Precise Measurements of the Hyperfine Structure of the Levels Belonging to the Terms $3d^5 4s$ ^5G and ^5P in Cr(I)

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The hyperfine structure intervals for the electronic levels belonging to the terms $3d^5$ (^4G) $4s$ a^5G and a^5P of a chromium 53 atom were precisely measured with the use of the method of atomic beam magnetic resonance detected by laser induced resonance fluorescence. Magnetic-dipole and electric-quadrupole hyperfine interaction constants (A and B, respectively) for the electronic levels of interest were determined with the accuracy of a few kHz. The high precision of measurements also enabled an estimation of the octupole-coupling constants (C).

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1. Introduction

In 1976 Ertmer and Hofer [1] performed a series of experiments which enabled determination of hyperfine splittings for relatively high lying metastable electronic levels. Those experiments yielded a number of very precise spectroscopic data and opened new perspectives for the progress in the semi-empirical method of the description of atomic structure.

Recently, Dembczyński et al. [2] proved that this method is especially efficient in the case of elements with open shell $3d$. The results are very promising for the solution of basic problems in atomic physics. However, the method requires large amount of experimental data concerning the hyperfine splittings of atomic levels. The quality of such description depends on both the number and the precision of the data.

On the other hand, the experimental knowledge of the spectrum of chromium atom is not very extensive. Heretofore, whereas the literature data on hyperfine coupling constants for even parity system are available for 14 levels, only for 6 levels the studies were performed with high precision methods.

The first high precision measurements of the hyperfine structure of the ground level $3d^5 4s$ a^7S_3 of chromium atom were performed in 1963 by Childs et al. [3] and in 1964 by Pendlebury and Smith [4] with the method of magnetic resonance on an atomic beam (ABMR). However, these experiments did not allow the determination of the sign of the hyperfine coupling constants but only of their absolute values. The sign of A constant was determined later by Reinhardt et al. [5].

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In 1982 Ertmer et al. [6] determined the values of the hyperfine structure constants A and B for levels $3d^4 4s^2$ $a^5D_{1,2,3,4}$ with a very precise method of atomic beam magnetic resonance detected by laser induced resonance fluorescence (ABMR-LIRF).

Lately Jarosz et al. [7] performed measurements of the hyperfine structure of the levels belonging to the multiplets $3d^5 4s$ a^5G and $3d^5 4s$ a^5P applying the method of laser induced fluorescence on an atomic beam (LIF). For the measurements of the level $3d^5 4s$ a^5S_2 more accurate ABMR-LIRF method was used, which enabled the determination of A, B, and C constants.

The present work is devoted to the experimental reinvestigations of the hyperfine structure of the levels belonging to terms $3d^5(^4G)$ $4s$ a^5G and a^5P (with the exception of the level $3d^5$ (^4G) $4s$ a^5G_2) with the aim at increasing the precision of the measurements. The ABMR-LIFR method was used as it gives three orders of magnitude better precision in comparison with standard LIF on an atomic beam method. The level $3d^5$ (^4G) $4s$ a^5G_2 was not investigated due to its very low magnetic dipole interaction constant A and thus a very small hyperfine splitting, well below the lower limit of the frequency range available with our equipment.

2. Experiment

The ABMR-LIRF method was chosen to perform the reported measurements since it provides a very good accuracy. The precision of determination of the frequencies of rf transitions between hyperfine sub-levels usually reaches the order of 1 kHz or better.

