Nuclear magnetic dipole moment of ^{181}Ta †

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(Received 5 June 1975)

The hyperfine structure of the $6s\,^2S_{1/2}$-$6p\,^2P_{1/2}$ line of Ta V at 1708 Å has been resolved using a 150 A sliding spark discharge. The $6p$-$8s$ multiplet was identified and the ionization energy was redetermined. With these new data a value for the nuclear dipole moment of ^{181}Ta of $(2.36\pm0.02)\mu_N$ is derived. New wavelengths are given for all previously classified lines.

[NUCLEAR MOMENTS Spectrum, tantalum, ionization energy.]

Optical determinations of the nuclear dipole moment μ_I of ^{181}Ta have been made utilizing the hyperfine structure (hfs) of the $5d^36s^5F_1$ level[1] of Ta II and the $5d^46s\,^6D_{1/2}$ and $^6D_{3/2}$ levels[2] of Ta I. In both cases the effects of intermediate coupling and configuration interaction were not included in the calculations. These complications are avoided by determining μ_I from the hfs of a single electron outside of closed shells. This configuration is found in four-times-ionized tantalum (Ta V) and is utilized in the present measurement of μ_I.

An interpretation of the spectrum of Ta V has been given by Meijer and Klinkenberg[3] who reported the $5d$, $5f$, $6s$, $6p$, $6d$, and $7s$ terms. We have recently observed this spectrum in connection with our study[4] of Ta VI and were able to identify the $6p$-$8s$ multiplet. Furthermore, we were able to resolve the $6s\,^2S_{1/2}$-$6p\,^2P_{1/2}$ line into its hyperfine components, which give directly the hfs of these levels. Thus the more accurate determination of the ionization energy from the three-member ns series and the measured splitting of the $6s\,^2S_{1/2}$ level provided the opportunity to make an improved optical determination of μ_I.

OBSERVATIONS

The natural relative abundance of ^{181}Ta is 99.99%. Isotopic structure is therefore absent in the present measurements. We obtained the $6s\,^2S_{1/2}$ - $6p\,^2P_{1/2}$ line at 1708 Å with the sliding spark light source[5,6] operating at a peak current of 150 A. Observations were made with the National Bureau of Standards 10.7-m normal incidence vacuum spectrograph in second order at a plate factor of 0.39 Å/mm. An interfering line of a lower ionization stage occurs in the middle of the hyperfine pattern at this current. It was identified as such by observing the line at 100, 150, and 200 A, the traces of which are shown in Fig. 1. The interfering line appears in trace A with no evidence of the Ta V line, while in trace B both lines appear. Three of the four components of the hfs of the Ta V line are distinguishable in this exposure. In the diagram of the hyperfine transitions appearing below the tracings it can be seen that the splitting of both the upper and lower level may be measured from these three components. Trace C shows the 1708-Å line at 200 A with no evidence of the interfering line. At this current the linewidths have increased, causing the blending of the close components of the hfs. Theoretical intensities of the hyperfine components are given with trace C, with measured spacings as shown in the lower part of the figure. These spacings were obtained by measuring the interval from component a to c and c to d on the exposure from which trace B was made.

Our measurements of the wavelengths of a number of the lines of Ta V differ significantly from those given in Ref. 3, in some cases by as much as 0.04 Å, whereas our wavelength uncertainty is ±0.005 Å. For this reason we give all our measurements in Table I, including the newly observed $6p$-$8s$ multiplet and the partially resolved hfs of the $6s$-$6p$ multiplet. These data were obtained at 200-A peak current, and therefore only the two components of the $6s\,^2S_{1/2}$-$6p\,^2P_{1/2}$ line shown in trace C of Fig. 1 are given. The energy levels of Ta V derived from these new data are contained in Table II. The $5d$, $6s$, and $6p$ level values have uncertainties of ±0.5 cm^{-1} while the remaining level values have uncertainties of less than 2 cm^{-1}. The hfs intervals given for $6s\,^2S_{1/2}$ and $6p\,^2P_{1/2}$ were obtained from the exposure of the 150-A spark.

