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OBSERVATION OF THE LAMB SHIFT IN A FAST HYDROGEN BEAM*

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A new technique of observing the Lamb shift which combines beam-foil and radiofrequency spectroscopy techniques is described. Measurements are made at zero magnetic field by sweeping the radiofrequency field. A radiofrequency hyperfine state selector is used to reduce the effect of overlapping lines.

Precise measurements of the fine structure of hydrogenlike atoms and in particular of the Lamb shift give one of the best tests of quantum electrodynamics.[1] At present the precision with which these intervals can be measured is limited by the lifetime of the states and the uncertainty of the corrections inherent in the techniques that have been used to make the measurements.[2] We wish to report in this paper a new method of measurement which combines beam-foil spectroscopy[3] and radiofrequency spectroscopy techniques. This technique uses a fast hydrogen beam and thus makes it feasible to use spatially separated oscillatory fields to reduce the linewidth by the selection of atoms which live longer than a mean life.[4,5]

Figure 1(a) shows a schematic diagram of the apparatus. Protons were extracted from a radiofrequency ion source, accelerated, and focused into a parallel beam. After the focusing lens, the protons passed through a carbon foil which was typically 10 $\mu g/cm^2$ thick. The proton energy was usually kept in the range from 20 to 40 keV; protons with an energy of 30 keV have a velocity of 2.4×10^8 cm/sec. At these energies approximately 90% of the protons capture an electron and form excited- or ground-state hydrogen atoms. After formation, the hydrogen atoms passed through two separate regions in which they were subjected to radiofrequency fields, and then passed in front of a photomultiplier tube. Observations were made on the $n=3$ state by using an interference filter to select Balmer α photons. The fine-structure transitions were observed by using a differential rate meter consisting of two switched scalers to compare the number of Balmer α photons emitted when the radiofrequency field was alternately switched on and off. The beam intensity was always kept below 5×10^{12} atoms/sec in order to increase the lifetime of the foil. This beam intensity resulted in a count rate at the photomultiplier of typically 70 000 counts/sec.

In previous experiments the atoms were studied in the presence of an external magnetic field. The transitions were induced with a fixed frequency of the rf field and they were swept through resonance by changing the magnetic field. This procedure introduced a number of sizable corrections which were not always easy to understand.[2] In this experiment, the atoms were studied in zero magnetic field and the transitions were swept through resonance by changing the frequency of the rf field.

In using a swept-frequency method, it is necessary to keep the rf power constant over the frequency range of interest. A coaxial transmission line was brought into the chamber at port 1 and connected to two parallel plates between which the beam traveled. The other ends of the rf plates were joined to a 50-Ω transmission line which was terminated with 50 Ω. Thus, a traveling wave was set up and ideally the total power incident on port 1 was propagated through the

