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Radiofrequency Spectroscopy of Hydrogen Fine Structure in $n = 3, 4, 5$*

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All of the fine-structure intervals in the hydrogen $n = 3, 4$ manifolds and all but the F-G transitions in $n = 5$ have been measured using radiofrequency spectroscopy on a fast hydrogen beam. The experimental results are in agreement with theoretical predictions.

Most of the measurements of the hydrogen fine structure in the higher excited states have been made by a bottle technique in which the atoms are located in a plasma of unknown constitution and thus subject to perturbing electric fields which can seriously shift and distort the resonance lines.[1] We report here measurements of all the fine-structure intervals in the $n = 3, 4$ manifolds and all but the F-G transitions in $n = 5$ using rf spectroscopy on a fast hydrogen beam.[2] In this experiment the atoms are located in a reproducible and well understood environment. This technique also gives a new method for studying the angular momentum states produced when protons collide with gas molecules to form hydrogen atoms.

The apparatus is shown schematically in Fig. 1. Excited-state hydrogen atoms are produced by collisions between a fast (20 keV) proton beam and a target consisting of either a thin (10 μg/cm^2) carbon foil or a windowless, differentially pumped chamber filled with nitrogen gas

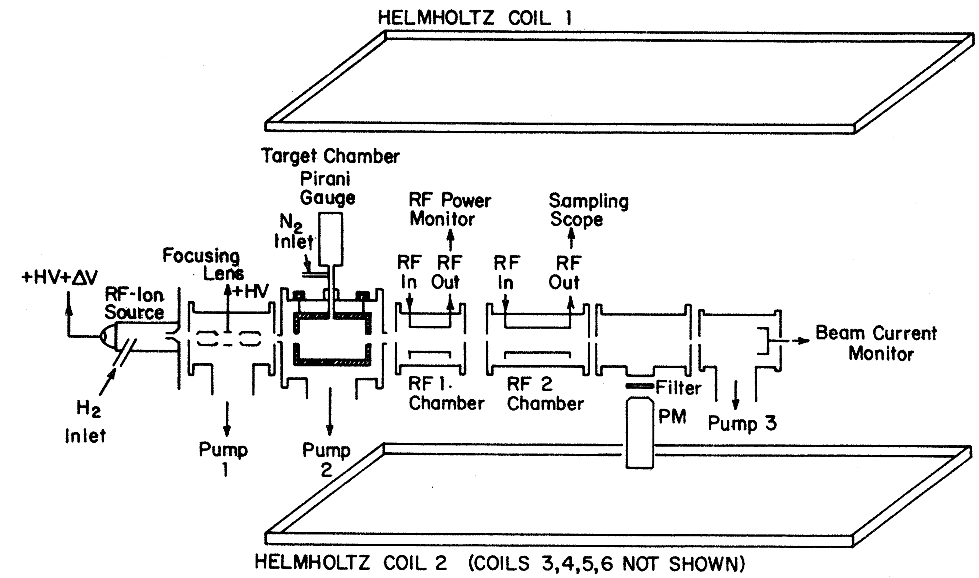


FIG. 1. Schematic diagram of apparatus used for observation of the fine-structure resonances using a fast hydrogen beam.