The vacuum apparatus used to produce an atomic beam is the one kindly donated to us by Ertmer; it was later modified in our laboratory to reduce the influence of Earth- and stray-magnetic field and thus to minimize
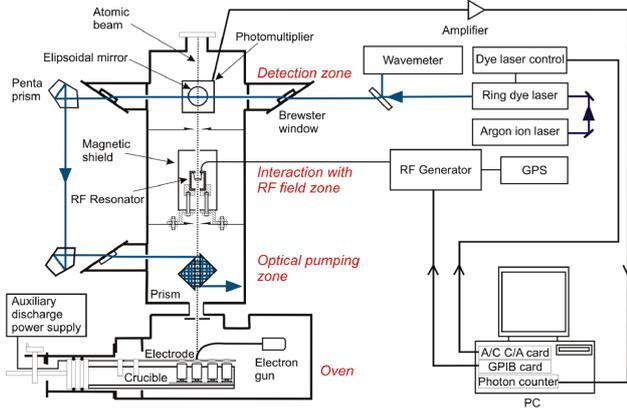
Fig. 1. Schematic diagram of experimental setup.

the Zeeman splitting. A schematic diagram of the experimental setup is presented in Fig. 1.

The crucible was heated by electron bombardment. Because of a very low thermal population of the high lying metastable levels an additional discharge was applied just above the crucible.

The laser system is based on a single-mode tunable dye laser (a modified version of Coherent, model CR 699-21), optically pumped with an argon ion laser and operating on the dye stilbene 3, with an active frequency stabilization system. In order to control the laser frequency a wavemeter (Burleigh, type WA-1500) and a frequency marker — a Fabry–Perot interferometer with FSR = 150 MHz were used.

As a source of radio-frequency microwaves a precise, high stability rf generator (Gigatronics, model GT9000S) was applied. The stability of the generator was additionally increased by the use of a frequency standard synchronized to a GPS signal.

The laser induced fluorescence signal was collected by an optical setup inside the vacuum chamber and detected with the use of a photomultiplier and a photon counting system.

As a first step, a smooth laser frequency scan over several GHz was applied to record the whole hyperfine structure of the spectral line corresponding to the transition involving the levels under the study.

As an example, the hyperfine structure of the selected spectral line of chromium 53 atom, recorded with the use of laser induced fluorescence on an atomic beam method, is presented in Fig. 2 (strong fine structure lines of other chromium isotopes are also visible). The corresponding transitions involve the levels: $3d^5 4s\ a^5 G_6$ at 20519.60 cm^{-1} (lower) and $3d^5 4p\ z^5 G_6^0$ at 42605.81 cm^{-1} (upper). A scheme of these transitions for ^{53}Cr(I) is shown below the recorded spectrum, and the hyperfine intervals chosen for further measurements with the ABMR-LIRF method are marked with arrows.

In the second step the laser radiation frequency was fixed on a particular hyperfine component and a radio--frequency scan of *ca*. 1 MHz width was applied.
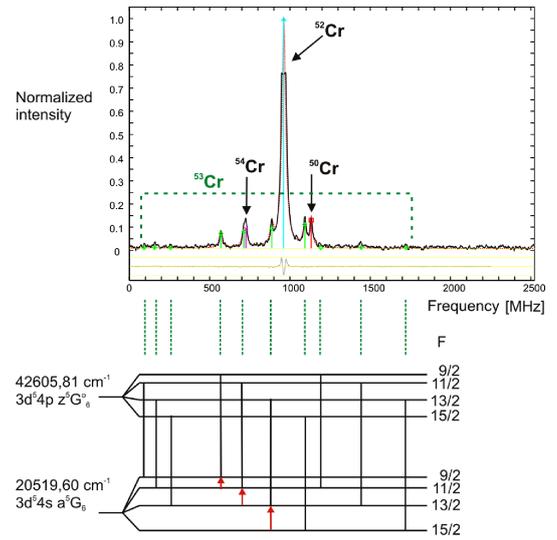

