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OPTICAL ANALYSIS OF THE HYPERFINE STRUCTURE OF Co^{59} IN THE REGION 4000-4300Å

by

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ABSTRACT

The hyperfine structure of several lines of the spectrum of Cobalt between 4000 and 4300Å has been analyzed using techniques of high resolution spectroscopy. As a result, the value of the magnetic hyperfine structure constant for 32 states has been found. The classification for four of the lines has also been inferred from the observed hyperfine structure patterns.

(*) *Part of this work has been done while the author was at the Physics Department of the University of California at Berkeley.*

1 - INTRODUCTION

In atoms with nuclear spin, I, different from zero, the fine structure energy levels suffer in general a splitting due to the hyperfine interaction between the nucleus and the electrons. The energy of the hyperfine structure (hfs) multiplets is given by (see for instance Kopfermann[1]).

$$W_F = W_J + \frac{1}{2} AK + B \frac{3/4\ K(K+1) - J(J+1)\ I\ (I+1)}{2I\ (2I-1)\ J\ (2J-1)} \qquad (1)$$

where W_J is the energy of the fine structure level, A and B are respectively the *magnetic-dipole* and the *electric-quadrupole hyperfine interaction constants*, and K is defined as:

$$K = F\ (F+1) - J\ (J+1) - I(I+1)$$

being F the quantum number associated with the total angular moment of the atom, namely:

$$F = I + J;\ I + J - 1; \ldots;\ |I - J|$$

The selection rules which govern hyperfine transitions are

$$\Delta F = 0; \pm 1 \qquad F = 0 \not\leftrightarrow F = 0$$

Optical determination of the constants A and B through the analysis of the splitting of the spectral lines requires the use of high resolution techniques. Although these techniques do not offer the same accuracy as other non-optical methods, they have the advantage of allowing the study of the ground state as well as any other higher terms.

2 - EXPERIMENTAL ARRANGEMENT

The light source used in this experience is a liquid-nitrogen-cooled hollow cathode similar to that described by Reader and Davis[2] with the cathode machined in aluminium and internaly covered by a few millimeter thick cobalt wall (see Figure 1). Argon was used as the carrier gas. The electric current varied within the range 30-70 mA, according to the intensity of the lines under observation.

The optical system is shown in Figure 2. It consists of a Czerny-Turner mounting spectrograph of 3m of focal length crossed with a Fabry-Perot interferometer. The spectrograph is the same as that described by Reader[3]. The grating has 300 grooves per millimeter and is blazed at 64^{o}. The spectrograph resolution is better than 300,000. In this experiment the grating was used at near the blaze angle which correspondes to the 14th and 15th diffraction order for the observed wavelength range.

The Fabry-Perot plates are of quartz covered by seven layers of Sb_2O_3 and Cryolite, with a reflection power of about 85% for the region of interest. Spacers of 5, 10 and 20 mm were used. A predisperser system, placed between the source and the interferometer, prevents the overlapping of different diffraction orders.

The spectrograph was used with a slit aperture of about 100 microns. Exposure times varied between 1 and 90 minutes according to the intensity of the lines. During these intervals the variation of the room temperature was not greater than 0.1^{o}C. The interferograms were recorded on Kodak 103-a-0 plates. The line spectrum was also reproduced for each region by removing the interferometer. Using slit apertures of about 20 microns reasonable narrow lines were obtained and those with wider hyperfine structure were also resolved in these spectrograms. The comparison source was an electrodeless thorium lamp.

3 - ANALYSIS OF INTERFEROGRAMS AND RESULTS

In general just the most intense hfs components were distinctly observed in the interferograms obtained in this experiment and only in a few cases the line was completely resolved. The ring diameters of the interferometer patterns were measured with a Grant automatic comparator and the wavenumber intervals were found by the method given by Meissner[4]. For most of the lines several interferograms were obtained for different spacers, currents and exposure times. A good agreement among them was sistematically found. Line spectrograms were also measured in order to determine the absolute wavelength of the line. Thorium standard wavelengths were taken from Giachetti, Stanley and Zalubas[5] and the interpolation was done by using previously existing programs given by Phillips[6] and Conway[7].

