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STARK-MIXING SIGNALS IN THE $n=4$ TERM OF SINGLY IONIZED HELIUM*

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We present data for signals associated with the crossing of fine structure levels of a hydrogenlike atom when these levels are excited at a uniform rate and coupled by the application of a static electric field. With modest electric field strengths, strong crossing signals are seen even when the lowest order of coupling for the two levels involved is third order.

Series[1] has proposed measuring Lamb shifts in hydrogenlike atoms by observing signals associated with the crossing of levels of opposite parity when these levels are coupled by a small, static electric field and the rate of excitation to them is modulated. He predicts that under these conditions there will be a sharp change in the amplitude of modulation of the fluorescent light from these levels as they are "tuned" through the region of crossing by varying an external magnetic field. In a recent Letter Hadeishi[2] reported the experimental confirmation of Series' prediction for S-P crossings in the $n=4$ term of He^+. The purpose of the present Letter is to present data which demonstrate that crossing signals of comparable strength can be seen even when the rate of excitation is held constant.

Series' detailed calculation was carried out only for the case where one of the two states involved in the crossing does not radiate. More specifically, he assumes that one of the states has an effectively infinite lifetime. For this particular situation he correctly predicts the absence of a crossing signal when the rate of excitation is constant.[3] Wieder and Eck[4] have examined the more general case where both states radiate but may have different lifetimes and may or may not be radiatively connected to common lower energy states. Their general result for the signal when the atoms are excited at a uniform rate [Eq. (1) of Ref. 4] is quite complicated, but simplifies considerably when there is no coherence in the excitation process and the two states involved cannot decay to common final states. This simple expression, which is just the one appropriate for discussing the dc signal for the S-P crossings investigated by Hadeishi, is

$$S=r_a f_a+r_b f_b-\frac{(f_a-f_b)(r_a/\gamma_a-r_b/\gamma_b)(\gamma_a+\gamma_b)|V|^2}{\Delta^2+[(\gamma_a+\gamma_b)/2]^2+[(\gamma_a+\gamma_b)/2]^2(|2V|^2/\gamma_a\gamma_b)}, \tag{1}$$

where r_a is the rate of excitation to state a; f_a is the fraction of the decay photons from state a which are detected; $\gamma_a=\frac{1}{2}\pi\tau_a$, where τ_a is the lifetime of state a; Δ is the separation of levels a and b; and V is the matrix element of the interaction coupling states a and b. All of the quantities γ, Δ, and V are to be expressed in frequency units. The signal is expressed in terms of the properties of the uncoupled states, i.e., those for $V=0$. Thus, Δ is very nearly a linear function of magnetic field strength in the region of the crossing. For our present discussion, V is the Stark matrix element connecting states a and b. The first two terms of Eq. (1) give the background signal from states a and b far from the crossing. Term three, the crossing signal, has a Lorentzian line shape with a full width at half-maximum of

$$(\gamma_a+\gamma_b)[1+|2V|^2/\gamma_a\gamma_b]^{1/2}.$$

Lamb and Sanders,[5] in connection with their investigation of the $n=3$ term of hydrogen, obtained an expression for the resonance signal when atoms are excited by electron bombardment and states of opposite parity are coupled by an rf electric field. Their result [Eq. (6) of Ref. 5] is identical in the limit of zero rf frequency to the third term of Eq. (1), when their V is replaced by $2V$. This factor of 2 follows from the fact that in the limit of zero frequency both of the rotating electric fields into which their linearly polarized rf field can be resolved are effective in coupling the states. Thus, the crossing signal predicted by Eq. (1) is just the zero-frequency limit of the more familiar electric dipole rf signal.

The predictions of Eq. (1) were verified using the apparatus shown in Fig. 1. An electron-bombardment tube with a Pyrex envelope was evacuated, outgassed, sealed off, and then filled to the desired pressure by diffusing helium through its walls. This tube was placed between the pole faces of a 12-in. electromagnet and oriented so that the magnetic field, $\vec{B}$, was parallel to the direction of the electron beam. The radiation emitted into a small solid angle at right angles to the electron beam was focused onto the face of a photomultiplier after passing through a polarizer and a 4686-Å interference filter to isolate the $n=4$ to $n=3$ line of He^+. The photomultiplier signal was amplified by a dc amplifier, filtered by an RC filter with a time constant of 0.3 sec, and recorded as a function of magnetic field strength. An electric field at right angles to the magnetic field could be produced by applying a dc voltage to a pair of Stark plates with a separation of 1.30 cm.