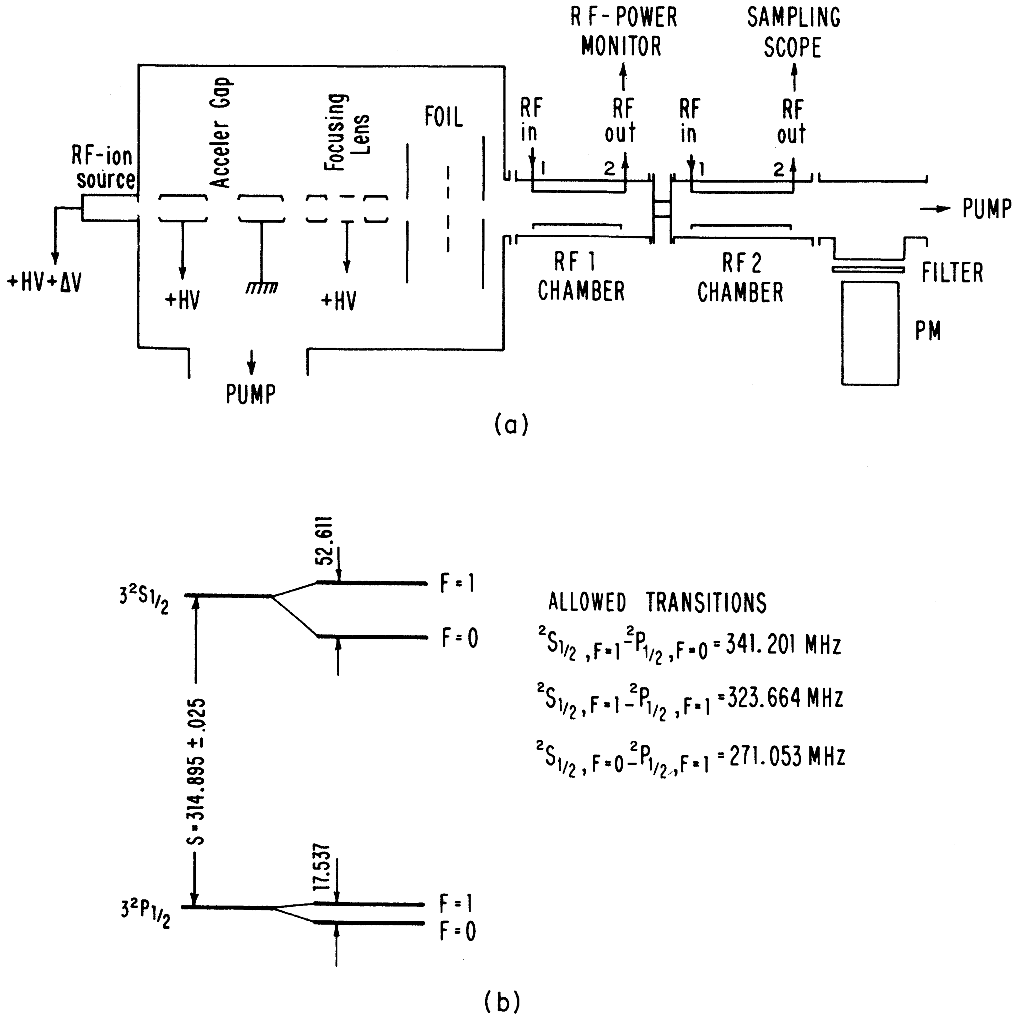

FIG. 1. (a) Schematic diagram of the apparatus used for observation of the Lamb shift in a fast hydrogen beam. (b) Energy levels and allowed transitions for the S and P states in the $n=3$ level of atomic hydrogen.

chamber and left through port 2. The power was absorbed in the rf power monitoring thermistor which was connected directly to port 2 and which to high accuracy acted as an ideal 50-Ω load. Measurements of the voltage standing-wave ratio at port 1 and port 2 and of the insertion loss of the chamber as a function of frequency were used to correct for any mismatch. The rf power correction for the chamber used in this experiment was at most 2% over a bandwidth of 100 MHz. More careful design and the use of precision coaxial connectors now available should reduce the size of this correction significantly. In the present design, the beam traveled parallel to the direction of the rf field. As a result all the resonance curves were shifted due to the first-order Doppler effect. The size of this correction was verified by measuring the fine-structure resonances with the beam both parallel and antiparallel to the traveling rf wave.

In hydrogen the analysis is complicated by the presence of hyperfine structure. Figure 1(b) shows the energy levels of, and the transition frequencies between the $3^2S_{1/2}$ and $3^2P_{1/2}$ states of atomic hydrogen. Figure 2(a) shows the observed fine structure when there is a radiofrequency field only in the chamber RF1. Also shown in Fig. 2(a) is a computer least-squares fit of a sum of three Lorentzian curves. For this fit it was assumed that the hyperfine structure was known but that the Lamb shift and the width and amplitude of each of the component Lorentzian curves were free parameters.

In order to make a more precise measurement of a single transition, the use of a rf hyperfine state selector was investigated. As shown in Fig.

