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Fine Structure of $n=3$ Hydrogen by a Radio-Frequency Method*

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A radio-frequency measurement of the fine structure of hydrogen atoms in the $n=3$ state is described. Transitions $3\,^2S_{\frac{1}{2}}\leftrightarrow 3\,^2P_{\frac{1}{2}}$, $3\,^2S_{\frac{1}{2}}\leftrightarrow 3\,^2P_{\frac{3}{2}}$, and $3\,^2P_{\frac{3}{2}}\leftrightarrow 3\,^2D_{\frac{5}{2}}$ have been observed. In this experiment rf-induced transitions are detected by their effect on the intensity of H_α radiation emitted by the atoms. Preliminary results are in agreement with the predictions of quantum electrodynamics to within the accuracy of the present measurements, namely, ± 10 Mc/sec.

THE success of experiments on fine structure of the $n=2$ levels of hydrogen[1,2] and interest in accurate measurements on simple systems have led us to attempt an examination of higher excited states of hydrogen atoms. It might be hoped that such measurements will shed some light on the reason for the small discrepancy[3] between theory and experiment in the $n=2$ case. The three-quantum excited state of hydrogen is predicted[4] to have the following fine structure: separation of $3\,^2P_{\frac{1}{2}}$ and $3\,^2P_{\frac{3}{2}}$ levels 3250 Mc/sec; separation of $3\,^2P_{\frac{1}{2}}$ and $3\,^2S_{\frac{1}{2}}$ levels 314.7 Mc/sec. Previous measurement of these separations by optical means[5] has indicated the possibility of a discrepancy between experiment and calculated splittings.

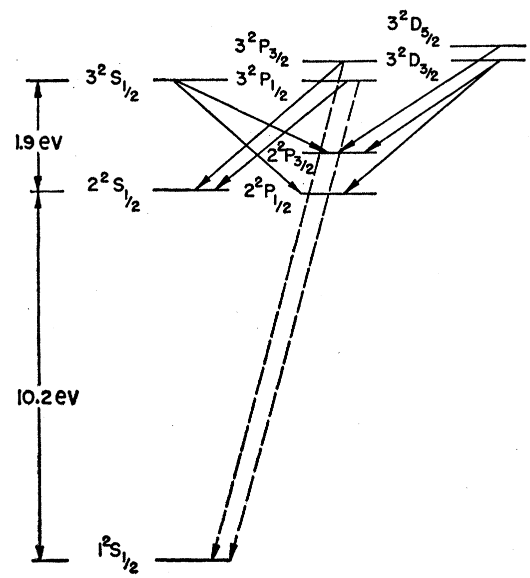

FIG. 1. The decay schemes of the $n=3$ levels of hydrogen atoms. The solid lines comprise the H_α complex, the dashed lines the L_β line. The figure is schematic and is not drawn to scale.

The experimental method employed in the measurements on the $n=2$ state is not directly applicable to the $n=3$ or other more highly excited states. The $2\,^2S_{\frac{1}{2}}$ state is unique in that it has a lifetime sufficient to permit the formation and transmission of a beam of excited atoms. In contrast to the lifetime of the $2\,^2S_{\frac{1}{2}}$ state[6] (1/7 second) the lifetime of the $3\,^2S_{\frac{1}{2}}$ state is 1.6×10^{-7} sec and that of the $3p$ states is 5.4×10^{-9} sec.[7] Thus the use of a low-velocity beam of atoms in the 3-quantum state is out of the question and another method must be sought. The principle of the method used is the following: If in a steady state atoms are excited to the $3s$ state and the $3p$ state at comparable rates, the lower decay rate of the $3s$ state will lead to an excess of population in this state over that in the $3p$

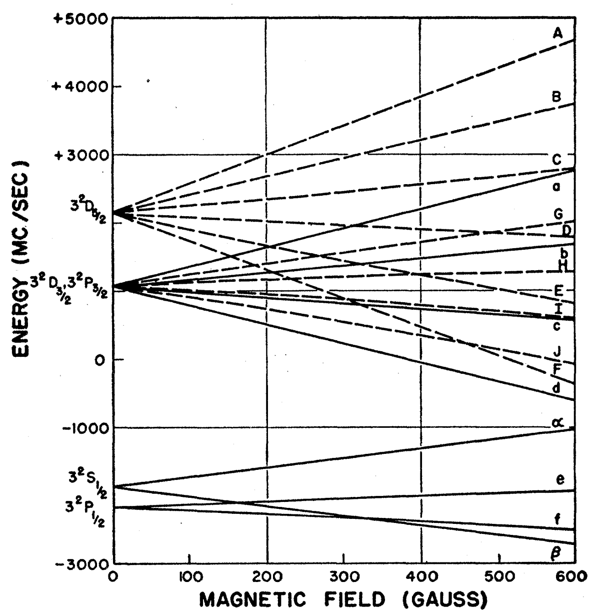

FIG. 2. Zeeman splitting of the fine structure of states $n=3$ of hydrogen. The $3\,^2S_{\frac{1}{2}}$ state has been raised 315 Mc/sec relative to the $3\,^2P_{\frac{1}{2}}$ state. The dashed lines are the $3\,^2D$ levels.

