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Investigation of the hyperfine structure of Ta I-lines (III)

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Abstract. By investigating the hyperfine structure of 41 Ta I lines we could determine the magnetic hyperfine interaction constants A and the electric quadrupole interaction constants B of 25 even parity levels and 32 odd parity levels. Additionally, we could classify one line. With 78 dipole allowed transitions which we tried to excite by laser light we obtained neither optogalvanic nor fluorescence signals. Therefore we conclude that some of the Ta I levels, listed in commonly used tables [e.g. Moore, Ch.: Atomic energy levels. Vol. III. Natl. Bur. Stand. (U.S.) Circ. No. 467. Washington, D.C.: U.S. GPO 1949], do not exist.

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1 Introduction

This work is a continuation of earlier hyperfine structure (hfs) investigations of Ta I lines [1–4] done by laser spectroscopy groups at Graz and Hamburg. Hfs constants were also determined by many other authors [5–17]. In this work we report on investigations of lines of the most abundant ^{181}Ta isotope possessing the nuclear spin quantum number I = 7/2. The investigated lines lay in the yellow spectral region from 570 nm up to 610 nm.

2 Experiment

The tantalum atoms were produced by sputtering in a hollow cathode discharge where a mixture of Argon and Neon was used as carrier gas. For details we refer to [2–4]. The experimental setup was the same as used before [4]. Two counterpropagating laser beams made it possible to record Doppler-limited spectra showing Lamb-dips by recording either optogalvanic or laser-induced fluorescence signals. This allowed us to determine the frequency positions of the hyperfine transitions with high accuracy by means of a fit program [18]. In the cases where we could not obtain Lamb-dips we proceeded as follows: taking Gaussian or modified Lorentzian spectral shape functions for the hfs components, the hyperfine spectrum of a fine structure transition was calculated using estimated values of the hyperfine interaction constants involved. This model function was adjusted to the measured hyperfine spectrum by an interactive least squares fitting procedure [19]. The shape parameters, the hyperfine interaction constants and the intensities (of the well resolved) hyperfine components were free parameters of this least squares routine. In this way it was possible to determine the frequency positions of the hyperfine transitions with an accuracy better than 2 MHz in the cases of Lamb-dips and to about 10 MHz when Doppler-limited signals were observed. The Doppler width amounted to about 600 MHz.

3 Results and discussion

By taking into consideration only the selection rules for dipole transitions – change of parity and $\Delta J = 0$ or ± 1 – all possible wavenumber differences (and from these differences all thinkable wavelengths) between all known Ta I levels taken from [20–22] can be calculated from the level energies. The conversion from the wavelength in vacuum to the one in air was done by using the dispersion formula of Peck and Reeder [23] for the refractive index n of air

$$(n-1)\cdot 10^8 = 8060.51 + \frac{2480990}{132.274-\sigma^2} + \frac{17455.7}{39.32957-\sigma^2} \qquad (1)$$

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Table 1. Ta I lines where an excitation was possible. The classifications for these lines were taken from [20] and [21]. The relative intensities (rel. Int) were taken from [25] and [26]. Lines marked with "–" are calculated lines [24] which are neither listed in [25] nor [26]

