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ELECTRIC-FIELD LEVEL-CROSSING SPECTROSCOPY

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In this Letter we report on the first observation of pure electric-field level crossings at finite electric field and the use of these observations to determine the differential Stark effect in the second excited state of the alkali metal atoms. In previous work Stark parameters have been measured by level crossing in combined electric and magnetic fields.[1,2] This work is the first experimental demonstration that the application of an electric field will cause certain hyperfine structure levels to intersect at other than zero electric field. These experiments are similar to the magnetic field level-crossing experiments in that if levels with m_F differing by one or two can be made to intersect by an electric field, then a change in the angular distribution and the polarization of the scattered resonance radiation will occur. Since our technique compares the shift of the levels due to an electric field with the hfs, the hfs of the excited state must be known in order to deduce the magnitude of the differential Stark effect.

The theory of resonance fluorescence from optically excited atoms has been adequately treated in the literature. The intensity, $R(\vec{f},\vec{g})$, of laterally scattered light is given by the Breit formula[3]

$$R(\vec{f},\vec{g}) = C \sum_{\mu\mu' mm'} \frac{f_{\mu m} f_{m\mu'} g_{\mu' m'} g_{m'\mu}}{1-2\pi i\tau\nu(\mu,\mu')}. \quad (1)$$

Here $f_{\mu m} = (\mu|\vec{f}\cdot\vec{r}|m)$, etc., where $\vec{f}$ and $\vec{g}$ are the polarization vectors of the exciting light and the fluorescent light, respectively.

The eigenvectors of the excited state and ground state are $|\mu\rangle$ and $|m\rangle$, respectively; τ is the radiative lifetime of the excited state, and $\nu(\mu,\mu') = (E_\mu - E_{\mu'})/h$ is the difference of excited-state term values. In (1) it is implicitly assumed that the line profile of the excited light is essentially flat over the hyperfine components of the atomic-resonance line. This is only approximately true for the lamps used in these experiments, and effects due to scanning of the absorption lines through the lamp profile do occur.

The effective Hamiltonian for the excited

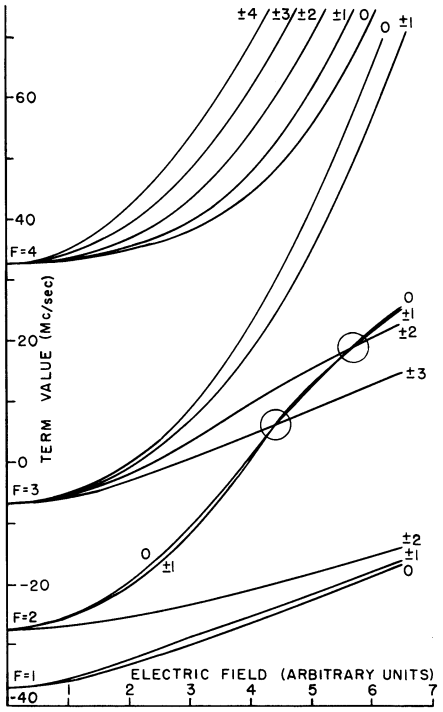

FIG. 1. Dependence of the Rb^{85} hfs levels on the applied electric field E. A common downward shift of all levels proportional to E^2 has been suppressed.

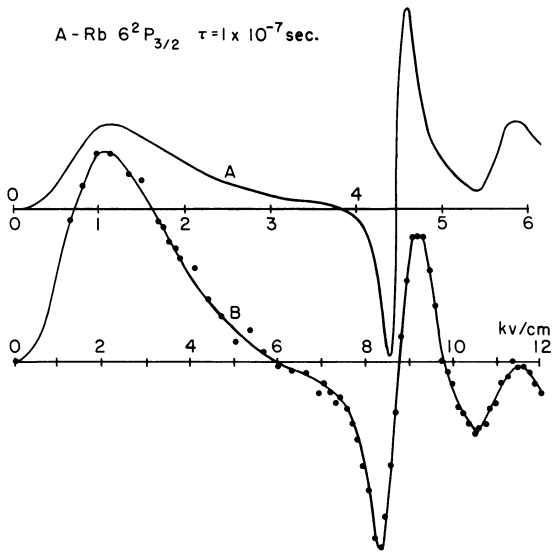

FIG. 2. Curve A: Theoretical derivative curve $dR(\vec{f},\vec{g})/dE$ for the natural isotope mixture of 72.15% Rb^{85} and 27.85% Rb^{87}. The incident light spectrum has been assumed to be flat over the absorption profile of both isotopes. The scale shown is the same as that in the energy-level diagram. Curve B: Observed phase-sensitive amplified output signal as a function of applied electric field.

state of an atom in an electric field is

$$\mathcal{H} = A\vec{I}\cdot\vec{J} + B\frac{3(\vec{I}\cdot\vec{J})^2 + \frac{3}{2}\vec{I}\cdot\vec{J} - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)} + (\beta E J_z)^2. \quad (2)$$

The first two terms are the usual magnetic-dipole and electric-quadrupole hyperfine-structure interactions, while the third term represents the differential Stark shift caused by an electric field, E, along the z axis. Only energy differences are represented correctly by (2) since a shift (proportional to E^2) of the center of gravity of the multiplet has been suppressed.

