

MEASUREMENTS OF THE HYPERFINE STRUCTURE OF ATOMIC ENERGY LEVELS IN Co I

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ABSTRACT

Most of the Co I lines recorded by high-resolution Fourier transform spectrometry in the region 3000–45000 cm^{−1} (30000–2222 Å) show significant hyperfine structure. Computer fits to 1020 of these line profiles have yielded values of the magnetic dipole hyperfine interaction constant A for 297 energy levels with an uncertainty of between 0.2% and 3%. The A factors range from -0.0236 to $+0.0598$ cm^{−1} for the even levels, and from -0.03387 to $+0.1028$ cm^{−1} for the odd levels. For 208 of these A factors no previous measurements are known. Approximate values of the electric quadrupole hyperfine interaction constant B were found for 156 levels. These measurements of A and B factors allow, for the first time, correct allowance to be made for the effects of hyperfine structure in Co I both for abundance analysis and in the resolution of blended lines.

Subject headings: atomic data — line: profiles — methods: laboratory

1. INTRODUCTION

Knowledge of hyperfine structure (hfs) in iron-group elements is important not only for theoretical atomic physics but also for determinations of elemental abundances in stellar atmospheres. It has been noticeable in work reporting on stellar abundances that elements with hfs have often been neglected because of the lack of good laboratory atomic data. For the iron-group elements with odd atomic number, such as cobalt, the effect of hyperfine structure as a line-broadening mechanism must be taken into account in abundance studies when using both curve-of-growth methods (Wolff & Wallerstein 1966; Holweger & Oertel 1971) and spectrum synthesis methods (Kerola & Aller 1976). This need for hfs data has become more urgent with the high-resolution stellar spectra now available from the *Hubble Space Telescope* Goddard High Resolution Spectrograph (Edvardsson et al. 1994). Another example of the importance of hfs data was highlighted recently (Pickering & Semeniuk 1995): the hfs of certain Co I lines was needed to calculate the contribution of cobalt lines to blends with the Th II lines used to estimate the age of the Galaxy by the radioactive chronology method of Butcher (1987). This method is based on the ratio of stellar abundances of thorium, which has only one long-lived isotope, to neodymium, a stable reference element. However, a rather young Galactic age was deduced from this ratio because blends of Co I and V I lines with the Th II line had not been fully taken into account (Morell, Källander, & Butcher 1992). Pickering & Semeniuk (1995) presented results for V I and for the hfs of the three relevant Co I lines that should lead to a more accurate determination of the Galactic age.

Hyperfine structure data are also of help in the term analysis of atomic spectra. The J -value of a level can often be determined unambiguously from the hfs pattern. An example is shown in Figure 1, where a strong IR 5p–5s transition in Co I is shown. The upper $3d^7 4s(^5F)5p$ level is new, first reported by Pickering & Thorne (1996), and a fit of the line profile gives a unique J -value.

Although hfs has been studied for many years, the methods used allowed observations of only a few selected lines, and as a result the A and B factors were known for relatively few levels. This paper reports the first use of high-

resolution Fourier transform spectroscopy (FTS) for comprehensive measurements of hfs over a wide spectral range, from 3.8 μm to 180 nm. This technique offers the important advantage that the wide spectral range allows observation of several thousand lines, as a result of which hfs constants for hundreds of levels can be derived, many of them from several transitions. In addition, accurate values of relative intensity are obtained, and the resolution is sufficient to ensure that the line widths are determined by Doppler rather than instrumental width.

From over 1000 lines showing hfs observed in this work, A factors have been determined for 297 levels, and 208 of these are new.

2. PREVIOUS WORK ON HYPERFINE STRUCTURE IN Co I

The first investigations of hyperfine structure in Co I were reported in 1934 (Kopfermann & Rasmussen 1934; More 1934) when the nuclear spin quantum number $I = 7/2$ was determined. These were followed by the analysis of 25 transitions, observed using a Fabry-Perot interferometer and photographic plates, leading to A factors for 22 levels (Rasmussen 1936). Highly accurate measurements of von Ehrenstein, Kopfermann, & Penselin (1960) for the ground-state A and B factors were extended by Childs & Goodman (1968) to give hfs data for the seven lowest atomic levels. Both sets of authors used the technique of atomic-beam magnetic resonance, and the accuracy of the A factors given is between 0.0001% and 0.0005%.

Oertel (1970) investigated 61 lines by optical spectroscopy using a Fabry-Perot interferometer, and found A factors for 36 levels, accurate to between 0.5% and 5%, and approximate B factors for 26 levels. Klotz, Becker, & Göbel (1977) used the level crossing technique to measure A and B factors for two levels to compare these values with their theoretical calculations, and optical methods for three levels in order to take account of hfs in radiative lifetime measurements by magnetic depolarization. The importance of hfs data for the iron-group elements in abundance determination work on stellar atmospheres was mentioned by Clúa-Gonzalez (1978), who used a Fabry-Perot interferometer and photographic observation to analyze 65 lines between 4000 and 4300 Å. Visual estimates of the intensities