Fig. 2. Hyperfine structure of the spectral line $\lambda = 452.6443$ nm from the level $3d^5 4s\ a^5 G_6$ to the level $3d^5 4p\ z^5 G_6^0$, recorded with the LIF method on an atomic beam. Besides the lines of interest, some fine structure lines of other chromium isotopes are visible. Below the spectrum there is a scheme of relevant levels and transitions. The intervals marked with arrows are chosen for further measurements with the ABMR-LIRF method.
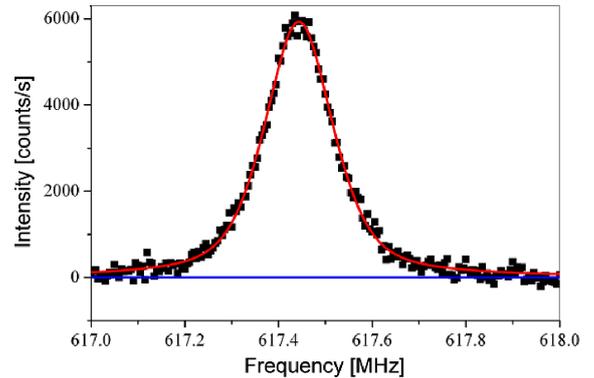

Fig. 3. The ABMR-LIRF signal for the transition between hyperfine sub-levels $F = 9/2$ — $F = 11/2$ of the level $3d^5 4s\ ^5 G_6$.

In Fig. 3 the ABMR-LIRF signal for the rf transition between hyperfine sub-levels $F = 11/2$ — $F = 9/2$ of the level $3d^5 4s\ ^5 G_6$ ($E = 20519.60$ cm^{-1}) is presented. The resonance curves were fitted with the Voight function. The widths of the resonance lines within the range 120–170 kHz were mainly caused by the time-of-flight effect (short time of atoms–rf-field interaction). For every rf transition investigated 10–30 scans were recorded. The errors quoted with the results are purely statistical ones (three times the standard deviations).

TABLE I
Details concerning the transitions investigated in chromium atom.

No	λ_{air} [nm]	E [cm^{-1}]	J	configuration	E [cm^{-1}]	J	configuration
		Line			**Lower level**		**Upper level**
1	452.6443	20519.60	6	$3d^54s\ ^5G_6$	42605.81	6	$3d^54p\ ^5G_6^0$
2	453.5125	20520.92	3	$3d^54s\ ^5G_3$	42564.85	4	$3d^54p\ ^5G_4^0$
3	454.1060	20523.69	4	$3d^54s\ ^5G_4$	42538.81	3	$3d^54p\ ^5G_3^0$
4	453.5746	20523.94	5	$3d^54s\ ^5G_5$	42564.85	4	$3d^54p\ ^5G_4^0$
5	429.5731	21840.84	3	$3d^54s\ ^5P_3$	45113.22	3	$3d^44s4p\ ^5P_3^0$
6	429.7031	21847.88	2	$3d^54s\ ^5P_2$	45113.22	3	$3d^44s4p\ ^5P_3^0$
7	453.5746	21856.94	1	$3d^54s\ ^5P_1$	44875.19	2	$3d^44s4p\ ^5P_2^0$

TABLE II
Obtained values of the hfs intervals in the levels belonging to terms $3d^54s\ ^5G$ and ^5P.

Energy [cm^{-1}]	J	Designation	rf transition	Interval [MHz]
20519.60	6	$3d^54s\ ^5G_6$	$F=11/2 \to F=9/2$	617.4432(5)
			$F=13/2 \to F=11/2$	727.7001(7)
			$F=15/2 \to F=13/2$	836.9505(18)
20520.92	3	$3d^54s\ ^5G_3$	$F=5/2 \to F=3/2$	141.6558(14)
			$F=7/2 \to F=5/2$	198.2177(12)
			$F=9/2 \to F=7/2$	254.6888(12)
20523.69	4	$3d^54s\ ^5G_4$	$F=7/2 \to F=5/2$	289.4988(16)
			$F=9/2 \to F=7/2$	371.3389(10)
			$F=11/2 \to F=9/2$	452.8418(14)
20523.94	5	$3d^54s\ ^5G_5$	$F=9/2 \to F=7/2$	443.9948(12)
			$F=11/2 \to F=9/2$	543.0679(10)
			$F=13/2 \to F=11/2$	642.5657(9)
21840.84	3	$3d^54s\ ^5P_3$	$F=5/2 \to F=3/2$	305.4279(42)
			$F=7/2 \to F=5/2$	434.7231(15)
			$F=9/2 \to F=7/2$	571.1499(9)
21847.88	3	$3d^54s\ ^5P_2$	$F=3/2 \to F=1/2$	237.3666(43)
			$F=5/2 \to F=3/2$	397.3715(19)
			$F=7/2 \to F=5/2$	560.0414(13)
21856.94	1	$3d^54s\ ^5P_1$	$F=3/2 \to F=1/2$	274.430(5)
			$F=5/2 \to F=3/2$	452.156(2)