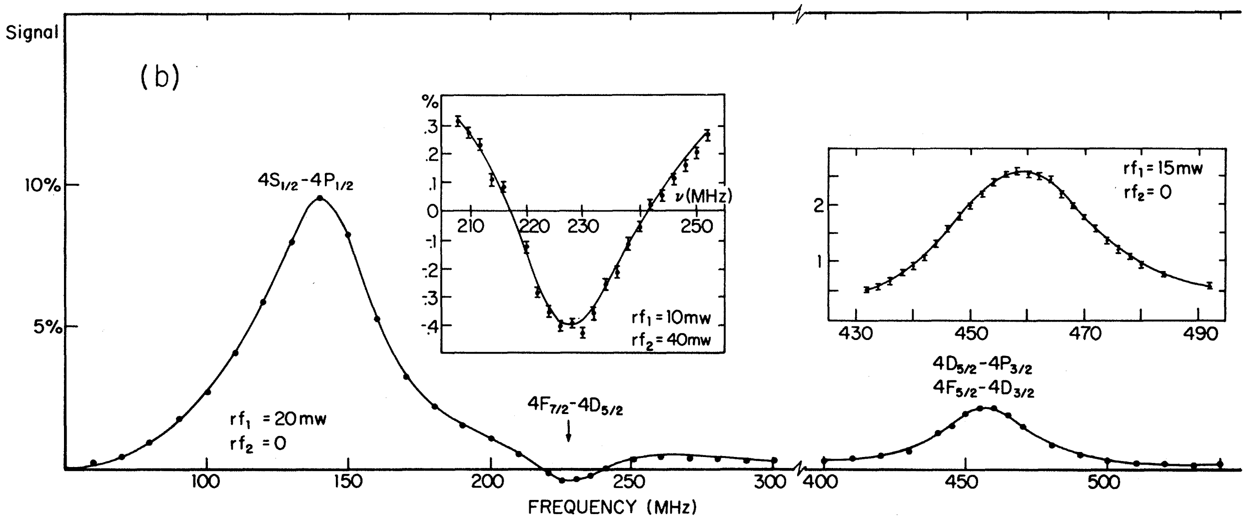


FIG. 2. (a) Energy levels and the allowed electric-dipole transitions for the $n=4$ state of atomic hydrogen. This diagram ignores the hyperfine splitting. (b) Pan-...

at 0.01 Torr. Because of the limited ability of the foil to dissipate heat, a larger beam can be used with the gas target. After formation the atoms pass through a switched rf field and in front of a photomultiplier tube. The optical signal is registered on two scalers which are switched synchronously with the rf field so that one counts for rf on and the other for rf off. As the frequency is varied through resonance, the change in population of the states involved is detected as a change in the optical signal. For the $n=3, 4, 5$ manifolds, the signal consists, respectively, of Balmer α, β, and γ light. Optical selection is provided by 50-Å bandpass interference filters. The rf power was monitored with a Hewlett-Packard 432A power meter. Helmholtz coils canceled the Earth's magnetic field.

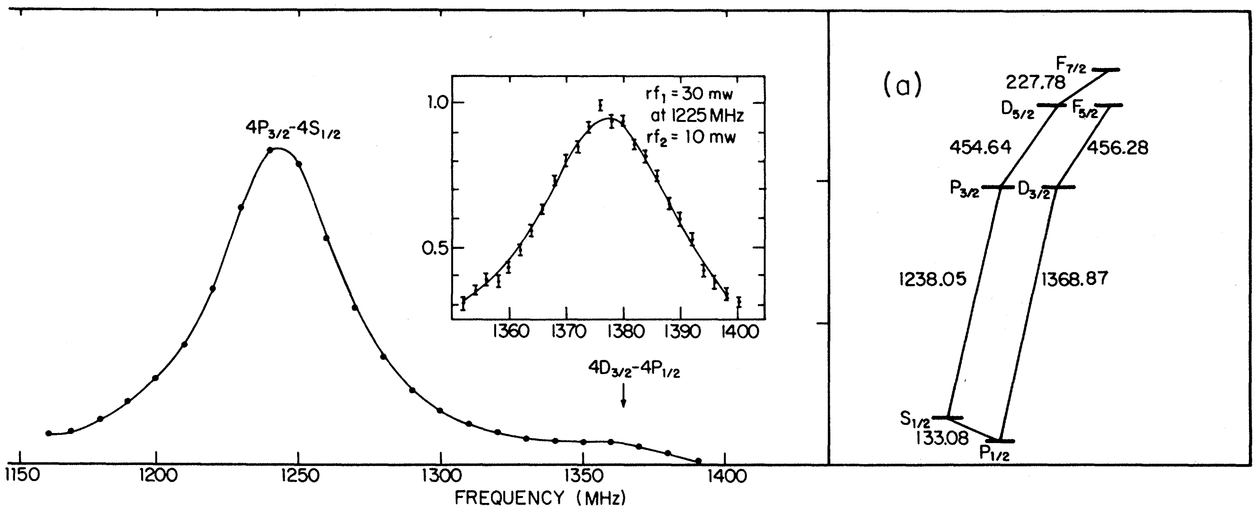
In the following analysis the signal is defined as