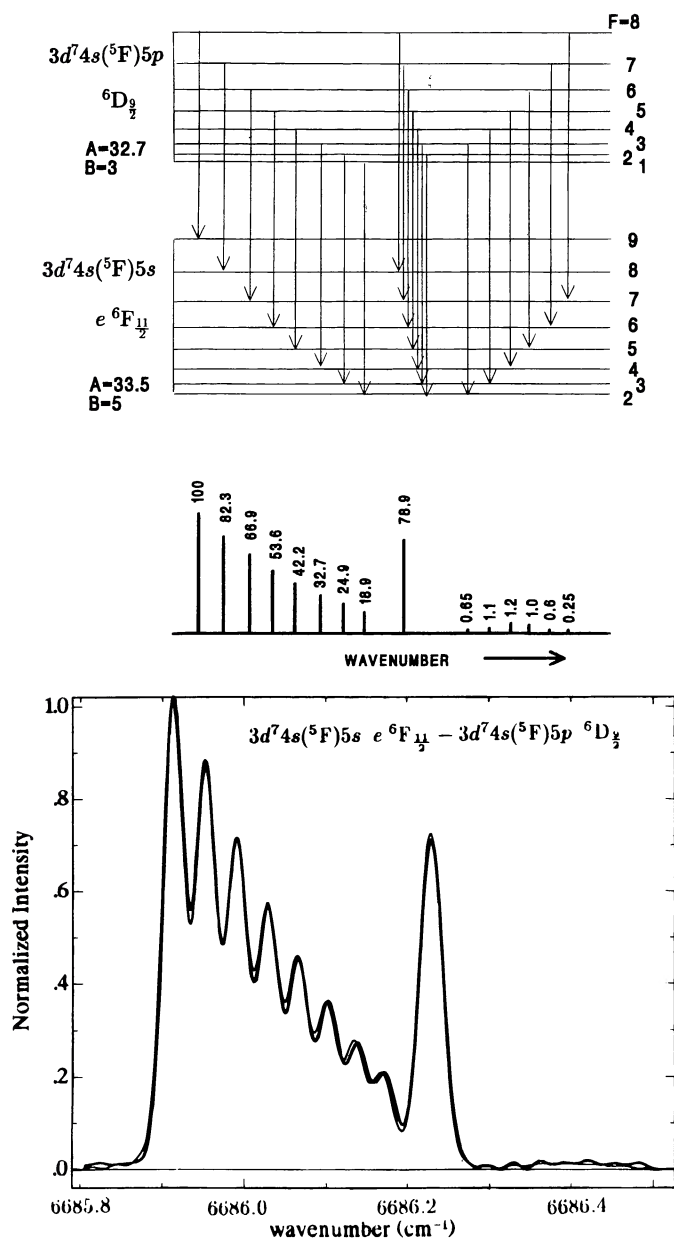


FIG. 1.—Observed (heavier trace in plot) and fitted line profiles, hyperfine components, and transition diagram for the Co I 14952.456 Å (6686.037 cm⁻¹) transition.

of components were given, and A factors for 32 levels with accuracy comparable to those of Oertel (1970) and Rasmussen (1936) were listed.

Anselment, Göring, & Meisel (1987) carried out a test of the accuracy of atomic-beam laser spectroscopy in the investigation of hyperfine splittings by determining the hfs constants for the $3d^8 4p \ ^2F_{7/2}$ level. In recent years Doppler-limited optogalvanic spectroscopy (Guthöhrlein & Keller 1988) and Doppler-free and Doppler-limited laser-induced fluorescence modulation spectroscopy (Ibrahim-Rüd 1985; Wenzel 1987; Guthöhrlein & Keller 1990) have been used to determine A and B hfs splitting factors for a limited number of levels with an accuracy between 0.05% and 0.5% for the A factors.

Dembczyński, Guthöhrlein, & Stachowska (1993) presented results of theoretical calculations for low even levels and compared these with experimentally determined values

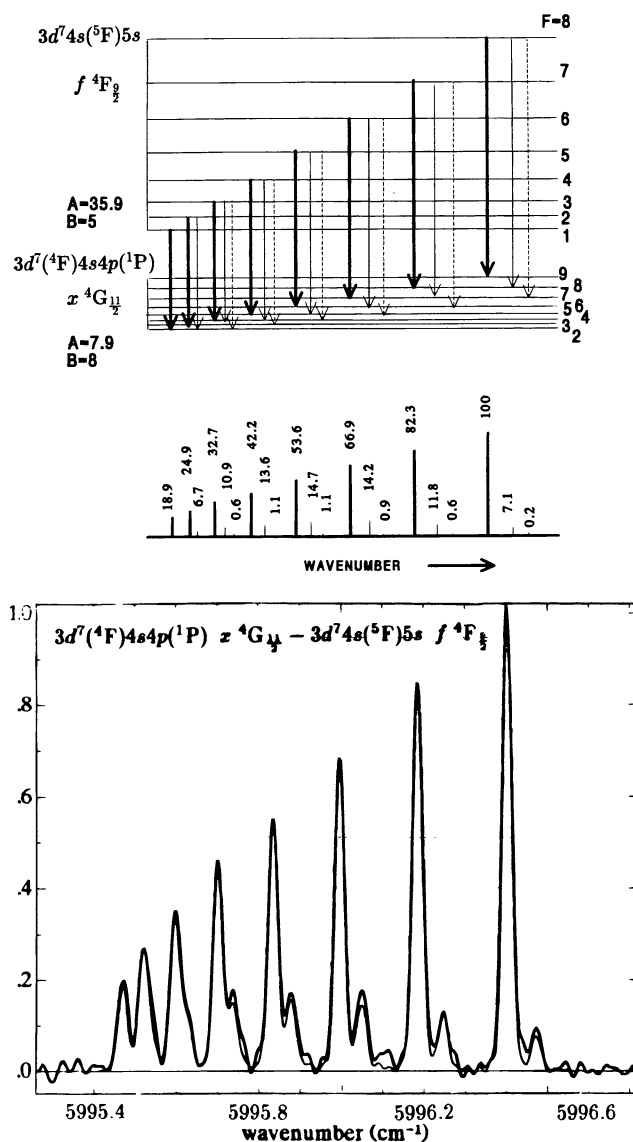


FIG. 2.—Observed (heavier trace in plot) and fitted line profiles, hyperfine components, and transition diagram for the Co I 16673.288 Å (5995.979 cm⁻¹) transition. For clarity in the transition diagram those transitions with $\Delta F = +1$ are shown by heavy arrows, those with $\Delta F = 0$ by light arrows, and those with $\Delta F = -1$ by dashed arrows.

where available. Behrens et al. (1994) reported laser-induced fluorescence line narrowing measurements of hfs and gave the hfs coupling constants for the level $3d^8(^3F)4s \ ^4F_{3/2}$.

Thus, prior to the measurements reported in this paper, accurate A factors were known for 35 levels. Less accurate A factors determined by “optical” methods were known for a further 54 levels.

3. SIMPLE THEORY

For atoms with nonzero nuclear spin I the fine-structure levels undergo splitting because of the hyperfine interaction between the nucleus and the electrons. In the absence of perturbations the energy of the hyperfine structure multiplets is given (Kopfermann 1958) by

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

where W_J is the energy of the fine-structure level of quantum number J ; A and B are the magnetic dipole and the electric quadrupole hyperfine interaction constants respectively; and K is defined as

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

where F is the quantum number associated with the total angular momentum of the atom,

$$F = I + J; I + J - 1; \dots; |I - J|.$$

The selection rules which govern the hyperfine transitions are $\Delta F = 0; \pm 1$ but not $F = 0 \leftrightarrow F' = 0$. In addition, there are intensity rules (Kuhn 1962): within a hyperfine multiplet the ratio of the sums of the intensities of all transitions from two states with quantum numbers F and F' are in the ratio of their statistical weights $(2F + 1):(2F' + 1)$.

This simple theory was used in the fitting of hfs of the Co I transitions in this work. No perturbations were evident.