Figure 2 shows recorder tracings of the photomultiplier signal versus magnetic field strength. Below 1000 G the signal is distorted by effects associated with the confinement of the electron beam by the magnetic field. A voltage of +45 V was applied from the last grid to the anode to help suppress the low-field confinement effects and secondary electron emission from the anode. Trace A of Fig. 2 is for zero volts on the Stark plates. The electric field responsible for the first and third of the S-P crossing signals is the transverse (i.e., perpendicular to $\vec{B}$) motional Stark field associated with the motion of the He^+ ions through the magnetic field. The second S-P crossing signal requires a longitudinal electric field. This is provided by the grid-to-anode volt-

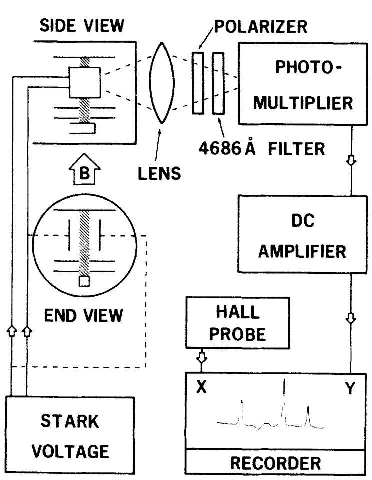

FIG. 1. Diagram of the experimental apparatus.

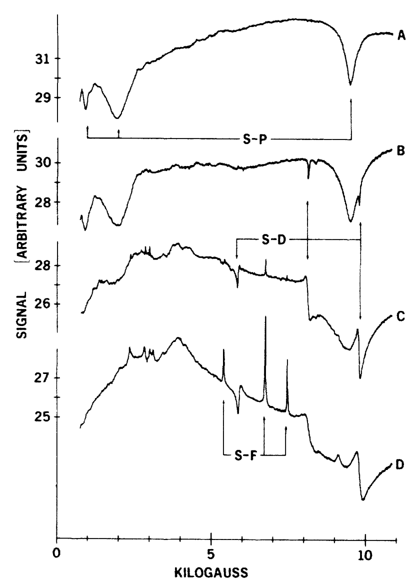

FIG. 2. Photomultiplier signal versus magnetic field strength for a helium pressure of 19 μ, an electron beam of 1 mA at 300 V, and with the polarizer oriented perpendicular to the magnetic field. Traces A, B, C, and D are for 0, 100, 200, and 300 V, respectively, applied to the Stark plates.

age mentioned above. All of the arrows in Fig. 2 are placed at the theoretical field strengths of the indicated crossings calculated using Garcia and Mack's[6] theoretical values for the fine structure splittings in the $n=4$ term of He^+.

Traces B, C, and D show the result of applying a voltage to the Stark plates. With increasing voltage the S-P crossing signals severely broaden and blend into the background. The S-D signals, which are the result of second-order Stark coupling, appear with a Lorentzian line shape (trace B) and change with increasing voltage to a predominantly dispersion line shape (traces C and D). This latter line shape is associated with the fact that the S and D levels involved in the crossings can decay to common P levels of the $n=3$ term of He^+. This gives rise to contributions to the signal from term 7 of Wieder and Eck's general expression [Eq. (1) of Ref. 4] which have been explicitly neglected in deriving Eq. (1) above. The S-F signals are the result of third-order Stark coupling. The strongest of these in trace D represents a 17% increase in the light signal reaching the photomultiplier. We are presently investigating the extent to which the S-F crossing signals and the S-P signal at 9.5 kG can be used for precision measurements of the fine-structure splittings.[7]

The S-P crossing signal at 1 kG has been seen by Hatfield and Hughes.[8]

Hadeishi[2] has investigated the S-P crossings at 1 and 2 kG employing 100% modulation of his electron beam at a frequency of 2.8 MHz and phase sensitive detection at this same frequency. This technique produces 100% modulation of the total light signal and, therefore, a signal through the phase detector proportional to the dc light level. Thus, one will see a crossing signal proportional to the third term of Eq. (1) above, even if there is no signal from the mechanism discussed by Series.[1] To separate a modulation-induced crossing signal from the dc signal one must take the difference between the signal for a given modulation frequency, f, and that for very small f. We have carried out the appropriate calculation for the 1-kG crossing and predict that approximately 60% of the dip at the crossing shown in Fig. 2 of Ref. 2 is a dc effect in the sense that it will still be there as the modulation frequency is reduced toward zero.

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[3]However, one must be careful in applying this result. For example, while the $2S$ state of hydrogen has a very long radiative lifetime, atoms in this state can be quenched to the ground state by collisions with either other atoms or molecules or the walls of the apparatus. To predict the signal for an S-P crossing in the $n=2$ term of hydrogen one must introduce into the theory a level width characteristic of this collision quenching. For realistic experimental conditions, we estimate that with electron-bombardment excitation the S-P crossing signals are appreciable even when the rate of excitation is constant.

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