TABLE III
Obtained values of hyperfine interaction constants for the levels belonging to terms $3d^54s\ ^5G$ and $3d^54s\ ^5P$ in Cr(I). Values for the level $3d^54s\ ^5G_2$ ($E = 20517.40$ cm^{-1}) are quoted after [7].

Designation	Energy [cm^{-1}]	A_{exp} [MHz]	A_{ref} [7] [MHz]	B_{exp} [MHz]	B_{ref} [7] [MHz]	C_{exp} [MHz]
$3d^54s\ ^5G_2$	20517.40	–	1.6(6)	–	1.9(21)	–
$3d^54s\ ^5G_6$	20519.60	$-111.87653(16)$	$-112.14(20)$	3.39682(84)	8.3(27)	0.00009(20)
$3d^54s\ ^5G_3$	20520.92	$-56.62031(10)$	$-57.47(52)$	0.13773(64)	9.5(14)	$-0.00012(50)$
$3d^54s\ ^5G_4$	20523.69	$-82.47239(3)$	$-82.80(34)$	1.1433(15)	$-1.3(8)$	$-0.0054(5)$
$3d^54s\ ^5G_5$	20523.94	$-98.77331(1)$	$-98.84(26)$	$-0.79924(65)$	4.5(54)	$-0.0038(8)$
$3d^54s\ ^5P_3$	21840.84	$-125.2251(5)$	$-125.89(33)$	$-10.1817(24)$	$-12.6(10)$	$-0.00009(8)$
$3d^54s\ ^5P_2$	21847.88	$-159.4806(7)$	$-161.9(20)$	$-2.1237(19)$	$-9.9(4)$	$-0.000136(55)$
$3d^54s\ ^5P_1$	21856.94	$-181.3851(14)$	$-183.3(6)$	1.0455(13)	0.1(6)	–

3. Results

Details concerning the transitions investigated are presented in Table I. The table is arranged according to the low level energy. Values of the hfs intervals in the levels belonging to terms ^5G and ^5P, obtained in the experiment are listed in Table II. Values for the level $3d^54s$ a^5G_2 ($E = 20517.40$ cm^{-1}) are quoted after [7].

The relative position of a hyperfine sub-level with respect to the level's center of gravity is expressed by the terms proportional to the constants A, B, and C [8].

For each level a set of equations corresponding to the measured intervals between hyperfine sub-levels (ΔE_{F1-F2}) was derived and solved with respect to A, B, C constants.

Table III presents the obtained values of the hyperfine interactions constants A, B, and C; A and B are compared with the previously measured ones [7] (A_{ref}, B_{ref}).

4. Conclusions

Within this work hyperfine splittings of four levels belonging to the term $3d^54s$ a^5G in the chromium atom and for three levels of the term $3d^54s$ a^5P have been precisely measured with the ABMR-LIRF method reaching the accuracy from hundreds Hz to few kHz. The accuracy of determination of A and B hyperfine interaction constants was improved by about three orders of magnitude, if compared with the values determined in Ref. [7]. The high precision of the measurements allowed the determination of the octupole magnetic coupling constants C for the first time for the investigated terms.

The very precise results obtained contribute to the data basis required in calculations aimed at solving basic problems in atomic physics, as discussed in Introduction with reference to paper [2].

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