4. EXPERIMENTAL DETAILS

The spectra used in this work were obtained as part of an extensive measurement of the Co I spectrum in the wavelength region 1800–38000 Å (55555–2630 cm⁻¹), resulting in the classification of 2442 spectral lines, the revision of 300 energy levels, and the determination of 64 new levels (Pickering & Thorne 1996).

High-resolution spectra of Co I were acquired in the visible–UV region with the f/25 UV Fourier transform (FT) spectrometer at Imperial College and in the infrared region with the 1 m f/55 FT spectrometer at the National Solar Observatory in Arizona. The resolutions used were 0.037 cm⁻¹ (0.006 Å) in the visible, 0.05 cm⁻¹ (0.003 Å) in the UV, and 0.0139 cm⁻¹ (0.028 Å) in the infrared, the individual line components being limited by their Doppler widths alone. The light source was a water-cooled hollow cathode lamp run in either Ar at 1 mbar or Ne at 2–3 mbar, with currents of 600–700 mA, using a pure cobalt cathode.

The center-of-gravity (COG) wavenumber and intensity of each transition were determined with the DECOMP program developed by Brault (Brault & Abrams 1989). Pickering & Thorne (1996) give the resulting identified line list together with tables of the energy levels which have been corrected or newly found.

5. HYPERFINE STRUCTURE ANALYSIS

The determination of the A and B factors for the Co I energy levels was carried out using a hfs analysis subroutine adapted by J. Brault and R. Engleman from the ANNEAL program in Press et al. (1987) and incorporated into the DECOMP program referred to above. The input information comprises the I -value, the J -values of both levels, the known intensity ratios of the transition components (Kuhn 1962), the widths of the components (having Gaussian and Lorentzian contributions), the COG of the pattern, and, where possible (see below), an A factor for one of the two levels. Using this fitting routine, values for the magnetic dipole hyperfine interaction constant A were found for 297 levels (82% of the known Co I energy levels), of which 208 had previously unmeasured A factors. It was not always possible to determine the electric quadrupole hyperfine interaction constant B because the contribution of the last term in equation (1) was so small, but B factors were found for 156 levels.

The values determined for A and B are listed in Tables 1 and 2 for even and odd levels respectively. The first four columns give, for each level investigated, the configuration, term designation, J -value, and energy reported in Pickering & Thorne (1996). The fifth and sixth columns give the A factor and its uncertainty in mK (1 mK = 0.001 cm⁻¹) determined in this work. The next column lists approximate values of B factors. The final columns give, where available, values of A and B reported by other authors. In cases where measurements of a particular A factor have been made by several authors, the measurement with the lowest uncertainty is listed in the tables. Where there are measurements carried out by widely differing experimental techniques, such as “optical” or “laser” methods, both measurements are given.

The analysis is much simplified when the hfs of one of the levels involved in a transition is known. The starting point for this analysis was the very accurate hfs information of Childs & Goodman (1968) for the levels $3d^7 4s^2 a^4 F_{9/2, 7/2, 5/2, 3/2}$ and $3d^8 ({}^3F) 4s b^4 F_{9/2, 7/2, 5/2}$, for which the errors are 2 orders of magnitude less than those of the present work. By fitting the hfs of transitions to these levels it was possible to determine directly reliable values for the hfs constants of the upper odd levels involved. These could in turn be used as “fixed” values in determining hfs constants of other levels, and so forth. Other levels for which some previous experimental or theoretical value for the A factor was available could also be used as starting points in the fitting procedure. In the few cases where no hfs information on either level was available, either in the literature or from transitions fitted in this work, a fit could still be carried out if an initial guess at the A factors could be made from a characteristic line profile pattern. For example, when one of the A factors is an order of magnitude greater than the other, the line profile has a characteristic “flag” pattern such as that shown in Figure 2.

In general, for each level studied the hfs A factor was determined from the analysis of line profiles for between three and six different transitions, resulting in a range of A -values usually differing by between 0.05 and 0.2 mK. The differences arise for several reasons: uncertainties in the A factor of the other level in a transition; a range of signal-to-noise ratios of observed lines from 50 to 10,000; and differing Doppler line widths. Typical Doppler widths are 25 mK at 6000 cm⁻¹, 100 mK at 23800 cm⁻¹, and 185 mK at 44000 cm⁻¹. The resolution of the FT spectrometer is such that the line widths are limited solely by the Doppler widths, and so, depending on the size of the A factors, the overall pattern is usually well resolved into individual components in the IR region but only partly so in the UV. However, even where a set of line profiles did not appear to be resolved into individual components, the fitting still gave consistent sets of A factors. In many cases A factors determined for a particular level from visible, UV, and IR transitions agreed to within 0.1 mK. The uncertainties listed in Tables 1 and 2 are estimated from the range of values of each particular A factor. It can be seen that the agreement with accurate laser spectroscopic results, where these are available, is usually well within this uncertainty.

When B factors could not be determined they were removed from the fitting program. In some cases the B factors determined from the line profile fitting of several transitions showed agreement to within 50%, and these values were considered to be meaningful; they should,