λ (Å)	Rel. int [26/25]	Transition		Energies (cm^{-1})	
		Upper level	Lower level	Upper level	Lower level
5712.32	–	$5d^3 6s(a\,^5F)7s\ e\,^4F_{5/2}$	$?^o_{7/2}$	44461.60	26960.46
5713.44	–	$?^o_{5/2}$	$5d^4(^3F)6s\ b\,^4F_{5/2}$	41010.07	23512.34
5746.71	23/60	$5d^3 6s(a\,^5F)7s\ e\,^6F_{7/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6F^o_{7/2}$	43982.43	26585.93
5753.97	–	$5d^3 6s(a\,^5F)7s\ e\,^4F_{3/2}$	$5d^2 6s^2(a\,^3P)6p\ z\,^4P^o_{3/2}$	43964.50	26590.03
5755.81[a]	30/40	$?^o_{9/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{11/2}$	43391.71	26022.74
5761.47	–	$5d^4(a\,^5D)6p\ y\,^6F^o_{3/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{1/2}$	39587.81	22235.97
5779.28	–	$5d^3 6s(a\,^5F)7s\ e\,^6F_{11/2}$	$?^o_{9/2}$	47319.57	30021.20
5783.24	–/2	$5d^3 6s(a\,^5F)6p\ z\,^6F^o_{1/2}$	$5d^3 6s^2\,a\,^4P_{3/2}$	23355.41	6068.91
5794.09	–	$?^o_{1/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{1/2}$	39490.14	22235.97
5797.65	–	$?^o_{7/2}$	$5d^4(^3F)6s\ b\,^4F_{5/2}$	40755.90	23512.34
5816.51	25/40	$5d^3 6s(a\,^5F)7s\ e\,^6F_{7/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6D^o_{5/2}$	43982.43	26794.76
5820.82	–	$?^o_{7/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{7/2}$	39936.13	22761.21
5825.09	–	$?^o_{11/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{11/2}$	43185.09	26022.74
5846.31	–	$?^o_{7/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{9/2}$	38253.39	21153.33
5848.83	–	$?^o_{11/2}$	$5d^3 6s^2\,a\,^2G_{9/2}$	27783.0	10690.32
5856.98	–	$?^o_{7/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{9/2}$	40981.79	23912.89
5861.36	–	$5d^3 6s(a\,^3G)6p\ y\,^4G^o_{7/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{5/2}$	38679.05	21622.92
5866.61	15/60	$5d^3 6s(a\,^3H)6p\ z\,^4H^o_{11/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{9/2}$	38194.22	21153.33
5874.81	–	$?^o_{3/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{1/2}$	39253.07	22235.97
5882.30	130/80	$5d^3 6s(a\,^3H)6p\ z\,^4G^o_{11/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{13/2}$	40510.38	23514.86
5895.16	–	$5d^3 6s(a\,^5F)7s\ e\,^6F_{11/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6F^o_{11/2}$	47319.57	30361.22
5904.29	–	$5d^3 6s(a\,^3H)6p\ z\,^4H^o_{13/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{11/2}$	39360.68	22428.56
5910.37	–	$?^o_{7/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{7/2}$	37561.25	20646.54
5912.77	–	$5d^3 6s(a\,^5F)7s\ e\,^6F_{1/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6F^o_{3/2}$	41151.26	24243.42
5925.83	–	$?^o_{9/2}$	$?_{9/2}$	42247.00	25376.41
5925.90	15/20	$5d^3 6s(a\,^5P)6p\ y\,^6D^o_{7/2}$	$5d^3 6s^2\ a\,^2F_{5/2}$	34094.66	17224.47
5944.82	–	$?^o_{9/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{7/2}$	43391.71	26575.02
5960.13	18/7	$5d^3 6s(a\,^3G)6p\ y\,^4G^o_{9/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{9/2}$	40686.42	23912.89
5973.28	–	$?_{5/2}$	$?^o_{3/2}$	48290.45	31553.89
5990.12	–	$?_{5/2}$	$?^o_{7/2}$	48290.45	31600.95
5993.18	–	$5d^3 6s(a\,^5F)7s\ e\,^4F_{5/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6D^o_{7/2}$	44461.60	27780.62
6003.81	–	$?^o_{3/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{5/2}$	41197.67	24546.20
6009.89	25/40	$5d^3 6s(a\,^5F)7s\ e\,^6F_{1/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6D^o_{1/2}$	41151.26	24516.69
6059.33	–/2	$?^o_{5/2}$	$5d^4(b\,^3H)6s\ a\,^4H_{7/2}$	37145.43	20646.54
6089.97	–	$?^o_{9/2}$	$5d^3 6s^2\ a\,^2H_{11/2}$	31530.02	15114.14
6092.07	–/30	$?^o_{3/2}$	$?_{3/2}$	39253.07	22842.84

[a] Classification given in [26] is not correct

Table 2. Ta I lines where an excitation was not possible and which could not be observed as fluorescence lines

