for *n*, the total quantum number and $n^* = n - \delta_n$. Doublet sign of terms is omitted.

regular, we extrapolated levels along these series to identify transitions involving members upto $n = 10$ (Figures 1a and 1b). We then took up *np* levels with the help of *ns* and *nd*; it also yielded a regular series for $n = 6$-10.

The *nf* levels were then searched with the help of *nd* and *ng*, and it turned out that they constitute perturbed series all through. The intervals for 8*f*, 9*f* and 10*f* are found inverted, and 9f levels depart from the hyperbola relationship which is observed when a series is perturbed by a single term. By using our levels values for (5, 6, 7, 8)*f* we have, however, tried to evaluate position of the perturbing levels to be 323267 cm^{-1} ($J = 5/2$) and 323741 cm^{-1} ($J = 7/2$); these may constitute a ^2F term of the $4f^{13}5d^2$ configuration. The nf series is plotted in Figure 1b on a scale reduced in comparison with 1a.

We evaluated the series limit from our ng level values by the use of the polarization formula of Edlén (1964) ; our value is in good agreement with 389340 ± 100 cm^{-1} evaluated by Sugar and Kaufman (1975). The polarization formula was then

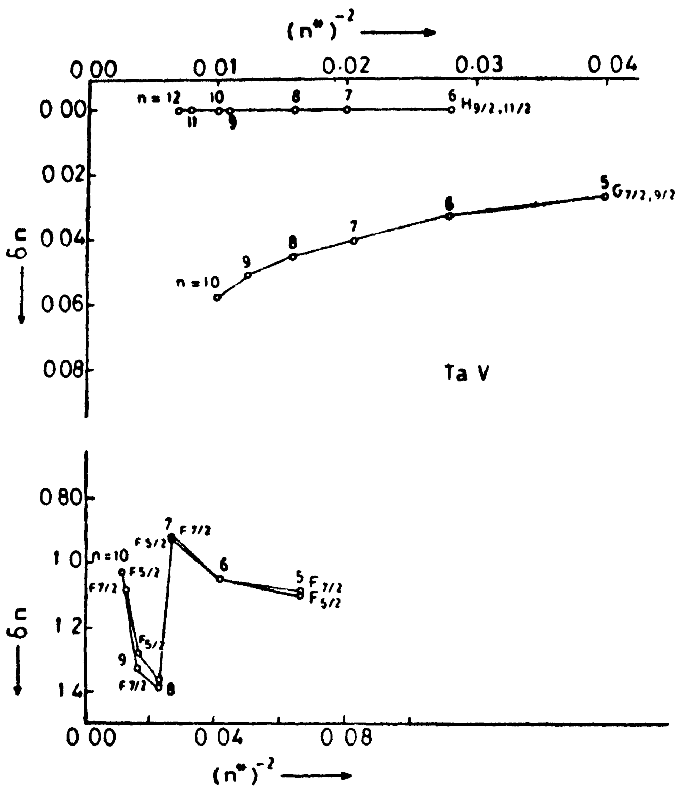

Figure 1(b). Ritz diagram for F, G and H term series of Ta V. δ_n is quantum defect for n, the total quantum number and $n^* = n - \delta_n$. Doublet sign of terms is omitted.

employed to estimate nh terms. Four terms of ni series (n=9-12) are also found through combinations with nh terms in a similar manner. The ng and nh series are plotted on a ten times more sensitive scale of δ_n. The ni series could not be plotted as the quantum defects were almost negligible.

In Table 2, we have listed all the 56 levels of Ta V so far known, including 41 new levels found in the present study. The classification of the 117 spectral lines of Ta V involving these 56 energy levels are given in Table 1. We have plotted all the observed levels and transitions between them on a Grötrian diagram in Figure 2. Wavelengths are not marked as they are tabulated in detail (Table 1).

Table 2. Energy levels of Ta *V*.