TABLE 1
HYPERFINE STRUCTURE INTERACTION CONSTANTS OF THE EVEN-PARITY ENERGY LEVELS OF CO I

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work A (mK)	err (mK)	B (mK)	Other authors A (mK)	B (mK)
$3d^7 4s^2$	$a^4 F$	9/2	.000	15.020*		4.64*	CG 15.01984(3)	4.644(1)
		7/2	816.000	16.364*		3.15*	CG 16.36358(7)	3.152(1)
		5/2	1406.852	20.459*		2.25*	CG 20.4591(1)	2.253(2)
		3/2	1809.313	34.790*		2.26*	CG 34.79016(3)	2.2555(6)
$3d^8(^3F)4s$	$b^4 F$	9/2	3482.780	27.646*		-3.96*	CG 27.6458(1)	-3.96(1)
		7/2	4142.631	22.313*		-2.64*	CG 22.3127(1)	-2.643(7)
		5/2	4690.141	18.752*		-1.83*	CG 18.7524(1)	-1.828(8)
		3/2	5075.788	10.20	0.05	-2	BD 10.10(6) Oe 2.5(4)	-2.7(6)
$3d^8(^3F)4s$	$a^2 F$	7/2	7442.399	13.01	0.05	-5	Oe 12.5(3) IR 13.06(5)	-3.54(90)
		5/2	8460.783	37.05	0.08	-3	Oe 35.3(5) IR 36.98(4)	-3.1(7)
$3d^7 4s^2$	$a^4 P$	5/2	13795.491	5.9	0.2	-8	GK 5.967(10)	-5.67(47)
		3/2	14036.241	10.6	0.2	4		
		1/2	14399.220	-23.6	0.2	0	We -23.71(3)	0
$3d^8(^3P)4s$	$b^4 P$	5/2	15184.013	37.4	0.2	5	GK 37.52(2)	4.8(3)
		3/2	15774.009	15.4	0.2	-2	GK 15.274(10)	-3.00(13)
		1/2	16195.610	57.6	0.2	0		
$3d^7 4s^2$	$a^2 G$	9/2	16467.833	20.45	0.07	2	IR 20.41(4)	2.8(5)
		7/2	17233.620	27.95	0.09		GK 27.999(13)	-3.2(1)
$3d^8(^1D)4s$	$a^2 D$	3/2	16470.597	13.0	0.2			
		5/2	16778.145	46.3	0.1	4	IR 46.28(3)	4.2(5)
$3d^8(^3P)4s$	$a^2 P$	3/2	18389.549	11.2	0.2	4	GK 11.07(5)	3.4(3)
		1/2	18774.990	20.1	0.4	0	IR 19.77(6)	0
$3d^7 4s^2$	$b^2 P$	3/2	20500.672	5.5	0.1	2		
		1/2	21215.860	17.2	0.2	0		
$3d^7 4s^2$	$a^2 H$	11/2	21780.442	22.6	0.2		CL 18	
		9/2	22475.303	26.4	0.3		CL 27	
$3d^7 4s^2$	$b^2 D$	5/2	21920.046	18.5	0.2	15		
		3/2	23152.539	30.75	0.09	4		
$3d^8(^1G)4s$	$b^2 G$	9/2	23184.197	36.9	0.3	0		
		7/2	23207.760	8.8	0.3			
$3d^9$	$c^2 D$	5/2	27496.998	11.24	0.05	-5		
		3/2	28470.445	33.95	0.07	-4		
$3d^8(^3F)5s$	$e^4 F$	9/2	44782.082	13.4	0.3		Oe 14(3)	
		7/2	45105.559	11.1	0.2	1		
		5/2	45876.529	18.4	0.3			
		3/2	46375.124	35.5	1.0			
$3d^7 4s(^5F)5s$	$e^6 F$	11/2	45675.937	33.47	0.07	5	Ra 33	
		9/2	46222.945	31.45	0.07	2	Ra 31	
		7/2	46706.765	28.70	0.07	-1	Ra 29	
		5/2	47090.583	25.7	0.1	-1	Ra 25	
		3/2	47364.658	19.35	0.07	-1	Ra 20	
		1/2	47528.408	-17.1	0.1	0	Ra -21	
$3d^8(^3F)5s$	$e^2 F$	7/2	45924.947	19.8	0.1			
		5/2	46745.990	32.0	0.1	-3		
$3d^7 4s(^5F)5s$	$f^4 F$	9/2	47524.435	35.92	0.07	5	Oe 37.6(3)	
		7/2	48201.556	28.25	0.07	3	Oe 27.3(3)	
		5/2	48718.519	19.48	0.07	3		
		3/2	49078.386	-1.5	0.2			

TABLE 1—Continued

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work A (mK)	err (mK)	B (mK)	Other authors A (mK) B (mK)	
$3d^8(^3F)4d$	e^4P	5/2	51042.173	16.7	0.1			
		3/2	52033.228	29.9	0.2			
		1/2	52634.543	36.1	0.2	0		
$3d^8(^3F)4d$	e^4D	7/2	51052.915	10.88	0.05			
		5/2	51560.711	14.35	0.07	0		
		3/2	52264.330	12.7	0.3			
		1/2	52040.834					
$3d^8(^3F)4d$	e^4H	13/2	51142.456	7.6	0.2			
		11/2	51174.230	8.9	0.1			
		9/2	52121.138	12.52	0.07	1		
		7/2	52716.641	13.4	0.1	5		
$3d^8(^3F)4d$	g^4F	9/2	51170.073	9.18	0.08	0		
		7/2	51199.534	11.17	0.08			
		5/2	52069.936	13.85	0.08			
		3/2	52702.692	14.0	0.2			
$3d^8(^3F)4d$	e^2P	3/2	51200.562	21.6	0.6			
		1/2	52715.710	59.8	0.5	0		
$3d^8(^3F)4d$	e^4G	11/2	51203.690	8.1	0.2			
		9/2	51267.867	9.5	0.2			
		7/2	52161.961	12.94	0.07			
		5/2	52772.228	16.8	0.2			
$3d^8(^3F)4d$	f^2F	7/2	52094.950	13.63	0.08			
		5/2	52970.594					
$3d^8(^3F)4d$	e^2H	11/2	52113.842	10.6	0.2			
		9/2	52775.398	14.5	0.2			
$3d^8(^3F)4d$	e^2G	9/2	52156.394	11.6	0.2	-2		
		7/2	52856.618	14.7	0.3			
$3d^8(^3F)4d$	e^2D	5/2	52460.041	20.6	0.3		CL	19.8(6)
		3/2	53343.187					
$3d^7 4s(^3F)5s$	g^2F	7/2	52763.614	12.8	0.1			
		5/2	53704.089	26.25	0.09	5		
$3d^7 4s(^3F)5s$	h^4F	9/2	52864.352	5.1	0.2	-1	CL	5.7(5)
		7/2	53694.526	18.3	0.2		CL	18.3(6)
		5/2	54258.703	35.8	0.1	6		
		3/2	54426.620				CL	58(3)
$3d^7 4s(^5F)4d$	f^4G	11/2	53511.734					
		9/2	54158.120					
		7/2	54282.770					
		5/2	55165.690					
$3d^7 4s(^5F)4d$	f^4H	13/2	53617.983	25.0	0.3		CL	24.5(3)
		11/2	54315.611	20.4	0.2			
		9/2	54860.878	15.5	0.5			
		7/2	55268.647					
$3d^7 4s(^5F)4d$	f^6F	11/2	53660.238	29.1	0.1	2		
		9/2	54356.347	23.4	0.1	0		
		7/2	54896.487	18.2	0.5			
		3/2	54949.880	33.0	0.4			
		5/2	55282.931	9.2	0.2			
		1/2	55288.624					
$3d^7 4s(^5F)4d$	f^4D	7/2	53702.089	35.8	0.2		CL	34(1)
		3/2	54514.641	54.4	0.3	0		
		5/2	54561.681	37.8	0.3	0		
		1/2	54949.777					

