REMOVAL OF ZEEMAN-LEVEL DEGENERACY IN ALKALI ATOMS BY AN ELECTRIC FIELD*

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When a uniform electric field is applied to an alkali atom in its ground state ($^2S_{1/2}$), the hyperfine splitting is reduced. This effect, which is quadratic in the applied field strength, was first observed by Haun and Zacharias[1] in an atomic-beam experiment; they examined the transition $(4,0) \leftrightarrow (3,0)$ in cesium where the frequency shift is large, amounting to approximately 20 kc/sec in a field of 10^5 V/cm. This same (but much smaller) effect has been observed recently in atomic hydrogen by Fortson, Kleppner, and Ramsey,[2] in an experiment with a hydrogen maser. Anderson[3] has given a quantitative explanation of the cesium shift in terms of the modification of the hyperfine-contact interaction due to the polarization of the atom by the electric field. Anderson's theory does not predict any splitting of the Zeeman levels by the electric field and this prediction is unchanged by the presence of a magnetic field. In the present experiment we have examined the effect of an electric field on the Zeeman transition $(4,-3) \leftrightarrow (4,-4)$ in cesium at a field of a few gauss, and we observe a small shift quadratic in the electric field strength.

We have used a novel method which enables us to measure easily shifts in the position of the resonance line as small as 10^{-3} of a linewidth and to detect shifts an order of magnitude smaller. A beam of cesium atoms passes between two closely spaced metal plates (length 3 in.) which lie between the loops of a Ramsey double-hairpin structure (loop separation 4 in.). The transition is induced, and the signal adjusted to the point of maximum slope on one side of the central peak of the resonance, at which point any displacement of the resonance will be reflected with maximum sensitivity as a change in the ion current at the hot-wire detector. The resonance is in effect used as a "displacement amplifier," a method similar to that used by Browne[4] in a paramagnetic-resonance experiment involving electric fields. Large dc and ac (25 cps) electric fields can be applied simultaneously to the beam as it passes between the plates; in the present apparatus fields of 60 000 V/cm are easily sustained.

Let

$$\delta\nu = k_1 E^2 \tag{1}$$

be the shift between the Zeeman levels due to a quadratic Stark effect in field E. If $E = E_{dc} + E_0 \sin\omega t$, then

$$\delta\nu = k_1[E_{dc}^2 + 2E_{dc}E_0 \sin\omega t + \tfrac{1}{2}E_0^2(1-\cos 2\omega t)], \tag{2}$$

so that the detector output S which is proportional to E_{dc} will contain frequency components at ω and 2ω, either of which can be singled out by phase-sensitive detection to yield a value of k_1 if the resonance slope is known. The latter quantity is found by observing the signal when the rf is frequency modulated by a known amount.

In our apparatus the width of the central Ramsey peak is 2 kc/sec, and shifts of 1 cps in the position of the resonance are easily measured. Figure 1 shows the signal at the fun-

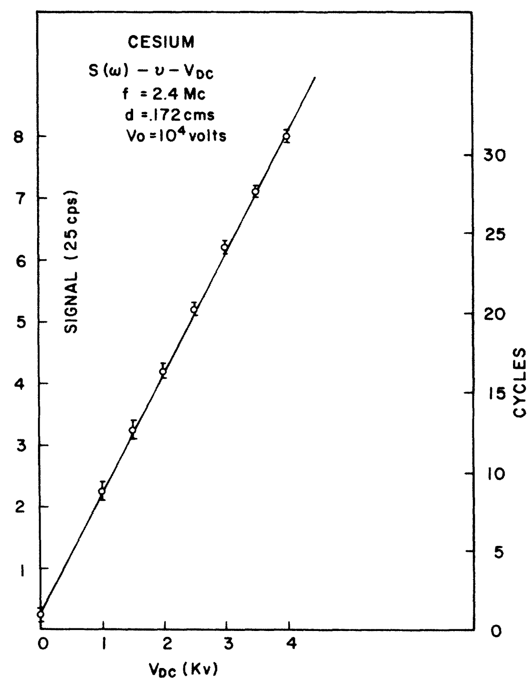

FIG. 1. Frequency shift modulated at ω vs dc voltage at fixed ac voltage.