Table I summarizes the main features of 68 of the observed lines. In the first three columns are given the approximate wavelength for each line, the value of the wavelength as reported by Russell, King and Moore[8], and the intensity and temperature classes found in that paper. The fourth column gives the wavelength of the center of gravity for some of the lines as determined in the present work. The good agreement between these values and the interferometric measurements done by Burns and cited by Russell et al[8] (indicated by the subscript 4 in the third column) should be noted. In the fifth column the structure of the lines is described. The positions of the hfs components (mÅ) are referred to the approximate center of gravity of each line. The relative intensity of the components (0-10), given by the number in brackets, is just an eye appreciation. For completely unresolved lines only the approximate hfs width is given. For some of the lines (indicated by an asterisc) no interferograms were obtained. The intervals given for them have to be considered as poor experimental results. One of the lines, λ4033, is not found in earlier references. From the present analysis it seems likely to be a Cobalt line. The wavelength as derived from its proposed classification (see Table III) as well as the expected splitting are in agreement with the observed values.

In Table II the values obtained for the hfs coupling constant, A, are listed. The first and second columns give, respectively, the designation and energy of each term according to Moore[9]. The third column shows the values for A resulting from this experiment, while in the fourth these values are compared to those measured by Rasmussen[10] and Oertel[11]. In general, the contribution of the last term in equation (1) was negligible and only the determination of the magnetic constant was possible. The analysis done for each level depends on whether the hfs of the other level in the transition is already known or not from previous experiments. The hfs of the terms $3d^7\ 4s^2\ {}^4F_{9/2,7/2,5/2,3/2}$ and $3d^8\ ({}^3F)\ 4s\ \ {}^4F_{9/2,7/2,5/2}$ has been very accurately analysed through the atomic beam magnetic-resonance technique by Childs and Goodman[12]. The values for A and B given by these authors were assumed here exempt from errors, so that from the splitting of the lines that occur as transitions to these levels, the hfs of the other level involved in the transistion was immediately found. There is a second set of lines for which the hfs of one of the levels is given by Rasmussen[10] or Oertel[11], with an experimental error comparable to ours. In these cases those values were taken as starting points for a new determination. Finally, for those lines occurring from transition between levels not analyzed in the above references, the hfs of each level was figured out from the observed pattern of the line.

Table III gives the proposed classification for four of the observed lines. The lines λ4109, λ4090 and λ4019 are reported in Ref. 8 with two possible alternative classifications. However, the hfs shown by them has suggested the present choice. The line λ4033, as mentioned above, is not found in previous papers. The observed hfs pattern of this line, as well as the measured wavelength and intensity, have led to propose the classification a $\ {}^4F_{3/2}$ - Z $\ {}^4F_{3/2}$, given here.

4 - DISCUSSION

The sensivity and accuracy obtained in this as well as in other similar experiments (see for instance Ref. 2), suggest the advantages of using high resolution spectroscopy techniques for the study of the hfs for exited states of the atom. Furthermore, a wealth of information about the spectrum of Cobalt could be obtained if the present analysis were extended to a wider wavelength range.

On the other hand, besides the direct spectroscopic information obtained by the study of the hfs, and the possibility to infer from it the value of nuclear parameters (for references on nuclear spin, nuclear magnetic-dipole and nuclear electric-quadrupole moments for ^{59}Co, see i.e., Ramsey[13] and Childs and Goodman[12]) one has with it a powerful way to check theoretical calculations and improve them by using a semiempirical approach (see, for instance, Rosén[14] for a study about the relativistic effects in the magnetic hfs of the $3d^n4s^2$ atoms, and Bauche-Arnoult[15] for considerations about the effect of configuration interaction on atomic hfs).