A computer program is used to solve (2) and (1). Input data to the program include the hyperfine-structure parameters, A, B, I, J, g_J, and β; the excited-state lifetime, τ; the polarization vectors, $\vec{f}$ and $\vec{g}$; and the electric or magnetic field intervals over which the signal (1) is to be computed. The curves shown in Figs. 1 and 2(a) require about 8 min of time on an IBM 7094 computer. The output includes the term values, the level-crossing signal, and its derivative with respect to the field parameter. The term-value diagram for Rb^{85} is reproduced in Fig. 1. Several hyperfine levels cross in passage from a region of low electric field to a region of high electric field. For comparison with the experimental signal obtained with phase-sensitive detection, a the-

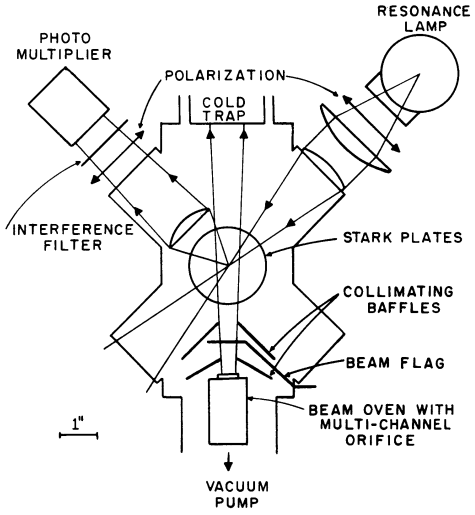

FIG. 3. Schematic diagram of the experimental apparatus.

Table I. Results of the present experiment and comparison with other experimental and theoretical work.

Nucleus	State	A (Mc/sec)	B (Mc/sec)	$2\beta^2 = E(\pm\frac{3}{2}) - E(\pm\frac{1}{2})$ [Mc/sec/(kV/cm)^2] Present experiment	Other determination	Crossing field (kV/cm) Present experiment
Cs^{133}	$7^2P_{3/2}$	16.609[a]	−0.16[a]	1.077 ± 0.043	1.02,[b] theor.	11.07 ± 0.2
Rb^{85}	$6^2P_{3/2}$	8.16[a]	8.40[a]	0.521 ± 0.021	0.72,[c] exptl.	8.77 ± 0.18, 11.0
Rb^{87}		27.63[a]	4.06[a]			14.0

[a]G. zu Putlitz, Ergeb. Exakt. Naturw. 37, 105 (1965).
[b]K. Murakawa and M. Yamamoto, J. Phys. Soc. Japan 20, 1057 (1965).
[c]Y. T. Yao, Z. Physik 77, 307 (1932).

oretical derivative curve $dR(\vec{f}, \vec{g})/dE$, for a natural mixture of Rb^{85} and Rb^{87}, is plotted in Fig. 2(a).

The experimental arrangement is shown in Fig. 3. The resonance radiation incident from the lamp is passed through a linear polarizer and focused onto a collimated atomic beam. A fraction of the light scattered by the beam is collected by a lens system, passed through a linear polarizer and interference filter, and detected by a photomultiplier. The incident and detected light, the direction of polarization, and the atomic beam all lie in a plane perpendicular to the electric field. Initial attempts to carry out the experiment in a glass cell failed because we were unable to produce a sufficient electric field between the electric field plates due to electrical conduction along the walls of the alkali-filled cell. The atomic beam has several advantages over a cell, viz. (1) the instrumental scattering can be distinguished from the atomic scattering by interrupting the beam with a flag, and (2) the region in which the atoms and the radiation interact can be confined to the center of the electric field plates. To improve the signal-to-noise ratio the voltage was modulated at 280 cps so that phase-sensitive amplification of the photomultiplier signal could be employed. The stainless-steel electric field plates were 2 in. in diameter and were accurately separated by $\frac{5}{8}$ in. by two quartz rods.

Figure 2(b) shows a plot of photomultiplier output as a function of the electric field. This curve differs from the calculated derivative curve, Fig. 2(a), in two respects: (1) The resonance signal is broadened due to modulation of the electric field, and (2) the effect of the scanning of the source mentioned earlier diminishes the height and lowers the base of the resonances at high fields.

The experimental results for the Stark parameter, $2\beta^2 = E(\pm\frac{3}{2}) - E(\pm\frac{1}{2})$, for cesium and rubidium are tabulated in Table I along with the values of the same quantity determined by other methods. The values of the electric field at which level crossings occur are also shown.

The criterion for the feasibility of this technique for other states or other elements is that the hfs levels be well resolved and that the differential Stark shift for attainable electric fields be comparable to the hfs separation. It is clear that this method is readily adaptable to many other systems, and that it should yield a number of Stark parameters which can be used to test proposed wave functions and oscillator-strength approximation methods.

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[1]W. Happer, A. Khadjavi, and A. Lurio, Bull. Am. Phys. Soc. 10, 1096 (1965).
[2]B. Budick, S. Marcus, and R. Novick, Phys. Rev. A140, 1041 (1965).
[3]P. A. Franken, Phys. Rev. 121, 508 (1961).