λ (Å)	Transition		Energies (cm^{-1})	
	Upper level	Lower level	Upper level	Lower level
5703.68	$?^o_{7/2}$	$?_{5/2}$	42751.72	[a]25224.06
5704.36	$?^o_{7/2}$	$?_{5/2}$	44693.40	[a]27167.82
5705.69	$5d^4(a\,^5D)6p\ y\,^4P^o_{3/2}$	$?_{5/2}$	44689.31	[a]27167.82
5710.80	$?_{9/2}$	$?^o_{9/2}$	[a]52723.73	35217.94
5711.23	$?^o_{5/2}$	$?_{3/2}$	42982.8	[a]25478.30
5712.12	$?^o_{7/2}$	$?_{5/2}$	39936.13	[a]22434.37
5712.23	$?^o_{7/2}$	$?_{5/2}$	44669.23	[a]27167.82
5719.21	$?^o_{3/2}$	$?_{1/2}$	42178.76	[a]24698.70
5727.69	$?^o_{3/2}$	$?_{5/2}$	38545.70	[a]21091.53
5732.54	$5d^3 6s(a\,^5F)7s\ e\,^4F_{9/2}$	$?^o_{11/2}$	[a]50509.7	33070.28
5734.77	$?^o_{3/2}$	$5d^3 6s(a\,^5F)7s\ e\,^6F_{1/2}$	[a]58583.88	41151.26
5740.05	$?^o_{7/2}$	$5d^3 6s^2\ a\,^2F_{7/2}$	34799.71	[a]17383.12
5743.87	$?_{1/2}$	$?^o_{1/2}$	[a]61551.17	44146.16
5751.58	$?_{3/2}$	$?^o_{5/2}$	[a]58391.76	41010.07

Table 2. (Continued)

