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Hyperfine-interaction constants of the $8D_{3/2}$ state in ^{85}Rb using quantum-beat spectroscopy

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Quantum beats due to the hyperfine interaction were observed in the radiative decay of the $8D_{3/2}$ state in ^{85}Rb. The data agree well with theory allowing determination of the magnetic-dipole ($|a|=0.879\pm0.008$ MHz) and electric-quadrupole ($|b|=0.15\pm0.02$ MHz) ($a/b>0$) hyperfine constants. The results are consistent with those obtained for other $D_{3/2}$ states in ^{85}Rb and ^{87}Rb. The observed magnetic-dipole constants for the $nD_{3/2}$ $n>7$ states of ^{85}Rb are given to within 2% by the relation $a(\mathrm{MHz})=252/n^{*3}$ where n^* is the effective principal quantum number.

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I. INTRODUCTION

The hyperfine interaction of excited alkali-metal states tests our understanding of atomic structure [1,2]. Alkali-metal atoms can be simply modeled as consisting of a single valence electron interacting with a central field generated by the nucleus and core electrons. For excited D states, it is well known that many-body refinements such as polarization of the inner electron core, electron correlation, and relativistic effects strongly perturb the hyperfine interaction [3]. The hyperfine Hamiltonian consists of the magnetic-dipole and electric-quadrupole interactions between the valence electron and the nucleus and is given below.

$$H=ah\mathbf{I}\cdot\mathbf{J}+bh\frac{[3(\mathbf{I}\cdot\mathbf{J})^2+\frac{3}{2}\mathbf{I}\cdot\mathbf{J}-(\mathbf{I}\cdot\mathbf{I})(\mathbf{J}\cdot\mathbf{J})]}{2I(2I-1)J(2J-1)}\;. \tag{1}$$

Here, h is Planck's constant, $\mathbf{J}$ is the angular momentum of the valence electron, $\mathbf{I}$ is the nuclear spin, and a and b are the magnetic-dipole and electric-quadrupole coupling constants, respectively. As far as we know, the magnetic-dipole coupling constant computed by Lindgren and Morrison [1] for the lowest $D_{3/2}$ state in ^{87}Rb is the only one in close agreement with experiment. In this brief report, measurements of the hyperfine coupling constants for the $8D_{3/2}$ state in ^{85}Rb are presented. The results are shown to be consistent with those previously obtained for other $D_{3/2}$ states in both ^{85}Rb and ^{87}Rb.

II. EXPERIMENT

This experiment used quantum-beat spectroscopy [4,5] to determine the hyperfine coupling constants. The same apparatus was used previously [6,7] and is therefore only briefly described. ^{85}Rb atoms are contained in an evacuated Pyrex cell. The atoms are excited by a tunable pulsed dye laser from the $5S_{1/2}$ ground state to the $8D_{3/2}$ state via a two-photon excitation as shown in Fig. 1. This excited state is a superposition of excited hyperfine states since the laser linewidth ($0.07\ \mathrm{cm}^{-1}$) exceeds the hyperfine splitting. Fluorescence, produced by the radiative decay of the $8D_{3/2}$ to the $5P_{1/2}$ state, was detected by a photomultiplier (Hamamatsu model R928). The intensity of fluorescence polarized parallel to the laser polarization direction, is given by the expression [4–8]

$$\begin{aligned}I(t)=I_0e^{-t/\tau}[1+K(\tfrac{1957}{1400}&+\tfrac{15}{8}\cos\omega_{43}t+\tfrac{2}{5}\cos\omega_{32}t\\&+\tfrac{7}{20}\cos\omega_{21}t+\tfrac{6}{7}\cos\omega_{42}t\\&+\tfrac{28}{25}\cos\omega_{31}t)]\;.\end{aligned} \tag{2}$$

I_0 is a constant dependent on the light-detection efficiency and τ is the excited-state radiative lifetime. The relative size of the beats is determined by K, which is a function of the fluorescence polarization. The modulation frequencies are listed in Table I.