IONIZATION ENERGY

A value for the ionization energy was derived from the three-member ns series by assuming a linear variation of the quantum defect with term value. A correction to this approximation was ob-

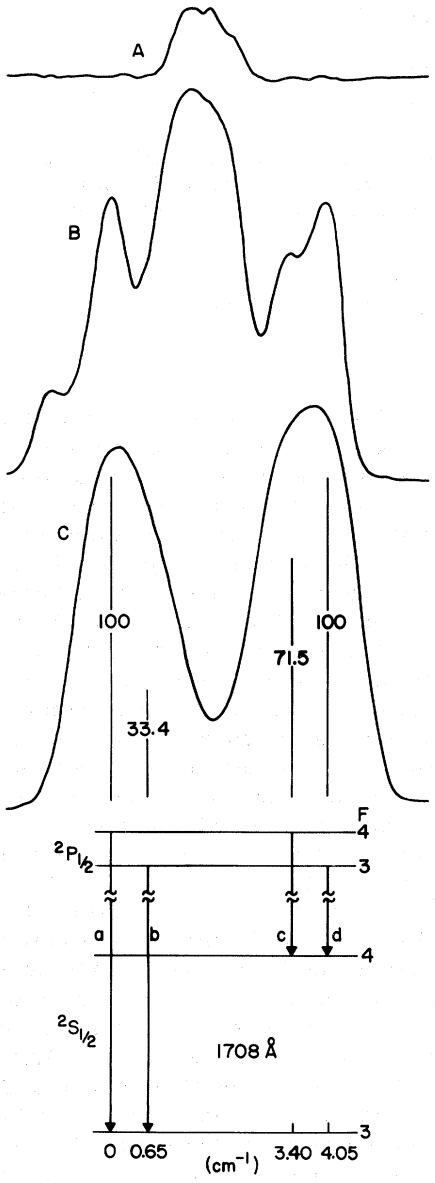

FIG. 1. Traces of 1708-Å line of Ta V at 100 A (trace A), 150 A (trace B), and 200 A (trace C). Trace A shows only the interfering line of lower ionization. In trace B both the interfering line and the Ta V line with resolved hfs appear. In trace C the interfering line is absent and the hfs is partially blended. The measured hfs and a diagram of the transitions are shown.

tained by noting that the limit obtained with a three-member series in Lu III is smaller than that given by the five-member observed series[6] by 140 cm^{-1}. This quantity, increased by the ratio of 6s term values derived for Ta V and Lu III, was added to the 6s term value of Ta V. The resulting ionization energy of Ta V is 389 340 cm^{-1} (48.272 eV) with an estimated uncertainty of ±100 cm^{-1}, approximately one third of the correction to the series limit.

TABLE I. Classified spectral lines of Ta V.

Wavelength (Å)	Int.	Wave number (cm^{-1})	Classification [a]
1709.140 bl [b]	4000	58 509.0	$6s\,^2S_{1/2}(4)-6p\,^2P^0_{1/2}$
1709.035 bl	3000	58 512.6	$6s\,^2S_{1/2}(3)-6p\,^2P^0_{1/2}$
1392.585 bl	3000	71 808.9	$6s\,^2S_{1/2}(4)-6p\,^2P^0_{3/2}$
1392.527 bl	2000	71 811.9	$6s\,^2S_{1/2}(3)-6p\,^2P^0_{3/2}$
1242.980	100	80 451.8	$6p\,^2P^0_{3/2}-6d\,^2D_{3/2}$
1213.423	500	82 411.5	$6p\,^2P^0_{3/2}-6d\,^2D_{5/2}$
1140.490	200	87 681.6	$6p\,^2P^0_{3/2}-7s\,^2S_{1/2}$
1066.642	200	93 752.2	$6p\,^2P^0_{1/2}-6d\,^2D_{3/2}$
990.286	100	100 980.9	$6p\,^2P^0_{1/2}-7s\,^2S_{1/2}$
947.302	500	105 563.0	$5d\,^2D_{3/2}-6p\,^2P^0_{1/2}$
890.868	1000	112 250.1	$5d\,^2D_{5/2}-6p\,^2P^0_{3/2}$
841.310	200	118 862.2	$5d\,^2D_{3/2}-6p\,^2P^0_{3/2}$
642.041	5	155 753	$6p\,^2P^0_{3/2}-8s\,^2S_{1/2}$
591.528	1	169 054	$6p\,^2P^0_{1/2}-8s\,^2S_{1/2}$
493.913	2	202 465	$5d\,^2D_{5/2}-5f\,^2F^0_{5/2}$
493.069	60	202 811	$5d\,^2D_{5/2}-5f\,^2F^0_{7/2}$
478.293	20	209 077	$5d\,^2D_{3/2}-5f\,^2F^0_{5/2}$

[a] The total angular momentum $F=J+I$ is given in parentheses.

[b] The symbol bl indicates a blend of the hyperfine components due to the splitting of the 6p level.