Energy (cm^{-1})[a]	Designation	Energy (cm^{-1})[a]	Designation	Energy (cm^{-1})[a]	Designation
47052.2 (MK)	6s $^2S_{1/2}$	272994.3	7d $^2D_{3/2}$	278437.0 (SK)	$^2G_{9/2}$
206544.0 (MK)	7s $^2S_{1/2}$	273666.5	$^2D_{5/2}$	312300.0 (SK)	6g $^2G_{7/2}$
274616.0 (SK)	8s $^2S_{1/2}$	309890.1	8d $^2D_{3/2}$	312296 0 (SK)	$^2G_{9/2}$
310632.65	9s $^2S_{1/2}$	310126.9	$^2D_{5/2}$	332706.9	7g $^2G_{7/2,9/2}$
331848.75	10s $^2S_{1/2}$	331445.95	9d $^2D_{3/2,5/2}$	345990.85	8g $^2G_{7/2,9/2}$
105563.0 (MK)	6p $^2P_{1/2}$	345251.53	10d $^2D_{3/2,5/2}$	355022.1	9g $^2G_{7/2,9/2}$
118862.2 (MK)	$^2P_{3/2}$	209077.0 (MK)	5f $^2F_{5/2}$	361587.6	10g $^2G_{7/2,9/2}$
233055.1	7p $^2P_{1/2}$	209423.0 (MK)	$^2F_{7/2}$	313130.42	6h $^2H_{9/2,11/2}$
237613.6	$^2P_{3/2}$	277215.4	6f $^2F_{5/2}$	333356.5	7h $^2H_{9/2,11/2}$
289137.4	8p $^2P_{1/2}$	277349.2	$^2F_{7/2}$	346480.8	8h $^2H_{9/2,11/2}$
290747.3	$^2P_{3/2}$	314965.3	7f $^2F_{5/2}$	355474.45	9h $^2H_{9/2,11/2}$
319221.05	9p $^2P_{1/2}$	315034.6	$^2F_{7/2}$	361908.0	10h $^2H_{9/2,11/2}$
319905.7	$^2P_{3/2}$	327125.7	8f $^2F_{5/2}$	366672.4	11h $^2H_{9/2,11/2}$
337422.2	10p $^2P_{1/2}$	326640.3	$^2F_{7/2}$	370291.4	12h $^2H_{9/2,11/2}$
337696.8	$^2P_{3/2}$	343315.0	9f $^2F_{5/2}$	355479.12	9i $^2I_{11/2,13/2}$
0.00 (MK)	5d $^2D_{3/2}$	342745.4	$^2F_{7/2}$	361909.02	10i $^2I_{11/2,13/2}$
6612.1 (MK)	$^2D_{5/2}$	355233.1	10f $^2F_{5/2}$	366632.42	11i $^2I_{11/2,13/2}$
199315.0 (MK)	6d $^2D_{3/2}$	354821.5	$^2F_{7/2}$	370295.32	12i $^2I_{11/2,13/2}$
201274.0 (MK)	$^2D_{5/2}$	278442.0 (SK)	5g $^2G_{7/2}$		

[a]Level established by—
MK : Meijer and Klinkenberg (1973) ; SK : Sugar and Kaufman (1975, 1979).

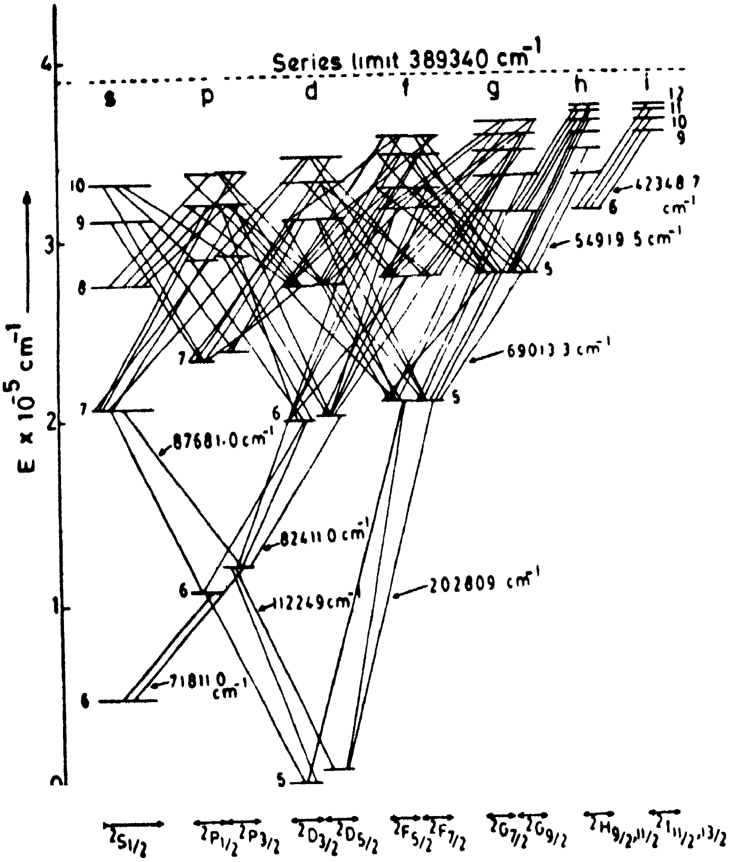

Figure 2. Grötrian diagram for Ta V. Wave numbers are marked for some transitions to illustrated the scale.

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