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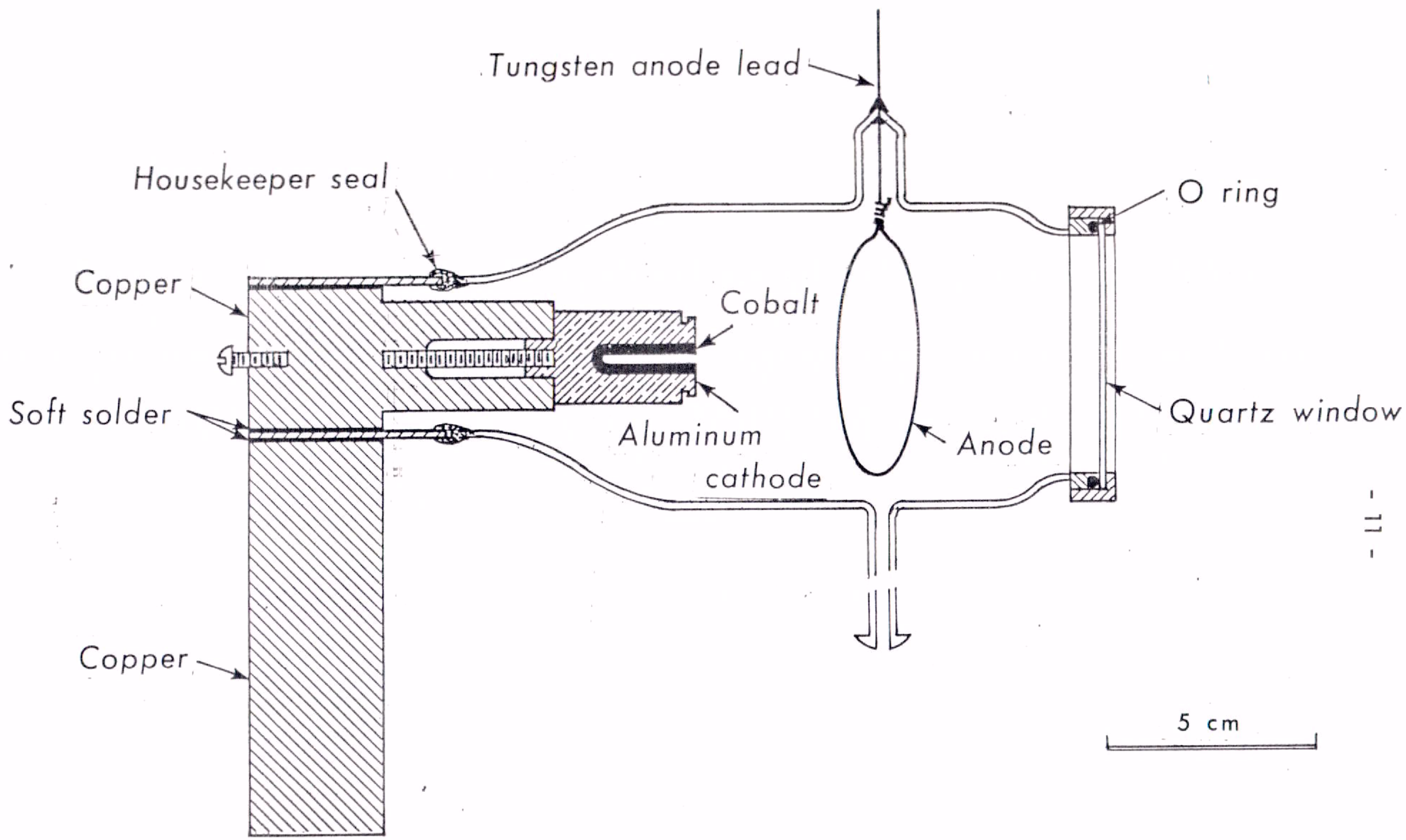
FIGURE CAPTIONS