TABLE 1—Continued

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work A (mK)	err (mK)	B (mK)	Other authors A (mK)	B (mK)
$3d^7 4s(^5F)4d$	e^6D	9/2	53725.111	34.3	0.2			
		7/2	54352.233	28.8	0.4			
		5/2	54946.920	25.6	0.3			
		1/2	55407.095					
		3/2	55635.986					
$3d^7 4s(^5F)4d$	e^6G	13/2	53728.230	25.8	0.2	0		
		11/2	54367.332	20.86	0.07	-6		
		9/2	54682.811	21.5	0.2		CL	24.0(5)
		7/2	54989.790	19.9	0.5			
		3/2	55389.653					
		5/2	55449.965	13.1	0.4			
$3d^7 4s(^5F)4d$	i^4F	9/2	53788.716	26.0	0.2			
		7/2	54477.003	18.5	0.4			
		5/2	54904.981					
		3/2	55447.576					
$3d^7 4s(^5F)4d$	e^6P	7/2	53789.092	45.0	0.5			
		5/2	54445.533	38.5	0.2			
		3/2	55078.647	31.7	0.2			
$3d^7 4s(^5F)4d$	e^6H	15/2	53821.958	23.5	0.2	12		
		13/2	54452.305	18.7	0.3			
		11/2	54947.632	13.9	0.2			
		9/2	55313.055					
		7/2	55520.556	5.7	0.2			
		5/2	55632.021	10.3	0.2			
$3d^7 4s(^5F)4d$	f^4P	5/2	53936.621	53.5	0.2		CL	53.6(1)
		3/2	55721.189					
		1/2	55826.803					
unknown	54989 ^e	9/2	54989.320	18.0	0.2	5		
unknown	55577 ^e	3/2	55577.297	15.0	0.6			
unknown	55598 ^e	7/2	55598.717	10.5	0.7			
$3d^8(^3F)5d ?$	56637 ^e	9/2	56637.391					
$3d^8(^3F)5d ?$	56644 ^e	7/2	56644.155					
$3d^8(^3F)5d ?$	56677 ^e	7/2	56677.997					
$3d^7 4s(^5F)6s$	^6F	11/2	56869.068					
		9/2	57261.620					
		7/2	57813.258					
$3d^7 4s(^5P)5s$	^6P	7/2	60019.606					
		5/2	60262.463					

NOTE.—Values followed by an asterisk are Childs & Goodman 1968 *A* and *B* factors used in this work (see § 5). Other author reference abbreviations are as follows: BD, Behrens et al. 1994; CG, Childs & Goodman 1968; CL, Clúa-Gonzalez 1978; GK, Guthöhrlein & Keller 1990; IR, Ibrahim-Rüd 1985; Oe, Oertel 1970; Ra, Rasmussen 1936; We, Wenzel 1987. For a level labeled with its energy level value a superscripted *e* is included in the label to indicate even parity.

TABLE 2
HYPERFINE STRUCTURE INTERACTION CONSTANTS OF THE ODD-PARITY ENERGY LEVELS OF Co I

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work A (mK)	err (mK)	B (mK)	Other authors A (mK)	B (mK)
$3d^7(^4F)4s4p(^3P)$	z^6F	11/2	23611.694	28.50	0.09	-2	Ra 28	
		9/2	23855.594	28.50	0.09	4	Ra 28	
		7/2	24326.055	26.4	0.2	5	CL 28.3(5)	
		5/2	24733.253	24.0	0.1	2	CL 24.2(2)	
		3/2	25041.111	20.1	0.1	0	CL 20.0(2)	
		1/2	25232.740	-2.1	0.3	0	CL -2.1(1)	
$3d^7(^4F)4s4p(^3P)$	z^6D	9/2	24627.743	28.05	0.08		CL 28.7(3)	
		7/2	25269.200	27.17	0.05	-3	Oe 27.55(10)	1
		5/2	25739.804	26.62	0.09	-6	Oe 27.8(4)	-10
		3/2	26063.141	27.0	0.3		CL 26(3)	
		1/2	26250.469	33.4	0.2	0		
$3d^7(^4F)4s4p(^3P)$	z^6G	13/2	25138.806	25.3	0.2	8	Ra 25	
		11/2	25568.635	22.94	0.06	7	Ra 22	
		9/2	25937.564	20.63	0.07	5	Oe 20.6(2)	6
		7/2	26232.020	18.27	0.09	6	Oe 18.8(3)	-10
		5/2	26449.912	14.4	0.2	3	CL 14.5(3)	
		3/2	26597.594	4.9	0.2	4	CL 5.3(5)	
$3d^7(^4F)4s4p(^3P)$	z^4F	9/2	28345.814	27.02	0.08	-2	Oe 27.6(2)	10.0
							vH 27.02(17)	-1.6(5)
		7/2	28777.236	21.86	0.08	1	Oe 24.1(3)	
							KB 22.0(4)	-1(3)
		5/2	29216.322	18.65	0.07	1	Oe 17.5(2)	
$3d^7(^4F)4s4p(^3P)$	z^4G	3/2	29563.111	14.15	0.07		Oe 14.7(3)	5
		11/2	28845.165	25.75	0.07	7	Oe 25.7(1)	-10
		9/2	29269.675	17.25	0.09	6	Oe 15.9(2)	5
							KB 17.5(9)	6.67
		7/2	29735.131	14.95	0.05	5	Oe 14.5(4)	
$3d^7(^4F)4s4p(^3P)$	z^4D	5/2	30102.912	13.29	0.06	5	Oe 14.0(2)	10
		7/2	29294.482	25.05	0.09		Oe 24.9(1)	3
							GK 25.07(1)	1.0(4)
		5/2	29948.730	23.22	0.09	1	Oe 21.8(3)	5
		3/2	30443.596	23.5	0.2	1	Oe 20.0(3)	-5
$3d^7(^4F)4s4p(^3P)$	z^2G						We 23.43(1)	0.5(1)
		1/2	30742.605	27.5	0.1	0	Oe 18.8(8)	
							GK 27.425(20)	0
		9/2	31699.638	16.5	0.1		CL 15(3)	
		7/2	32733.008	30.67	0.06	5	IR 16.47(40)	21(5.5)
$3d^7(^4F)4s4p(^3P)$	z^2F						Oe 30.5(4)	
							GK 30.67(2)	3.2(2)
		7/2	31871.118	14.97	0.06	6	Oe 14.6(2)	
$3d^7(^4F)4s4p(^3P)$	z^2F	5/2	32781.672	34.90	0.08	0	CL 32.7(3)	
							IR 34.7(4)	-1.6(6)
$3d^8(^3F)4p$	y^4D	7/2	32027.440	15.95	0.08	5	Oe 15.1(3)	
		5/2	32654.463	15.5	0.2		Oe 14.8(2)	10
		3/2	33150.616	19.65	0.09		Oe 16.3(5)	
		1/2	33449.086	58.9	0.6	0		
$3d^8(^3F)4p$	y^4G	11/2	32430.535	10.0	0.2		KB 10.5(7)	13.34
		9/2	32464.688	11.15	0.09			
		7/2	33466.823	12.9	0.2		Oe 18.5(3)	
		5/2	33674.326	26.85	0.09	-4		
$3d^8(^3F)4p$	y^4F	9/2	32841.916	9.9	0.1	8	KB 10.0(1)	-16.67
		7/2	33173.313	16.95	0.07		CL 14.6(2)	
		5/2	33945.846	20.1	0.1			
$3d^8(^3F)4p$	y^2G	3/2	34196.147	39.72	0.08	-2		
		9/2	33439.661	14.73	0.06	0	Oe 21.5(2)	
							IR 14.65(40)	1.1(7)
$3d^8(^3F)4p$	y^2G	7/2	34133.537	24.75	0.05	-4	IR 24.7(30)	-0.7(15)