λ (Å)	Transition		Energies (cm^{-1})	
	Upper level	Lower level	Upper level	Lower level
5755.07	$?_{5/2}$	$5d^3 6s(a\,^3G)6p\ y\,^4G^o_{7/2}$	[a]56050.2	38679.05
5755.79	$5d^3 6s(a\,^3H)6p\ z\,^4G^o_{11/2}$	$?_{11/2}$	40510.38	[a]23141.4
5756.63	$?^o_{5/2}$	$?_{3/2}$	42844.73	[a]25478.30
5759.94	$5d^3 6s(a\,^3G)6p\ y\,^4F^o_{5/2}$	$?_{5/2}$	38447.99	[a]21091.53
5761.37	$?^o_{5/2}$	$?_{5/2}$	39786.52	[a]22434.37
5761.88	$?_{5/2}$	$?^o_{5/2}$	[a]61737.0	44386.40
5764.19	$?^o_{7/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{9/2}$	[a]41256.56	23912.89
5773.35	$?^o_{3/2}$	$?_{5/2}$	44483.96	[a]27167.82
5778.60	$?^o_{3/2}$	$?_{3/2}$	42778.70	[a]25478.30
5779.92	$?_{5/2}$	$?^o_{5/2}$	[a]56050.2	38753.75
5780.42	$5d^3 6s(a\,^5F)8s\ f\,^4F_{3/2}$	$?^o_{5/2}$	[a]54440.57	37145.60
5782.16	$?_{9/2}$	$5d^3 6s(a\,^3H)6p\ z\,^4I^o_{9/2}$	[a]55232.59	37942.84
5793.24	$?^o_{7/2}$	$?_{5/2}$	32132.38	[a]14875.70
5803.49	$5d^3 6s(a\,^5F)7s\ e\,^4F_{7/2}$	$?^o_{7/2}$	[a]47817.16	30590.95
5803.54	$?_{9/2}$	$?^o_{9/2}$	[a]52723.73	35497.65
5806.06	$?^o_{5/2}$	$?_{5/2}$	44386.40	[a]27167.82
5810.01	$?^o_{7/2}$	$?_{5/2}$	39641.24	[a]22434.37
5810.91	$?^o_{1/2}$	$?_{1/2}$	41902.92	[a]24698.70
5812.00	$?_{1/2}$	$?^o_{3/2}$	[a]61551.17	44350.19
5817.71	$?^o_{3/2}$	$?_{5/2}$	42408.16	25224.06
5818.30	$?^o_{3/2}$	$?_{5/2}$	44350.19	[a]27167.82
5829.40	$?^o_{7/2}$	$5d^3 6s^2\ a\,^2D_{5/2}$	[a]30015.61	12865.97
5851.21	$5d^3 6s(a\,^5P)6p\ z\,^6P^o_{5/2}$	$?_{5/2}$	31961.42	[a]14875.70
5857.37	$?_{5/2}$	$?^o_{7/2}$	[a]61737.0	44669.23
5857.56	$?_{1/2}$	$?^o_{3/2}$	[a]61551.17	44483.96
5858.02	$?^o_{5/2}$	$5d^5\ a\,^6S_{5/2}$	28862.01	[a]11796.14
5869.30	$?_{1/2}$	$5d^4(a\,^5D)6p\ x\,^6D^o_{1/2}$	[a]61551.17	44518.10
5876.38	$5d^3 6s(a\,^5F)7s\ e\,^4F_{9/2}$	$?^o_{9/2}$	[a]50509.7	33497.15
5881.51	$?^o_{7/2}$	$?_{5/2}$	44165.58	[a]27167.82
5882.81	$?^o_{3/2}$	$?_{1/2}$	41692.64	[a]24698.70
5884.51	$?^o_{3/2}$	$5d^3 6s(a\,^5F)7s\ e\,^6F_{3/2}$	[a]58583.88	41594.83
5887.95	$5d^3 6s(a\,^5F)8s\ f\,^4F_{3/2}$	$?^o_{1/2}$	[a]54440.57	37461.46
5588.49	$?_{9/2}$	$?^o_{7/2}$	[a]52723.73	35746.18
5896.43	$?^o_{3/2}$	$?_{5/2}$	42178.76	[a]25224.06
5905.08	$?^o_{3/2}$	$?_{3/2}$	42408.16	[a]25478.30
5908.58	$?_{5/2}$	$?^o_{7/2}$	[a]54481.09	37561.25
5909.56	$5d^3 6s(a\,^5F)8s\ f\,^4F_{3/2}$	$?^o_{3/2}$	[a]54440.57	37523.54
5912.96	$?_{9/2}$	$5d^3 6s(a\,^5F)6p\ z\,^6F^o_{7/2}$	[a]43493.24	26585.93
5917.91	$?^o_{3/2}$	$5d^5\ a\,^6S_{5/2}$	28689.31	[a]11796.14
5928.89	$?_{1/2}$	$5d^4(a\,^5D)6p\ y\,^4P^o_{3/2}$	[a]61551.17	44689.31
5931.34	$?^o_{7/2}$	$?_{9/2}$	43533.3	[a]26678.4
5947.02	$5d^3 6s(a\,^5F)8s\ f\,^4F_{3/2}$	$?^o_{5/2}$	[a]54440.57	37630.09
5951.74	$?_{5/2}$	$?^o_{3/2}$	[a]56050.2	39253.07
5952.89	$?^o_{7/2}$	$?_{5/2}$	42017.95	[a]25224.06
5960.89	$?^o_{11/2}$	$?_{11/2}$	45057.34	[a]28285.99
5962.97	$?^o_{7/2}$	$5d^4(b\,^3G)6s\ a\,^4G_{7/2}$	[a]39526.7	22761.21
5977.32	$?^o_{7/2}$	$?_{5/2}$	31600.95	[a]14875.70
5981.70	$?^o_{5/2}$	$?_{5/2}$	43880.84	[a]27167.82
5982.65	$?^o_{7/2}$	$5d^4(a\,^5D)6s\ a\,^4D_{5/2}$	[a]41256.56	24546.20
5986.19	$?^o_{3/2}$	$?_{3/2}$	42178.76	[a]25478.30
5993.57	$5d^3 6s(a\,^5F)8s\ f\,^4F_{3/2}$	$?^o_{3/2}$	[a]54440.57	37760.67
6002.47	$?^o_{5/2}$	$?_{5/2}$	41879.23	[a]25224.06
6004.04	$?^o_{3/2}$	$?_{5/2}$	43818.63	[a]27167.82
6039.76	$?^o_{5/2}$	$?_{5/2}$	31428.05	[a]14875.70
6044.79	$?^o_{5/2}$	$?_{5/2}$	37630.09	[a]21091.53
6046.91	$?_{9/2}$	$?^o_{7/2}$	[a]43493.24	26960.46
6050.30	$?_{5/2}$	$?^o_{7/2}$	[a]56050.2	39526.7
6051.35	$5d^4(a\,^5D)6p\ y\,^6F^o_{9/2}$	$?_{11/2}$	44806.64	[a]28285.99