The beat amplitudes are reduced by a magnetic field that decouples the electronic and nuclear angular momenta. The vapor cell is therefore located at the center of three pairs of orthogonal Helmholtz coils that cancel

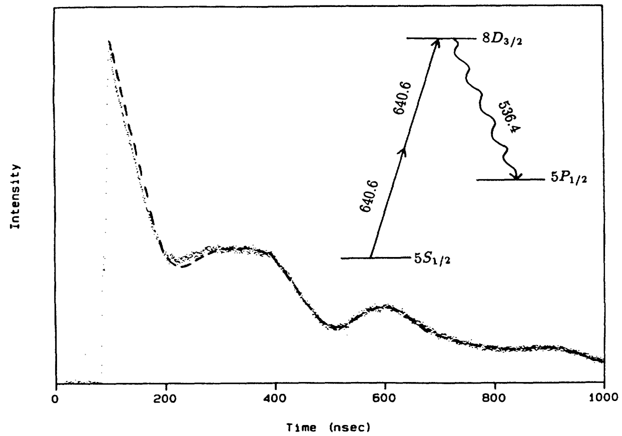

FIG. 1. Sample experimental data. A laser pulse of wavelength 640.6 nm excites the $8D_{3/2}$ state in ^{85}Rb via a two-photon excitation of the ground state. The fluorescence produced by the $8D_{3/2}\rightarrow5P_{1/2}$ transition is detected by a photomultiplier using an interference filter transmitting at 536.4 nm. The dashed curve is the best theoretical fit to the data points.

TABLE I. Quantum-beat frequencies.

F	F'	$\omega_{FF'}/2\pi$
4	3	$4a+4b/5$
4	2	$7a+b/5$
3	2	$3a-9b/20$
3	1	$5a-5b/4$
2	1	$2a-4b/5$

the Earth's field. The residual field was measured using a Hall-effect gaussmeter to be less than 10 mG. Data resulting from 1000 laser pulses were accumulated in a transient digitizer (LeCroy Waveform Digitizer 6880A). It has an analog bandwidth of 400 MHz and digitized the signal every 742 psec. The data were then fitted to Eq. (2) by a computer using a least-square algorithm.

A typical set of data is shown in Fig. 1. The residual discrepancy between the fitted curve and the data evident at times less than 300 nsec corresponds to the laser-pulse duration of about 7 nsec. The precise temporal profile of the laser pulse is not known, and therefore the fitted curve given by Eq. (2) assumes all atoms are excited at the same time $t=0$. The resulting a and b values were found to be independent of cell temperatures and laser-pulse energies. The cell temperature was varied from 80 °C to 120 °C, corresponding to rubidium densities of $10^{12}-10^{13}$ atoms/cm^3 [8]. Data were taken with laser-pulse energies between 1 and 10 mJ. The quoted value of the ^{85}Rb $8D_{3/2}$ hyperfine coupling constants is the average value of nine separate runs. The error bars are equal to one standard deviation of the best-fit parameters about their mean values. The sign of the coupling constants could not be found since Eq. (2) is unchanged if a and b have opposite sign. The ratio a/b was found to be positive.

III. DISCUSSION

Table II lists values found for the magnetic-dipole and electric-quadrupole coupling constants of the $nD_{3/2}$ states in ^{85}Rb. The table includes data that were scaled from measurements taken for ^{87}Rb using the following:

$$\begin{aligned}\frac{a_{85}}{a_{87}} &= \left[\frac{\mu}{I}\right]_{85} \Big/ \left[\frac{\mu}{I}\right]_{87} \\ &= \frac{1.3482}{5/2} \Big/ \frac{2.7414}{3/2} \\ &= 0.295\ ,\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{b_{85}}{b_{87}} &= \frac{Q_{85}}{Q_{87}} \\ &= 2.00\ .\end{aligned} \tag{4}$$

Here we have used values for the nuclear magnetic-dipole μ and electric-quadrupole Q moments found in Refs. [9,10]. The magnetic-dipole hyperfine coupling constants measured in ^{85}Rb are consistent with data scaled from ^{87}Rb observations. This confirms the validity of the various experimental methods, which include level crossing, magnetic decoupling and quantum-beat spectroscopy. The electric-quadrupole constants have substantially larger uncertainties than the magnetic-dipole results because the hyperfine interaction is dominated by the magnetic-dipole term. In principle, it is easier to determine the electric-quadrupole constant in ^{85}Rb since its quadrupole moment is twice as large as that for ^{87}Rb.