TABLE 2—Continued

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work		B (mK)	Other authors	
				A (mK)	err (mK)		A (mK)	B (mK)
$3d^7(^4F)4s4p(^3P)$	z^2D	5/2	33462.795	15.4	0.3		Oe	13.5(3)
		3/2	34352.358	46.1	0.1	2	GK	15.68(5)
							Oe	46(1)
							IR	45.96(5)
$3d^7(^4P)4s4p(^3P)$	^6S	5/2	33802.860	33.6	0.3			
$3d^8(^3F)4p$	y^2F	7/2	35450.503	13.9	0.1	0	AG	14.0(3)
		5/2	36329.834	30.4	0.5			-2.6(6)
$3d^8(^3F)4p$	y^2D	5/2	36092.420	16.4	0.1			
		3/2	36875.089	41.98	0.08		Oe	35(1)
$3d^7(^4P)4s4p(^3P)$	^6D	9/2	38832.218					
		7/2	38845.373	26.73	0.09	-5		
		5/2	38902.844	29.15	0.09			
		3/2	38980.822	32.6	0.1	2		
$3d^7(^4F)4s4p(^1P)$	x^4D	7/2	39649.124	10.13	0.07		CL	30
		5/2	40345.908	11.85	0.09	1		
		3/2	40827.712	17.6	0.2			
		1/2	41101.756	55.8	0.3	0		
$3d^7(^4P)4s4p(^3P)$	z^4S	3/2	40621.588	36.88	0.09	1		
$3d^7(^4P)4s4p(^3P)$	^6P	7/2	41041.348					
		5/2	41104.912	26.41	0.09	-1		
		3/2	41247.585	36.6	0.2			
$3d^7(^4F)4s4p(^1P)$	x^4F	9/2	41225.710	14.7	0.2			
		7/2	41918.353	17.1	0.2			
		5/2	42434.160	22.0	0.8			
		3/2	42796.626	34.0	0.3			
$3d^7(^4F)4s4p(^1P)$	x^4G	11/2	41528.455	7.9	0.2	8		
		9/2	42269.229	11.0	0.3			
		7/2	42811.351	17.9	0.9			
		5/2	43199.624	31.0	0.3	0		
$3d^8(^3P)4p$	z^4P	5/2	41968.824	18.4	0.9			
		1/2	41969.827	29.8	1.0	0	CL	27
		3/2	41982.609	21.0	2.0			
$3d^7(^2G)4s4p(^3P)$	^4H	11/2	42866.715	25.9	0.3			
		9/2	42988.029	18.55	0.08	0		
		7/2	43211.083	14.6	0.2			
$3d^8(^1D)4p$	z^2P	1/2	43130.181	23.2	0.2	0	CL	21
		3/2	43537.659	23.3	0.5			
$3d^7(^4P)4s4p(^3P)$	w^4D	5/2	43242.903	22.7	0.2	2		
		3/2	43263.512	19.0	0.1			
		7/2	43398.557	23.7	0.2			
		1/2	43435.530	19.0	0.5	0	CL	9
$3d^7(^2G)4s4p(^3P)$	w^4F	9/2	43295.293	32.8	0.2	-5		
		7/2	43847.891	26.0	0.1			
		5/2	44201.849	22.0	0.8			
		3/2	44555.647	14.5	0.3	6		
$3d^8(^1D)4p$	x^2F	5/2	43425.665	19.4	0.2	10		
		7/2	43555.150	23.7	0.3	-5		
$3d^8(^1D)4p$	x^2D	3/2	43911.309	17.3	0.1			
		5/2	43921.830	19.5	0.8			
$3d^7(^2G)4s4p(^3P)$	w^4G	11/2	43951.907	32.76	0.09	-5		
		9/2	44183.169	26.15	0.09	-6		
		7/2	44394.360	18.2	0.4			
		5/2	44568.409	11.4	0.9			