(Table 2 continued on the next page)

Table 2. (Continued)

λ (Å)	Transition		Energies (cm^{-1})	
	Upper level	Lower level	Upper level	Lower level
6065.83	$?^o_{1/2}$	$?_{1/2}$	41179.9	ᵃ24698.70
6070.06	$?^o_{7/2}$	$?_{5/2}$	37561.25	ᵃ21091.53
6086.73	$?^o_{1/2}$	$?_{3/2}$	41902.92	ᵃ25478.30
6095.52	$?^o_{5/2}$	$?_{3/2}$	41879.23	ᵃ25478.30
6099.92	$5d^3 6s(a\,^5F)7s\; e\,^4F_{7/2}$	$?^o_{5/2}$	ᵃ47817.16	31428.05
6100.90	$?^o_{7/2}$	$5d^5\; a\,^6S_{7/2}$	28182.60	ᵃ11796.14

ᵃ Marks levels to which combinations have not been observed

Table 3. Supposed fortuitous (really non existing) Ta I levels

Level	Energy (cm^{-1})
Even parity	
$5d^5\; a\,^6S_{5/2}$	11796.14
$?_{5/2}$	14875.70?
$?_{5/2}$	21091.53
$?_{1/2}$	24698.70
$?_{5/2}$	25224.06
$?_{3/2}$	25478.30
$?_{5/2}$	27167.82
$?_{11/2}$	28285.99
$?_{9/2}$	43493.24?
$5d^3 6s(a\,^5F)7s\; e\,^4F_{7/2}$	47817.16
$5d^3 6s(a\,^5F)7s\; e\,^4F_{9/2}$	50509.7
$?_{9/2}$	52723.73
$5d^3 6s(a\,^5F)8s\; f\,^4F_{3/2}$	54440.57
$?_{5/2}$	56050.2
$?_{1/2}$	61551.17
$?_{5/2}$	61737.0
Odd parity	
$?^o_{7/2}$	39526.7
$?^o_{7/2}$	41256.56
$?^o_{7/2}$	44669.23
$?^o_{3/2}$	58583.88

where the real number σ means the vacuum wave number of the transition, expressed in μm^{-1}.

In this work we tried to investigate a large number of these calculated lines [24] although many of them could be found neither in the MIT wavelength tables [25] nor in the NBS tables [26]. Table 1 shows all lines where the excitation was successful and the hyperfine structure could be determined. Lines for which no signals could be detected are compiled in Table 2. It turns out that a certain subset of the combining levels appearing in this table does not show any matching combination in the spectral region from 2000 Å to 10000 Å in the wavelength tables [25, 26]. These levels are listed in Table 3. We think that they are doubtful, perhaps introduced during the early classification work as fortuitous coincidences.

By evaluating the hyperfine structure of the 36 Ta I lines listed in Table 1 we could determine the hfs constants of 23 even parity levels and 31 odd parity levels. These A- and B-factors are listed in Tables 4 and 5.