Figure 1 - Hollow Cathode Discharge Tube

Figure 2 - Optical System



HOLLOW CATHODE DISCHARGE TUBE

OPTICAL SYSTEM

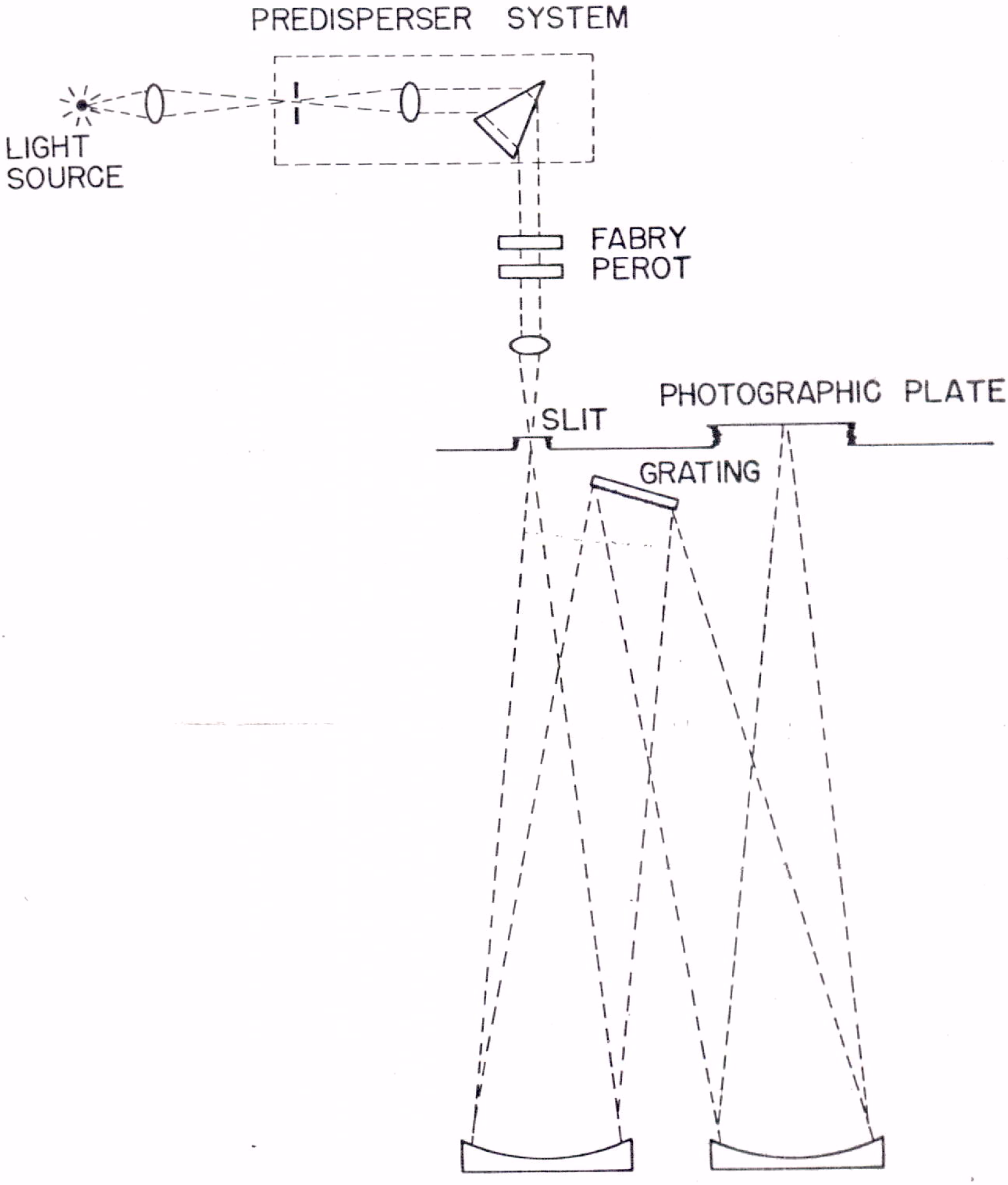


TABLE I

WAVELENGTH AND STRUCTURE OF THE OBSERVED LINES

Wavelength	Wavelength as given by RKM	Int. TC(ref)	Measured Wavelength (Å)	hfs Components: Distance from the center (mÅ) and relative intensity	Comments
4310.10	4310.093	2(4)	-	+20(10) 0(9) -16(8)	-
4309.44	4309.437	2(4)	-	+44(8) : + 6(8) - 8(8) -25(9) -44(10)	-
4307.44	4307.439	2.V(4)	-	+11(9) -10(10)	-
4303.23	4303.235	3.IA(4)	-	+18(1) 0(10) -14(8) -38(9)	-
4301.03	4301.026	3(4)	-	+19(5) 0(10)	-
4292.25	4292.250	3h(4)	-	+48(10) +26(9) + 7(8) -10(7) : -48(6)	-
4285.78	4285.782	6.I(4)	-	+22(5) 0(10)	-
4268.45	4268.446	2.III(4)	-	W = 54	unresolved
4268.03	4268.032	3h(5)	-	+39(10) + 6(9) -20(8) -39(7)	-
4170.89	4170.888	4(4)	4170.888*		diffuse

TABLE I (continuation)