TABLE 2—Continued

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work			Other authors	
				A (mK)	err (mK)	B (mK)	A (mK)	B (mK)
$3d^7(^4P)4s4p(^3P)$	$z\ ^2S$	1/2	44454.455	-7.5	0.9	0		
$3d^7(^2P)4s4p(^3P)$	^4P	5/2	44480.085	37.6	0.1			
		3/2	44657.950	39.15	0.08			
		1/2	44857.509					
$3d^7(^2G)4s4p(^3P)$	$z\ ^2H$	9/2	45111.408	14.2	0.2			
		11/2	45540.190	34.17	0.08			
$3d^8(^3P)4p$	^2D	5/2	45688.071	10.35	0.09	2		
		3/2	46186.336	14.57	0.09			
$3d^7(^2G)4s4p(^3P)$	$x\ ^2G$	7/2	45766.596	12.85	0.09		CL 14	
		9/2	46032.095	39.65	0.09		CL 35	
$3d^8(^3P)4p$	^4S	3/2	45904.617	2.4	0.3			
$3d^7(^4P)4s4p(^3P)$	$x\ ^4P$	1/2	45957.191	16.8	0.9	0		
		5/2	46002.771	22.0	0.2	1		
		3/2	46259.940	8.55	0.09			
$3d^8(^3P)4p$	^4D	7/2	45971.083	26.6	0.9			
		5/2	46329.575	18.9	0.3			
		1/2	46502.068					
		3/2	46562.784	18.5	0.5	-10		
$3d^7(^4P)4s4p(^3P)$	^2D	3/2	46454.883	17.85	0.08	3		
		5/2	46671.880	5.3	0.7	0		
$3d^8(^3P)4p$	$y\ ^2P$	3/2	46685.371	7.6	0.2	0		
		1/2	47091.095	41.8	0.2	0		
$3d^7(^2P)4s4p(^3P)$	$u\ ^4D$	7/2	46872.659	26.4	0.2			
		5/2	47393.893	18.6	0.2	1		
		3/2	47612.110	1.7	0.3	1		
		1/2	47905.198	4.5	0.3	0		
$3d^7(^2G)4s4p(^3P)$	^2F	5/2	47128.898	18.1	0.1			
		7/2	47225.026	28.9	0.2			
$3d^7(^2H)4s4p(^3P)$	^4G	11/2	47395.638	34.9	0.2			
		9/2	47838.985					
		7/2	48317.063	31.4	0.2			
		5/2	48615.402	15.8	0.4			
$3d^7(^2H)4s4p(^3P)$	^4I	11/2	47898.312					
		9/2	48105.962					
$3d^8(^3P)4p$	^2S	1/2	48026.240	-33.87	0.09	0		
$3d^7(a^2D)4s4p(^3P)$	$t\ ^4D$	7/2	48217.260	31.25	0.09	-1		
		5/2	48443.716	27.0	0.2	-2		
		3/2	48546.026	14.1	0.1	2		
		1/2	48571.681	-16.0	0.8	0		
$3d^7(^4P)4s4p(^3P)$	^2P	3/2	48334.327	28.3	0.4			
		1/2	48837.688	51.85	0.09	0		
$3d^7(^2P)4s4p(^3P)$	$x\ ^4S$	3/2	48753.666					
$3d^7(^2P)4s4p(^3P)$	^2D	5/2	48828.801					
		3/2	49025.378					
$3d^7(a^2D)4s4p(^3P)$	^4F	9/2	49197.654					
		7/2	49483.975					
		5/2	49847.050	19.7	0.4			
		3/2	50104.979					
$3d^7(^2P)4s4p(^3P)$	^2S	1/2	49754.699	102.8	0.2	0		
$3d^7(^2H)4s4p(^3P)$	^2I	11/2	49952.488	16.3	0.3			

TABLE 2—*Continued*

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work		B (mK)	Other authors	
				A (mK)	err (mK)		A (mK)	B (mK)
$3d^8(^1G)4p$	y^2H	9/2	50210.743	19.8	0.2			
		11/2	50375.835	22.6	0.1			
$3d^8(^1G)4p$	u^2F	7/2	50578.643	23.7	0.2			
		5/2	50712.401	24.32	0.09			
$3d^8(^1G)4p$	w^2G	9/2	50593.290	23.3	0.3			
		7/2	50611.197	17.75	0.09			
$3d^7(^2H)4s4p(^3P)$	^4H	11/2	50703.011	25.95	0.09			
		9/2	50902.534	22.3	0.2			
		7/2	51184.571	17.8	0.2	-3		
$3d^8(^3F)5p$	^2G	9/2	50738.176	17.7	0.2			
		7/2	51731.562	17.5	0.3	-2		
$3d^8(^3F)5p$	s^4D	7/2	50741.617	13.8	0.2			
		5/2	51139.346	18.4	0.2	-2		
		3/2	51847.266	24.7	0.2	-5		
		1/2	52263.935					
$3d^7(^2P)4s4p(^3P)$	v^2P	3/2	50925.051					
		1/2	50945.437					
$3d^8(^3F)5p$	^4G	11/2	50932.630					
		9/2	51803.311					
		7/2	52390.278	18.7	0.3	-4		
		5/2	52476.584	25.9	0.3	-2		
$3d^8(^3F)5p$	^4F	9/2	50979.758	12.2	0.3	-1		
		7/2	51896.627	17.4	0.2	-4		
		5/2	51989.373	21.1	0.2	-3		
$3d^7(a^2D)4s4p(^3P)$	w^4P	5/2	51159.980					
		3/2	52014.412					
		1/2	52355.084					
$3d^8(^3F)5p$	^2D	5/2	51863.148	20.4	0.3	4		
$3d^74s(^5F)5p$	^6D	9/2	52361.974	32.7	0.2	3		
		7/2	52920.731	31.0	1.0			
		5/2	53387.654	29.0	0.2	-2		
		3/2	53738.086	27.9	0.2	1		
$3d^74s(^5F)5p$	^6F	11/2	52543.444	30.7	0.2	2		
		9/2	53065.508	28.3	0.2	0		
		7/2	53517.201	25.3	0.2	-3		
		5/2	53874.188	22.0	0.3	-1		
		3/2	54129.140	15.9	0.3	0		
$3d^8(^3F)5p$	^2F	5/2	52578.100	22.8	0.3	-3		
$3d^74s(^5F)5p$	^6G	13/2	52785.854	26.9	0.2	2		
		11/2	53265.981	25.9	0.2	-2		
		9/2	53729.716	22.3	0.2	20		
		7/2	54101.147	18.3	0.2	0		
		5/2	54372.703	11.0	0.2	0		
$3d^7(a^2D)4s4p(^3P)$	^2F	5/2	52796.106					
		7/2	53103.692	35.5	0.4			
$3d^7(a^2D)4s4p(^3P)$	u^2D	3/2	53074.869					
		5/2	53195.946					
$3d^7(^2H)4s4p(^3P)$	v^2G	9/2	53275.956	26.0	1.0			
		7/2	53373.425	25.1	0.3			
$3d^7(a^2D)4s4p(^3P)$	^2P	1/2	53962.567					
		3/2	54165.239					

TABLE 2—Continued

Assigned Configuration	Term	J	Energy (cm ⁻¹)	This work A (mK)	err (mK)	B (mK)	Other authors A (mK)	B (mK)
3d ⁷ 4s(⁵ F)5p	⁴ G	11/2	54098.422	28.3	0.2	4		
		9/2	54791.088	21.5	0.2	2		
3d ⁷ 4s(⁵ F)5p	⁴ F	9/2	54277.671	31.5	0.2	5		
		7/2	54932.253	23.0	0.2	1		
		5/2	55386.380	12.5	0.2	4		
		3/2	55622.759					
3d ⁷ 4s(⁵ F)5p	⁴ D	7/2	54398.578	35.73	0.08	2		
		5/2	54958.984	17.3	0.8			
		3/2	55737.807	9.0	4.0			
mixture	54860°	9/2	54860.935					
3d ⁷ (² H)4s4p(³ P)	² H	11/2	54873.996	32.9	0.4			
3d ⁷ (⁴ P)4s4p(¹ P)	⁴ D	5/2	55061.427	11.3	0.6	0		
		7/2	55120.200					
		3/2	55430.283					
3d ⁷ (⁴ P)4s4p(¹ P)	⁴ S	3/2	55226.856					
3d ⁷ (⁴ P)4s4p(¹ P)	⁴ P	5/2	55508.717	14.8	0.6	0		
		3/2	55818.801					
		1/2	56133.258					
mixture	55921°	3/2	55921.803	12.5	0.9			
3d ⁷ (² G)4s4p(¹ P)	² F	7/2	58173.375					
		5/2	59388.828					
3d ⁷ (² G)4s4p(¹ P)	² H	9/2	58187.274					
3d ⁷ (² G)4s4p(¹ P)	² G	9/2	58589.076					
unknown	59020°	5/2	59020.985					
unknown	59947°	11/2	59947.830					
unknown	59951°	13/2	59951.300					