Besides these lines we investigated the hyperfine structure of the line $\lambda = 6059.333$ Å which is listed in the MIT [25] table but for which no classification is given in [22, 23]. This line has been investigated both by optogalvanic detection and laser induced fluorescence spectroscopy. Wavelengths, energy levels, classification and the fluorescence lines used for detection are listed in Table 6. From the observed hfs spectra we have calculated A and B assuming plausible J-values for this line. The obtained hyperfine structure constants A and B were compared with a collection of hfs constants known from earlier measurements [2–18]. We could find three matching transitions among our calculated transition wavelengths [24]. Therefore a double blend situation occurred. The agreement of the observed A- and B-values with values determined earlier for the levels coming into consideration made it possible to classify this line beyond all doubt.

4 Conclusion

Although the hyperfine structure constants of many levels are measured by now only for a limited number of multiplets the A- and B-factors are known completely. As mentioned in a former paper [3], isotopic shifts between ^{181}Ta and ^{180}Ta can not be explained with the electron configurations given in the tables of Moore [22]. Therefore we think that some of these configuration assignments are partially incomplete. Moreover, the list of levels is not complete, but contains on the other hand some levels which probably are not existent. A theoretical analysis on the basis of a parametrisation using experimental energy levels with the aim to calculate wave functions in intermediate coupling has to fail if not existing levels are introduced into such calculations. With the help of our results and more information [36] recently a fine structure analysis [37] could be performed for even parity levels of the configurations $(d+s)^5$, showing that only half of all existing tantalum levels of this configuration are identified till now. Therefore further spectroscopic investigations are needed to complete the knowledge of the Ta I level structure.

Table 4. A- and B-constants of measured levels with even parity and comparison with other authors

Config. desig.	Energy (cm^{-1})	A (MHz)		B (MHz)		Ref.
$5d^3 6s^2\ a\,^4P_{3/2}$	6068.91	379	±2	−1350	±20	This work (DL)
		379.27	±0.09	−1348.7	±0.6	[14]
		378.7	±0.3	−1351	±2	[11]
		379.0	±0.3	−1349	±2	[17]
		376	±3	−1370	±26	[10]
		372		−1411		[5]
		374.4		−1406		[6]
$5d^3 6s^2\ a\,^2G_{9/2}$	10690.32	327	±1	2138	±10	This work
		333.6	±2.5	2255	±182	[13]
		326.7	±1.2	2146	±25	[2]
$5d^3 6s^2\ a\,^2H_{11/2}$	15114.14	289	±1	4410	±10	This work
		289	±4	4411	±151	[13]
		289	±2	4410	±50	[4]
$5d^3 6s^2\ a\,^2F_{5/2}$	17224.47	368	±2	1940	±20	This work (DL)
		379.5	±4.3	2002	±91	[13]
		368.4	±1	1939	±20	[2]
$5d^4(b\,^3H)6s\ a\,^4H_{7/2}$	20646.54	−399	±1	1533	±5	This work
		−299.4	±0.5	1534.7	±2	[2]
		−399.2	±0.1	1515.6	±4.2	[30]
		−400.40	±0.44	1546	±17	[31]
$5d^4(b\,^3H)6s\ a\,^4H_{9/2}$	21153.33	731.5	±1	1275	±10	This work
		731.5	±5	1271	±100	[2]
		734.5	±0.7	1496	±53	[29]
		731.7	±1.6	1424	±31	[31]
$5d^4(b\,^3H)6s\ a\,^4H_{11/2}$	22428.56	836	±2	1862	±15	This work
		829	±12	1817	±150	[2]
		836	±2	1868	±60	[4]
		832.8	±0.2	1878.6	±2.8	[30]
		834.4	±1.4	1823	±54	[31]
$5d^4(b\,^3H)6s\ a\,^4H_{13/2}$	23514.86	963	±1	1729	±25	This work
		963.8	±3	1727	±140	[2]
		965.1	±2.1	1719	±49	[29]
$5d^4(a\,^5D)6s\ a\,^4D_{1/2}$	22235.97	3993	±1	0		This work
		3995	±2	0		[4]
$5d^4(a\,^5D)6s\ a\,^4D_{5/2}$	24546.20	274	±1	−837	±10	This work
		269.2	±0.2	−827	±3	[27]
		272.2	±1.6	−876.9	±20.5	[28]
		272.6	±0.3	−867.5	±2.4	[29]
$5d^4(a\,^5D)6s\ a\,^4D_{7/2}$	26575.02	1408	±2	514	±20	This work
		1402.4	±1.3	498	±21	[29]
$5d^4(b\,^3G)6s\ a\,^4G_{5/2}$	21622.92	−478.3	±0.2	788	±20	This work
		−478.5	±0.1	782.4	±1.2	[27]
		−478.1	±0.1	770.0	±2.8	[28]
		−478.92	±0.03	779.8	±0.5	[31]
$5d^4(b\,^3G)6s\ a\,^4G_{7/2}$	22761.21	346	±2	−125	±20	This work
		338	±6	−36	±70	[4]
		377.1	±15	−88	±266	[29]
		347.47	±0.76	−151	±15	[32]
$5d^4(b\,^3G)6s\ a\,^4G_{9/2}$	23912.89	814	±1	−624	±10	This work
		814.0	±1.8	−625	±4	[1]
		811.1	±0.5	−610	±12	[29]
$5d^4(b\,^3)6s\ a\,^4G_{11/2}$	26022.74	844	±2	−1257	±10	This work
$?_{3/2}$	22842.84	−293	±1	−537	±10	This work
		−293.4	±0.2	−532.1	±1.1	[30]
		−290.3	±1.3	−542.5	±61	[32]