4162.17	4162.169	2.IV(5)	4162.162*	+72(10) +38(9) + 9(8) -17(7) -40(6) ⋮ -60(6)	-
4150.43	4150.429	3.III(4)	4150.429*	+28(8) ⋮ +10(8) - 7(9) -29(10)	-
4139.45	4139.452	3.III(4)	4139.454*	+23(7) + 4(7) -26(10)	-
4131.85	4131.85	3.V(9)	4131.824*	+44(7) +24(8) -20(9) -47(10)	incompletely resolved
4122.27	4122.271	2.III(5)	4122.266	+35(6) +25(6) +15(7) + 3(8) -14(9) -34(10)	-
4121.32	4121.318	60.II(4)	4121.318	W = 27	unresolved
4118.77	4118.774	50.II(4)	4118.775	+12(8) -12(10)	-
4110.53	4110.532	25.I(4)	4110.536	+24(8) 0(10) -28(8)	-
4110.07	4110.073	3h(5)	4110.056	+38(8) ⋮ +20(8) - 4(9) -38(10)	-
4109.71	4109.706	1d-IA(7)	4109.656	W = 29	unresolved
4108.49	4108.488	1(11)	4108.483	+26(6) 0(10)	-
4104.74	4104.743	4.III(4)	4104.739	+14(8) 0(10) -14(8)	-

TABLE I (continuation)

4104.42	4104.418	2.III(4)	4104.418*	+69(4) +31(4) + 7(9) - 7(10)	-
4097.19	4097.193	2(4)	4097.192*	+11(10) -12(5)	-
4095.92	4095.925	2.V(4)	4095.917	+40(8) 0(8) -11(10)	-
4093.05	4093.053	2.V(5)	4093.046	0(10) -14(5)	-
4092.85	4092.848	3.III(5)	4092.847	+38(4) +17(10) + 1(6) -18(10)	-
4092.39	4092.386	25.I(4)	4092.386	+13(4) 0(10)	-
4090.35	4090.354	20h(5)	4090.300*	+25(10) - 4(8) -20(5)	-
4088.29	4088.291	1.IA(4)	4088.293	+21(10) : -21(10)	-
4086.92	4086.92	1(9)	4086.922*		fairly sharp
4086.30	4086.300	15.II(4)	4086.298	+36(10) +10(8) -12(8) : -32(8)	-
4085.58	4085.579 (MIT tables)	2h	4085.573*	+30(10) +15(7) -18(10) -42(8)	-
4084.11	4084.113	2(4)	4084.114*	+ 8(9) - 8(10)	-

TABLE I (continuation)

4082.59	4082.593	2.IA(4)	4082.592		-
4081.44	4081.440	2.V(4)	4081.440	+16(7) -12(10)	-
4079.42	4079.42	1(9)	4078.449*	: +17(9) 0(10) :	hidden by Argon lines
4077.41	4077.406	2.V(5)	4077.387	+65(10) +36(9) +10(8) -12(7) -32(6) -50(5) : -64(5)	-
4076.56	4076.565	3h(4)	4076.566*	: 0(10) -24(10)	hidden by Argon lines
4076.12	4076.124	3.IA(4)	4076.123*		unresolved
4069.54	4069.540	1.IV(4)	4069.543	+17(8) + 2(10) -20(10)	-
4068.54	4068.541	8.II(4)	4068.546*		unresolved
4066.36	4066.365	15.I(4)	4066.367	+15(4) 0(10)	-
4061.76	4061.76	1(9)	4061.756	+30(10) - 9(9) -21(10)	-
4059.32	4059.321	1.IA(10)	4059.316	+36(8) : +23(8) +10(8) - 3(9) -19(9) -36(10)	-
4058.76	4058.762	1(7)	4058.753*		diffuse

TABLE I (continuation)

4058.60	4058.600	6.II(4)	40.58.598	+17(3) 0(10) -18(3)	-
4058.18	4058.183	8.I(4)	4058.188*		unresolved
4057.19	4057.195	5.I(4)	4057.202	+12(10) - 2(9) -12(8)	-
4056.98	4056.979	2.V(5)	4056.946	+32(7) +15(8) - 4(9) -28(10)	-
4054.62	4054.618	2.IA(4)	4054.619	+ 7(10) - 9(8)	-
4053.92	4053.918	1.II(4)	4053.916	+10(10) ⋮ 0(10) ⋮ -10(10)	-
4052.91	4052.912	3.III(4)	4052.923*		unresolved
4049.28	4049.283	4(4)	4049.283*		-
4045.39	4045.386	20.I(4)	4045.388	+35(1) +17(10) 0(9) -14(8) -25(7)	-
4040.79	4040.794	2.III(4)	4040.792*		unresolved
4040.65	4040.647	2(5)	4040.601*		unresolved
4038.96	4038.963	0(4)	4038.963*	+18(9) + 4(10) -17(10) ⋮	bad resolution (the line is too weak)
4037.20	4037.198	2(4)	4037.185	+21(9) 0(10) -40(7)	id.
4036.76	4036.763	0(4)	4036.766*	+20(10) + 2(10) -21(10)	too weak