DERIVATION OF μ_I

From the hfs given in Table II, the hyperfine splitting factors of the $6s\,^2S_{1/2}$ levels are found to be[7]

$$a(6s) = 0.850 \pm 0.005 \text{ cm}^{-1},$$

$$a(6p) = 0.162 \pm 0.005 \text{ cm}^{-1}$$

assuming the nuclear spin I is[8] $\frac{7}{2}$. The factor $a(6s)$ is related to μ_I through the Goudsmit-Fermi-Segrè formula[7]

$$a_s = \pi a_0^3 \psi_s^2(0)\,\mu_I F_r (1-\delta)(1-\epsilon)/117.8I,$$

where $\psi_s^2(0)$ is the probability density of the s electron at the nucleus, F_r is the relativistic correction tabulated in Ref. 7, $(1-\delta)$ is the correction for the volume distribution of nuclear charge, and $(1-\epsilon)$ is the correction for the volume distribution of nuclear magnetic moment. The value of $\psi_s^2(0)$ may be obtained from the relationship[7]

$$\pi a_0^3 \psi_s^2(0) = Z Z_a^2 [(dn^*/dn)/n^{*3}],$$

where Z is the atomic number, Z_a is the charge seen by the outer electron (5 in this case), and n^* is the effective principal quantum number of the 6s term. Reference 7 gives

TABLE II. Energy levels of Ta V for configurations $4f^{14}5s^25p^6(^1S_0)nl$.

nl designation	J	F	Level (cm^{-1})	Fine structure interval	hfs interval	n^*
$5d\,^2D$	$\frac{3}{2}$		0.0	6612.1		2.6681
	$\frac{5}{2}$		6612.1			
$6s\,^2S$	$\frac{1}{2}$	3	47 050.5		3.40	2.8311
		4	47 053.9			
$6p\,^2P^0$	$\frac{1}{2}$	3, 4	105 563.0	13 299.2	0.65	3.1590
	$\frac{3}{2}$		118 862.2			
$6d\,^2D$	$\frac{3}{2}$		199 315	1959		3.8114
	$\frac{5}{2}$		201 274			
$7s\,^2S$	$\frac{1}{2}$		206 544			3.8740
$5f\,^2F$	$\frac{5}{2}$		209 077	346		3.9033
	$\frac{7}{2}$		209 423			
$8s\,^2S$	$\frac{1}{2}$		274 616			4.8901

$$dn^*/dn = \frac{n^*/2T}{n^*/2T - d\sigma/dT} .$$

From Lu III we find $d\sigma/dT = 1.11(\Delta\sigma/\Delta T)$ where $\Delta\sigma$ is the difference in quantum defects between the $6s$ and $7s$ terms and ΔT is the difference in term energies.[9] Then using this factor for Ta we obtain

$$(dn^*/dn)/n^{*3} = 0.047\,50 .$$

From formulas given by Wybourne[10] we find

$$(1 - \delta) = 0.9243$$

and

$$(1 - \epsilon) = 0.9682$$

assuming $(r/r_0)_{av} = \frac{4}{5}$ for the nucleus. Thus, with $I = \frac{7}{2}$, we obtain for the nuclear magnetic dipole moment of ^{181}Ta

$$\mu_I = (2.36 \pm 0.02)\mu_N .$$

The uncertainty equals the rms error arising from the uncertainty of 0.02 cm^{-1} in the measurement of the hyperfine splitting and the uncertainty in the $(1 - \epsilon)$ correction according to whether $\frac{3}{5}$ or 1 is chosen[10] for $(r/r_0)_{av}$. Each of these contributes an uncertainty of $0.015\mu_N$ to μ_I. The uncertainty of ± 100 cm^{-1} in the ionization energy has too small an effect on n^* to count among the others.

A comparison of this result with other determinations is given in Table III. Direct measurements of the nuclear gyromagnetic ratio μ_I/I have been made by nuclear magnetic resonance of Ta in potassium tantalate[11] and in a solution[12] of HF and in HNO_3. The optical method is somewhat less accurate than these experiments but it provides an independent determination of μ_I that is relatively insensitive to the nuclear spin. This is shown by the following:

$$a_s = \frac{\Delta E_{6s}(\text{hfs})}{I + \frac{1}{2}} = C\frac{\mu_I}{I}$$

or

$$\mu_I = \frac{1}{C}\Delta E_{6s}(\text{hfs})\frac{I}{I + \frac{1}{2}} .$$

The nuclear magnetic resonance (NMR) method determines μ_I/I, for which the spin must be known in order to evaluate μ_I. The agreement of these results with the NMR data also provides verification of the Goudsmit-Fermi-Segrè formula,[7] used in the optical method, for a very heavy atom where the relativistic correction is large and for an ionization stage greater than has heretofore been utilized.

TABLE III. Values of μ_I for ^{181}Ta derived by various methods.

μ_I (μ_N)	Method	Source
2.36 ± 0.02	Optical	This paper
2.1	Optical	Ref. 1
2.4 ± 0.2	Optical	Ref. 2
2.35 ± 0.01	NMR	Ref. 11
2.361 ± 0.01	NMR	Ref. 12

†Work carried out with the partial support of the U. S. Energy Research and Development Agency.

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