The hyperfine interaction decreases rapidly for higher-lying states. Kopfermann [11] showed that the magnetic-dipole constant is proportional to the expectation value of r^{-3}, where r is the distance between the nucleus and valence electron. For highly excited electrons, the valence electron is far from the core electrons and $\langle r^{-3}\rangle$ is well approximated by the hydrogenic result

$$\langle r^{-3}\rangle = \frac{A}{a_0^3 n^{*3}}\ , \tag{5}$$

where A is a constant that depends on the nuclear charge and various angular momenta, a_0 is the Bohr radius, and n^* is the effective principal quantum number. Figure 2

TABLE II. Hyperfine constants for ^{85}Rb $nD_{3/2}$ states. a_{scal} and b_{scal} are scaled from measurements in ^{87}Rb as is discussed in the text.

n	n^*	$\lvert a\rvert$	$\lvert a_{\text{scal}}\rvert$	$\lvert b\rvert$	$\lvert b_{\text{scal}}\rvert$
4	2.77	7.3±0.5[a]	7.41±0.27[a]		
5	3.71	4.18±0.20[b]	4.26±0.7[b]		
6	4.68	2.32±0.06[c]	2.31±0.15[d]	1.62±0.06[c]	1.06±0.12[d]
7	5.67	1.415±0.030[e]	1.34±0.01[d]	0.31±0.6[e]	0.52±0.08[d]
8	6.67	0.879±0.008	0.838±0.004[f]	0.15±0.02	0.34±0.04[f]
9	7.66		0.561±0.003[f]		0.22±0.06[f]
10	8.66		0.388±0.005[g]		0.14±0.02[g]
11	9.66		0.282±0.003[g]		0.098±0.012[g]
12	10.66		0.211±0.0035[g]		0.074±0.016[g]

[a] Reference [12].

[b] Reference [13].

[c] Reference [6].

[d] Reference [14].

[e] Reference [7].

[f] Reference [15].

[g] Reference [16].

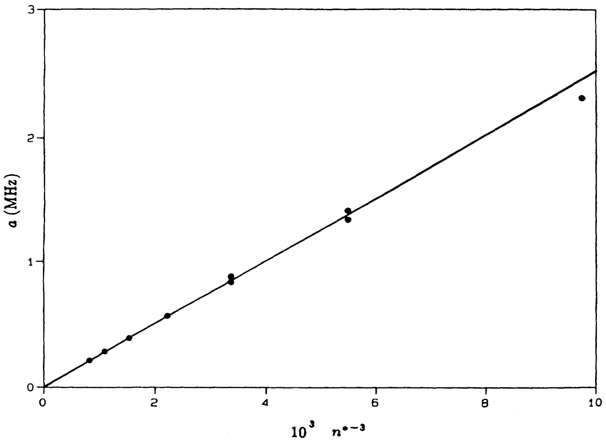

FIG. 2. Dependence of magnetic-dipole coupling constant a on effective principal quantum number n^* for the (6–12) $D_{3/2}$ states.

verifies that for the $nD_{3/2}$ $n=7-12$ states, $a=Cn^{*-3}$ where C is found using a least-squares fit to be 252. The factor C increases less than 1% if data for the $7D_{3/2}$ state are excluded from the fit.

In conclusion, we have measured the magnetic-dipole and electric-quadrupole constants for the ^{85}Rb $8D_{3/2}$ state. The values are consistent with data measured for other $D_{3/2}$ states in ^{85}Rb and ^{87}Rb. For the $nD_{3/2}$ $n=7-12$ states, the observed magnetic-dipole constant values agree to better than 2% with those given by $a=252/n^{*3}$. This result provides information for high-lying $D_{3/2}$ states not studied by experiment.

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