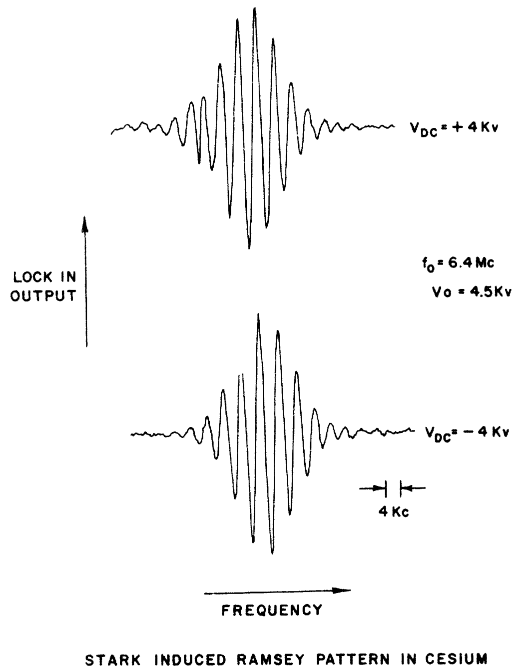

FIG. 2. Signal observed on Zeeman transition $(4,-3) \leftrightarrow (4,-4)$ with electric-field modulation of Zeeman levels. The signal is the derivative of the Ramsey pattern. Note that the phase of the signal changes by π when the dc electric field is reversed, as expected from Eq. (2).

damental frequency, $S(\omega)$, as a function of the dc voltage between the plates at a fixed ac voltage, and Fig. 2 exhibits the derivative of the Ramsey pattern obtained with electric-field modulation instead of the more customary magnetic-field modulation. The linear relationship expected from Eq. (2) is well in evidence, but the line does not pass through the origin; the reason for this is nontrivial and will be discussed in the following Letter. The second-harmonic signal $S(2\omega)$ is found to be proportional to the square of the applied ac voltage. The values of k_1 obtained at the two frequencies are in excellent agreement with each other. From eight runs, six at the fundamental frequency and two at the second-harmonic frequency, we find for cesium

$$k_1 = -(1.1 \pm 0.1)\times 10^{-8} \text{ cps}/(\text{V/cm})^2,$$

so that the shift between the Zeeman levels in a field of 10^5 V/cm is 110 ± 10 cps. The major source of uncertainty at the present time is in the measurement of the frequency-modulation amplitude.

We believe that the splitting of the Zeeman levels is due to a third-order process involving the hyperfine interaction in excited states. The general expression for the shift of a single Zeeman level will contain terms of the form

$$e^2E^2 \frac{\langle s|Z|p\rangle\langle p|\text{hfs}|p\rangle\langle p|Z|s\rangle}{(\Delta W)^2}.$$

If we neglect all excited states except the $6p$, a step justified by the large oscillator strength ($f \approx 1$) and small energy denominator ($\Delta W \approx 1$ eV) involved, we obtain the following expression for the quadratic Stark shift in the observable Zeeman transition:

$$\delta\nu = -\frac{3}{4}\frac{\alpha E^2}{\Delta W}\frac{[3IA_{3/2} - 2b_{3/2}]}{2I+1}. \quad (3)$$

Here α = polarizability of cesium[5] $48 \pm 6\times 10^{-24}$ cm^3, E = electric field in V/cm, $\Delta W = W(6p) - W(6s) = 2.28\times 10^{-12}$ erg, $A_{3/2}$ = magnetic-dipole hfs constant in $6P_{3/2}$ state,[6] $A_{3/2} = 50.7$ Mc/sec, $b_{3/2}$ = electric-quadrupole constant in $6P_{3/2}$ state[6] ≈ 0, I = nuclear spin = $\frac{7}{2}$. Substituting, we find at a field of 10^5 V/cm that

$$\delta\nu = -117 \text{ cps},$$

in satisfactory agreement with the experimental result.

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[1]R. D. Haun, Jr., and J. R. Zacharias, Phys. Rev. 107, 107 (1957).

[2]E. N. Fortson, D. Kleppner, and N. F. Ramsey, Phys. Rev. Letters 13, 22 (1964).

[3]L. W. Anderson, Nuovo Cimento 22, 936 (1961).

[4]M. E. Browne, Phys. Rev. 121, 1699 (1961).

[5]G. E. Chamberlain and J. C. Zorn, Phys. Rev. 129, 677 (1963).

[6]P. Buck, I. I. Rabi, and B. Senitzky, Phys. Rev. 104, 553 (1956).