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[1] W. E. Lamb, Jr., and R. C. Retherford, Phys. Rev. **72**, 241 (1947).
[2] W. E. Lamb, Jr., and R. C. Retherford, Phys. Rev. **79**, 549 (1950).
[3] E. E. Salpeter, Phys. Rev. **89**, 92 (1953).
[4] J. M. Harriman, Phys. Rev. **101**, 594 (1956).
[5] H. Kuhn and G. W. Series, Proc. Roy. Soc. (London) **A202**, 127 (1950); G. W. Series, Proc. Roy. Soc. (London) **A208**, 277 (1951).
[6] G. Breit and E. Teller, Astrophys. J. **91**, 215 (1940).
[7] H. A. Bethe, *Handbuch der Physik* (Verlag Julius Springer, Berlin, 1933), Vol. 24, Part 1.

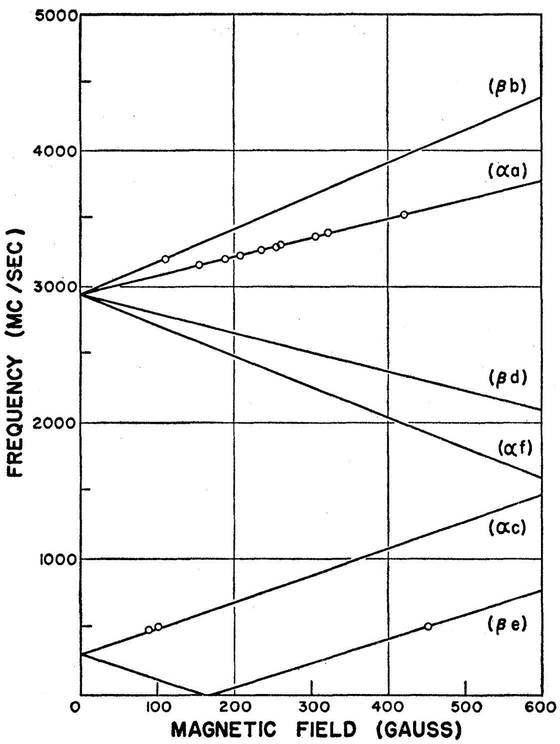

FIG. 3. Resonance frequencies, computed from the levels shown in Fig. 2, plotted as a function of magnetic field. Only transitions between s and p levels obeying the selection rule $\Delta m = \pm 1$ are shown. Some experimental points are indicated by circles.

state. All atoms decaying from the $3s$ state do so with the emission of a quantum of Balmer H_α(λ 6563A) light arising from a transition to the $2p$ level (Fig. 1). An atom in the $3p$ state may decay to the $2s$ level with the emission of an H_α quantum, or may proceed directly to the $1s$ level emitting a Lyman L_β(λ 1026A) photon. The branching ratio for these two decay schemes is 1:7.5.[7] If a radio-frequency electric field is applied at a frequency appropriate to the $3\,{}^2S_{\frac{1}{2}} \leftrightarrow 3\,{}^2P_{\frac{1}{2}}$ or $3\,{}^2S_{\frac{1}{2}} \leftrightarrow 3\,{}^2P_{\frac{3}{2}}$ energy difference, then the population of the $3p$ level will be made more nearly equal to that of the $3s$ level and the intensity of H_α light emitted will decrease, with a corresponding increase in the intensity of L_β radiation.

The experimental arrangement was as follows. Hydrogen gas at a pressure near 1 micron was admitted to an electron bombarder which included an electric field-free region approximately one centimeter in length through which drifted a monoenergetic electron beam of known energy in the range 10 to 50 ev. An optical system consisting of a Lucite light pipe or a lens, a transmission interference filter, and an RCA 6217 photomultiplier detected H_α light emitted from this drift space. A parallel plate transmission line placed around the outside of the glass envelope of the electron bombarder produced radio-frequency electric fields in the interaction region. A resonance could be swept through by variation of an axial magnetic field. The observed resonances correspond to transitions among the Zeeman levels indicated in Fig. 2. The notation is that of reference 2, with an obvious extension to the d states. Transitions αa, αc, αf, βe, and βb have been observed, as well as transitions involving the $3\,{}^2D$ state.

Preliminary measurements indicate that the splittings are at least in rough agreement with those predicted by quantum electrodynamics, and are sufficient to indicate that no glaring (>10 Mc/sec) discrepancy exists. For various reasons the resonance that has been studied most carefully is αa. Figure 3 shows experimental resonance centers plotted *versus* oscillator frequency. Also shown are experimental points for several other resonances. These data are presented in rather "raw" form, and are subject to large errors. Among the sources of error in these measurements are inaccuracies in the magnetic field calibration, shifts of resonances due to Stark effect, and for some measurements, sufficiently poor signal-to-noise ratio to prevent accurate determination of the line centers. An improved version of the apparatus is currently in operation. A more detailed report on the experiment and relevant theory is in preparation.