(Table 4 continued on the next page)

Table 4. (Continued)

Config. desig.	Energy (cm^{-1})	A (MHz)		B (MHz)		Ref.
$5d^4(^3F)6s\ b\,^4F_{5/2}$	23512.34	−411	±1	−609	±10	This work
$?_{9/2}$	25376.41	984	±1	−767	±10	This work
		983	±0.1	−960	±22	[30]
		984.1	±1.2	−800	±24	[33]
		983.7	±1.1	−779	±26	[34]
$5d^36s(a\,^5F)7s\ e\,^6F_{1/2}$	41151.26	−3515.5	±1	0		This work
		−3514.7	±1.5	0		[13]
$5d^36s(a\,^5F)7s\ e\,^6F_{7/2}$	43982.43	1425	±1	−571	±20	This work
		1453.0	±5.4	−637	±59	[13]
$5d^36s(a\,^5F)7s\ e\,^6F_{11/2}$	47319.57	1413.5	±1	−1295	±10	This work
		1415.4	±2.3	−1281	±12	[34]
$5d^36s(a\,^5F)7s\ e\,^4F_{5/2}$	44461.60	884	±1	600	±10	This work
$?_{5/2}$	48290.45	−828	±1	−666	±10	This work

DL, Doppler-limited data evaluation

Table 5. A- and B-constants of measured levels with odd parity and comparison with other authors

Config. desig.	Energy (cm^{-1})	A (MHz)		B (MHz)		Ref.
$5d^36s(^5F)6p\ z\,^6F^0_{1/2}$	23355.41	−1785	±2	0		This work (DL)
		−1784	±2	0		[10]
		−1822		0		[5]
		−1786.5	±6	0		[2]
$5d^36s(a\,^5F)6p\ z\,^6F^0_{3/2}$	24243.42	−594.5	±1	−279	±5	This work
		594	±6	−278	±5	[3]
		593	±2	−279	±24	[4]
$5d^36s(a\,^5F)6p\ z\,^6D^0_{1/2}$	24516.69	4154	±1	0		This work
		4155	±0.1	0		[3]
		4138	±16	0		[13]
		4147		0		[5]
		4132		0		[6]
$5d^36s(a\,^5F)6p\ z\,^6F^0_{7/2}$	26585.93	1014	±1	106	±10	This work
		1014.6	±0.8	116	±15	[2]
		1023	±10	−108	±140	[13]
$5d^26s^2(a\,^3P)6p\ z\,^4P^0_{3/2}$	26590.03	1445.5	±2	227	±10	This work (DL)
		1445.7	±0.8	231	±1	[2]
		1447.4	±11.1	233	±55	[13]
$5d^36s(a\,^5F)6p\ z\,^6D^0_{5/2}$	26794.76	1035	±1	705	±15	This work
		1035	±2	691	±33	[15]
		1034.4	±1	712	±15	[2]
		1035.7	±0.4	711.8	±1.2	[17]
		1036	±2	719	±12	[16]
$?^0_{11/2}$	27783.0	1041.5	±1	−447	±20	This work
		1042	±1	−427	±18	[17]
$?^0_{9/2}$	30021.20	439	±1	20	±10	This work
		439	±2	56	±26	[16]
		445	±5	34	±71	[13]
$5d^36s(a\,^5F)6p\ z\,^6F^0_{11/2}$	30361.22	671	±1	569	±10	This work
		671.4	±0.8	571	±5	[2]
		673	±4	489	±64	[13]
$?^0_{9/2}$	31530.02	815	±2	1045	±20	This work
$?^0_{3/2}$	31553.89	198.5	±2	−760	±20	This work
$?^0_{7/2}$	31600.95	338	±2	1426	±20	This work
		338	±2	1431	±40	[4]