$$S(\nu)=[N(0)-N(\nu)]/N(0).$$

Here ν is the rf frequency, $N(0)$ is the counting rate with rf off, and $N(\nu)$ is the counting rate with rf on. Figure 2(a) shows the energy levels and the allowed electric-dipole transitions for the $n=4$ manifold. The states for the $n=3$ and $n=5$ manifold are similar; the $n=3$ manifold does not contain F states; the $n=5$ manifold contains, in addition, G states. Since the F and G manifolds have no allowed transitions to the $n=2$ state, no F-G resonances were observed in this experiment.

Figure 2(b) shows the observed transitions for the $n=4$ manifold. In most cases the resonance signals are positive and indicate a decrease in the optical signal at resonance. For cases involving transitions between long- and short-lived states (e.g., $S_{1/2}\rightarrow P_{1/2}$ or $S_{1/2}\rightarrow P_{3/2}$), the interpretation is clear. The short-lived P states created in the target region have essentially all decayed by the time the beam enters the rf field; at resonance the rf field converts the long-lived S states to short-lived P states thus diminishing the number of S-state atoms which reach the detector. For transitions such as $F_{5/2}$-$D_{3/2}$ and $D_{5/2}$-$P_{3/2}$ in which the lines overlap, the interpretation of the observed negative signal is more complicated. The $F_{7/2}$-$D_{5/2}$ transition at 228 MHz yields a positive signal when the target is a foil and a negative signal when the target is nitrogen gas. The $F_{7/2}$-$D_{5/2}$ transition is very small and negative in the $n=4$ manifold. In the $n=5$ manifold it is negative and larger than the other signals by a factor of 10.

The analysis of the hydrogen fine-structure measurements is complicated by the nuclear spin. In some of the measurements, higher precision was obtained by using a hyperfine quenching field after the spectroscopy field.[2] The quenching field was a nonswitched field set at the resonance frequency of one of the hyperfine components. It served to reduce the overlapping components and to give a signal primarily due to one hyperfine component. Such a field can also be employed in the case of overlapping fine-structure transitions to quench one component so that the other may be observed. Dramatic proof of the value of this technique is illustrated



...orama of all the fine-structure resonances in hydrogen, $n=4$. The resonance frequencies have not been corrected for the first-order Doppler shift.

Table I. A summary of the fine-structure intervals determined in this experiment, the theoretical values for the fine-structure intervals, and the results of previous determinations of these intervals. All errors are one standard deviation.