NOTE.—Author reference abbreviations not explained in Table 1: AG, Anselment et al. 1987; KB, Klotz et al. 1977; vH, von Hartrott 1968. For a level labeled with its energy level value a superscripted *o* is included in the label to indicate odd parity.

however, be regarded as very approximate, and they are listed in Tables 1 and 2 without an error estimate. Examples of fitted line profiles together with schematic diagrams of the energy levels involved in the transitions are shown in Figures 1, 2, 3, and 4.

6. CONCLUSION

This paper reports the first use of high-resolution Fourier transform spectroscopy for comprehensive measurements of hfs over a wide spectral range. Over 1000 observed Co I transitions were analyzed to determine the hfs splitting factors *A* and *B*. *A* factors for 297 levels are presented, of which 208 had previously unmeasured *A* factors. *B* factors for 156 levels are reported. In the few cases where *A* factors have been measured very accurately by laser spectroscopy, the agreement with the values in this paper is well within their uncertainty.

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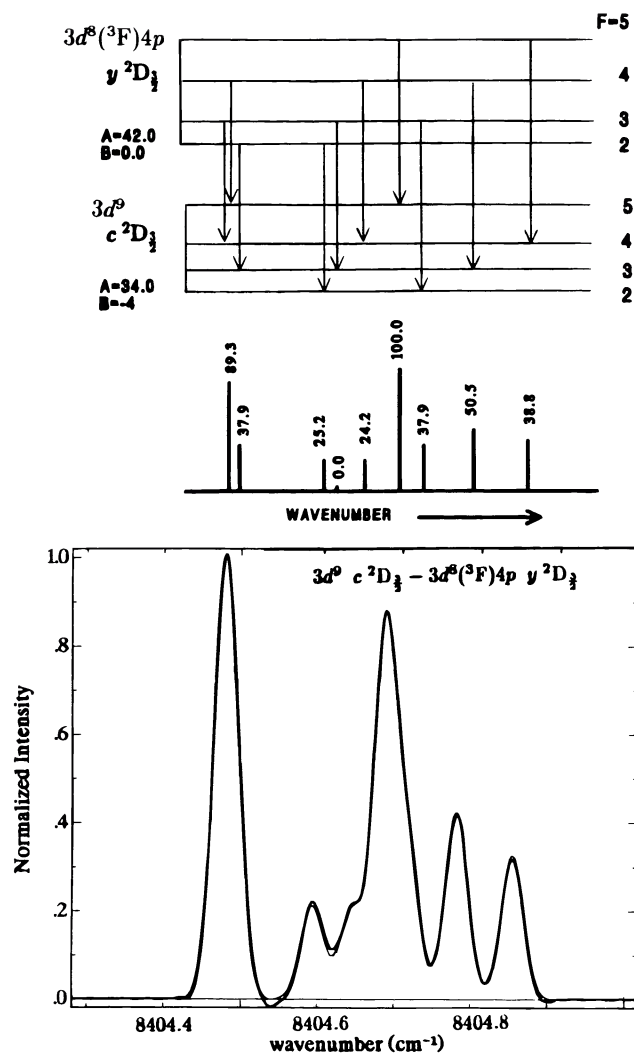


FIG. 3.—Observed (*heavier trace in plot*) and fitted line profiles, hyperfine components, and transition diagram for the Co I 11894.931 Å (8404.642 cm⁻¹) transition.

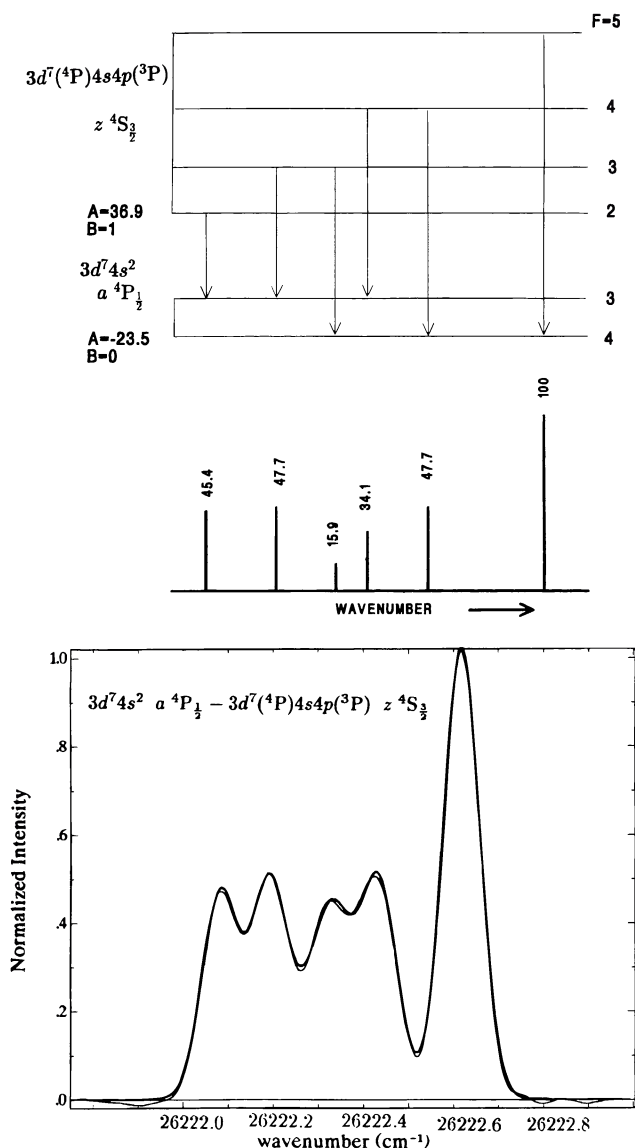


FIG. 4.—Observed (*heavier trace in plot*) and fitted line profiles, hyperfine components, and transition diagram for the Co I 3812.4561 Å (26222.367 cm⁻¹) transition.

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