TABLE I (continuation)

4035.54	4035.542	8.III(4)	4035.552	+30(2) + 9 }(10) - 8 }	incompletely resolved
4033.01	-	-	4033.015	+32(10) + 7(9) -14(8) -29(7)	
4027.03	4027.032	10.I(4)	4027.032	+ 8(9) - 8(10)	
4025.50	4025.497	1(10)	4025.481		sharp
4023.40	4023.399	4.III(4)	4023.393	+21(9) + 3(9) -20(10)	
4020.90	4020.898	20.I(4)	4020.894	+24(8) 0(10) -24(9)	
4019.29	4019.288	5.I(4)	4019.287	+13(10) -13(10)	
4019.14	4019.140	5(5)	4019.120	W = 18	unresolved

* Interferometric results are not avaible.

TABLE II

MAGNETIC HFS COUPLING CONSTANT

Level	Energy (cm^{-1})	Magnetic hfs Coupling Constant (mk)	
		This paper	Other Authors
$b^4P_{5/2}$	15184.04	5	-
$a^2P_{1/2}$	18775.01	21.2 (±0.5)	-
$a^2H_{11/2}$	21780.47	18	-
$a^2H_{9/2}$	22475.36	27	-
$z^6F_{7/2}$	24326.11	28.3 (±0.5)	26 (*)
$z^6F_{5/2}$	24733.38	24.2 (±0.2)	24 (*)
$z^6F_{3/2}$	25041.16	20.0 (±0.2)	20 (*)
$z^6F_{1/2}$	25232.79	-2.1 (±0.1)	0 (*)
$z^6D_{9/2}$	24627.79	28.7 (±0:3)	27 (*)
$z^6D_{5/2}$	25739.93	26 (±2)	27.8 (±0.4) (**)
$z^6D_{3/2}$	26063.11	26 (±3)	-
$z^6G_{5/2}$	26450.02	14.5 (±0.3)	15 (*)
$z^6G_{3/2}$	26597.64	(***) 5.3 (±0.5)	-
$z^4F_{9/2}$	28345.86	27.6 (±0.4)	27.6 (±0.2) (**)
$z^2G_{9/2}$	31699.69	15 (±3)	-
$z^2F_{5/2}$	32781.71	32.7 (±0.3)	-
$y^4G_{7/2}$	33173.36	14.6 (±0.2)	-
$x^4D_{7/2}$	39649.16	30	-
$z^4P_{1/2}$	41969.90	27	-

(*) Rasmussen (Ref. 10)
(**) Oertel (Ref. 11)
(***) This result is based on the hfs of line λ4033.02 which has not been observed by other authors.

TABLE II (Continuation)

$z^2P_{1/2}$	43130.24	21	-
$w^4D_{1/2}$	43435.58	9	-
$x^2G_{9/2}$	46032.10	35	-
$x^2G_{7/2}$	45766.63	14	-
$c^2D_{5/2}$	52460.10	19.8 (±0.6)	-
$h^4F_{9/2}$	52864.41	5.7 (±0.5)	-
$h^4F_{7/2}$	53694.57	18.3 (±0.6)	-
$h^4F_{3/2}$	54426.64	58 (±3)	-
$f^4H_{13/2}$	53618.08	24.5 (±0.3)	-
$f^4D_{7/2}$	53702.13	34 (±1)	-
$i^4F_{9/2}$	54682.91	24.0 (±0.5)	-
$f^4P_{5/2}$	53936.68	53.6 (±0.1)	-
$1_{5/2}$	54561.74	6	-

TABLE III

PROPOSED CLASSIFICATION

WAVELENGTH	CLASSIFICATION
4109.65	$a^4F_{9/2} - z^6F_{7/2}$
4090.30	$a^4F_{3/2} - z^6D_{1/2}$
4033.02	$a^4F_{3/2} - z^6G_{3/2}$
4019.30	$b^4F_{5/2} - z^4F_{3/2}$