Transition	Theoretical Frequency (MHz) (Ref. 1, 5, 6)	Experimental Frequency (MHz)	Mode of Analysis	Previous Results (MHz) Frequency	Ref
$3S_{1/2}-3P_{1/2}$	314.90	315.11 ± 0.89	3 Lorentzians-5 Parameters	313.6 ± 2.9 314.93 ± 0.40	4 3
$3P_{3/2}-3S_{1/2}$	2935.19	2933.5 ± 1.2	1 Lorentzian-3 Parameters	2935.4 ± 2.0	3
$3D_{3/2}-3P_{1/2}$	3244.62	3255.6 ± 8.4	Symmetrical points		
$3D_{5/2}-3P_{3/2}$	1077.96	1080.3 ± 2.9	Symmetrical points-Simulation		
$4S_{1/2}-4P_{1/2}$	133.08	133.18 ± 0.59	3 Lorentzians-5 Parameters	133.0 ± 10.	3
$4P_{3/2}-4S_{1/2}$	1238.05	1235.9 ± 1.3	3 Lorentzian- 4 Parameters		
$4D_{3/2}-4P_{1/2}$	1368.87	1371.1 ± 1.2	Symmetrical points-Simulation		
$4D_{5/2}-4P_{3/2}$	454.64	455.7 ± 1.6	Symmetrical points-Simulation		
$4F_{5/2}-4D_{3/2}$	456.28	456.8 ± 1.6	Symmetrical points-Simulation		
$4F_{7/2}-4D_{5/2}$	227.78	227.96 ± 0.41	1 Lorentzian- 3 Parameters		
$5S_{1/2}-5P_{1/2}$	68.14	64.6 ± 5.0	Symmetrical points		
$5P_{3/2}-5S_{1/2}$	633.85	622.4 ± 10.1	Symmetrical points		
$5D_{3/2}-5P_{1/2}$	700.71	704.3 ± 7.1	Symmetrical points		
$5D_{5/2}-5P_{3/2}$	232.70	232.2 ± 2.9	Symmetrical points		
$5F_{7/2}-5D_{5/2}$	116.62	117.2 ± 1.5	Symmetrical points		

by the inserts in Fig. 2(b). Without a quenching field the $4D_{3/2}$-$4P_{1/2}$ resonance is merely an elongation of the right wing of the $4P_{3/2}$-$4S_{1/2}$ resonance; with a quenching field set at 1225 MHz, the $4D_{3/2}$-$4P_{1/2}$ resonance is a distinct, symmetrical resonance centered at 1375 MHz. A similar elucidation of the $4F_{7/2}$-$4D_{5/2}$ resonance is obtained by using the $4S_{1/2}$-$4P_{1/2}$ transition at 140 MHz to quench 4S states.

Several methods were used to reduce the data. The method employed was determined by the number of data points, the statistical errors, and the separation of the hyperfine components. Detailed resonances with small statistical errors and large hyperfine separations were fitted with a fitting function involving five free parameters and three Lorentzian components. The five parameters were the half-width, the resonance frequency for one component, and the amplitude of each of the three components. For resonances where there was only a small hyperfine structure or severe overlap of fine-structure components, the center of the line was located by measurements at symmetrical points on each side of the line, and the limits of error were determined by computer simulation of the resonances. Calculations were made for different choices of the initial hyperfine-state amplitudes in order to determine the effect of different weighting schemes on the measured frequency. The data were separately corrected for variations in the rf power, for the first-order Doppler shift, and for Stark shifts.

Table I summarizes the measured fine-structure intervals. It also gives the results of earlier experiments[3,4] and the theoretical values for the fine-structure intervals.[1,5,6] The agreement between experiment and theory is quite satisfactory. Work is now in progress to understand in detail the signal amplitudes and to use this information to study the relative populations of the angular momentum states produced in the collisions which form the hydrogen atoms.

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Enhanced Damping of Large-Amplitude Plasma Waves

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The collisionless damping of small-amplitude plasma waves is independent of the exciting voltage V_{ex}. For large-amplitude waves, the damping rate increases linearly with V_{ex} and amplitude oscillations are observed. A phase transition appears at amplitude minima.

The amplitude oscillation of an electron plasma wave has been studied experimentally by Malmberg and Wharton.[1] In their experiment where the wave potential φ is within the range $e\varphi/T_e \lesssim 0.3$ (where T_e is the electron temperature in eV), the damping length of the amplitude seems to be independent of the exciting voltage. Theoretically, Armstrong[2] and Dawson and Shanny[3] showed that the initial temporal damping rate of the wave increases rapidly with amplitude. For ion acoustic waves, Sato et al.[4] have observed enhanced damping followed by growth when $e\varphi/T_i$