Table 5. (Continued)

Config. desig.	Energy (cm^{-1})	A (MHz)		B (MHz)		Ref.
$5d^3 6s(a\,^5P)6p\; y\,^6D^o_{7/2}$	34094.66	1338	±2	583	±20	This work (DL)
$5d^3 6s(a\,^3H)6p\; z\,^4H^o_{11/2}$	38194.22	860	±1	2351	±10	This work
$?^o_{5/2}$	37145.60	1474	±1	−752	±10	This work
$?^o_{7/2}$	37561.25	569	±2	220	±20	This work
$?^o_{7/2}$	38253.39	374	±2	725	±15	This work
$5d^3 6s(a\,^3G)6p\; y\,^4G^o_{7/2}$	38679.05	500.5	±2	−63	±20	This work
		502.87	±0.27	−136.5	±14.2	[31]
		501.1	±0.2	−120	±3	[27]
		502.1	±0.2	−119	±47	[34]
$?^o_{3/2}$	39253.07	453	±1	435	±10	This work
$5d^3 6s(a\,^3H)6p\; z\,^4H^o_{13/2}$	39360.68	1095	±2	2071	±20	This work
		1085	±4	2277	±198	[13]
		1090.9	±3	2184	±170	[2]
$?^o_{1/2}$	39490.14	1394	±1	0		This work
$5d^4(a\,^5D)6p\; y\,^6F^o_{3/2}$	39587.81	425.5	±1	−18	±20	This work
$?^o_{7/2}$	39936.13	1182	±1	185	±20	This work
$5d^3 6s(a\,^3H)6p\; z\,^4G^o_{11/2}$	40510.38	934	±2	857	±50	This work
		933.3	±2	932	±80	[2]
$5d^3 6s(a\,^3G)6p\; y\,^4G^o_{9/2}$	40686.42	584	±1	−922	±20	This work
$?^o_{7/2}$	40755.90	656	±2	−316	±20	This work
$?^o_{7/2}$	40981.79	962	±2	1101	±20	This work
$?^o_{5/2}$	41010.07	35	±2	1003	±20	This work
$?^o_{3/2}$	41197.67	−588	±2	214	±20	This work
$?^o_{9/2}$	42247.00	1033	±1	1926	±20	This work
		1030.4	±0.9	1962	±26	[29]
$?^o_{11/2}$	43185.09	192	±1	1959	±20	This work
		202	±2	1663	±40	[4]
$?^o_{9/2}$	43391.71	1130	±1	−501	±20	This work

DL, Doppler-limited data evaluation

Table 6. New-classified line, energy levels and observed fluorescence lines

λ (Å)	Rel. int. [26/25]	Transition		Energy (cm^{-1})		λ_F (Å)	Energy (cm^{-1})	
		Upper level	Lower level	Upper level	Lower level		Upper level	Lower level
6059.333	−/2	$?^o_{5/2}$	$5d^4(b\,^3H)6s\; a\,^4H_{7/2}$	37145.60	20646.54	2845.45	37145.60	2010.10
						2691.31	37145.60	0.00

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