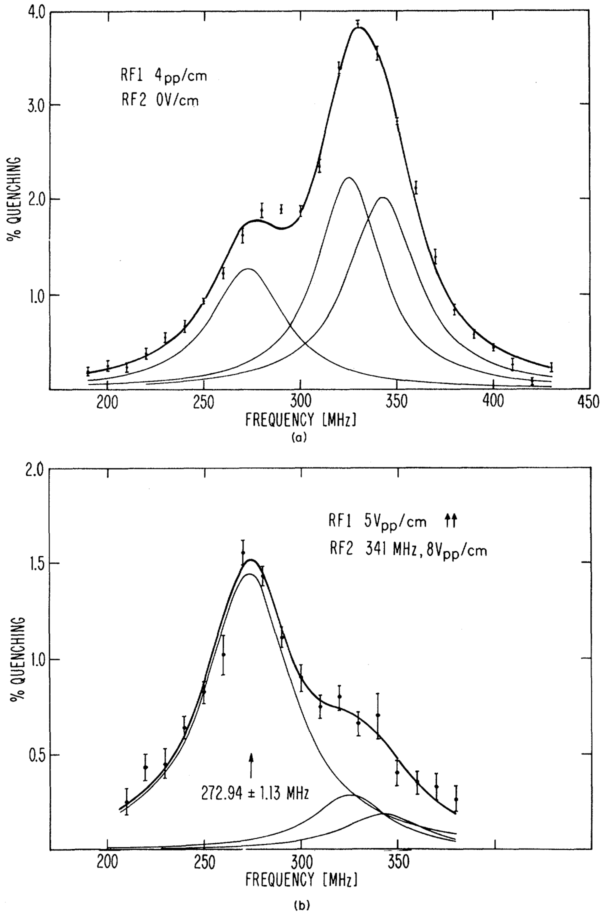

FIG. 2. (a) A plot of the fractional quenching as a function of frequency when there is an rf pulse only in the region RF1. Also shown is the result of a least-squares fit of the sum of three Lorentzian components. For the fit, the hyperfine structure was assumed to be known. (b) A plot of the fractional quenching as a function of the frequency of the rf field in the region RF1 when there is also present at all times an rf field in the region RF2 whose frequency is fixed at that for the $3^2S_{1/2,F=1} \rightarrow 3^2P_{1/2,F=0}$ fine-structure transition. Also shown is the result of a least-squares fit of the sum of three Lorentzian components.

1(a), the beam first traversed the spectroscopy chamber RF1 and subsequently chamber RF2 where an unswitched rf field corresponding to the $3^2S_{1/2,F=1} \rightarrow 3^2P_{1/2,F=0}$ or the $3^2S_{1/2,F=1} \rightarrow 3^2P_{1/2,F=1}$ transition was present. This field reduced the number of atoms in the $3^2S_{1/2,F=1}$ state and as a result the differential counting rate depended primarily on the transition $3^2S_{1/2,F=0} \rightarrow 3^2P_{1/2,F=1}$. Figure 2(b) shows a typical scan taken with this configuration. Also shown is a least-squares resolution into three Lorentzian curves and the frequency of the $3^3S_{1/2,F=0} \rightarrow 3^2P_{1/2,F=1}$ transition determined from the least-squares fit. The relative enhancement of the $F=0$ to $F=1$ transition is clearly evident.

For the rf configuration used in this experiment the linewidth is determined by the time spent in the rf field and the applied rf power. It approaches the natural linewidth in the absence of power broadening when this time is much longer than the natural lifetime. The 4-cm-long rf field gives an observation time of 20 nsec and an expected linewidth of about 50 MHz. This agrees well with the observed linewidth. For the type of experiment reported here the natural linewidth is given by

$$\Delta\nu = \frac{1}{2\pi}[\gamma(^2P_{1/2}) - \gamma(^2S_{1/2})],$$

where $\gamma(^2P_{1/2})$ and $\gamma(^2S_{1/2})$ are the decay constants for the $^2P_{1/2}$ and $^2S_{1/2}$ states of interest. For the $n=3$ state of hydrogen

$$\Delta\nu = 28.6 \text{ MHz}.$$

We have obtained a number of resonance curves similar to that shown in Fig. 2(b) under various conditions and with both frequencies for the hyperfine selecting field. For each of the fits, the widths of the Lorentzian components were allowed to be free parameters; in all cases, however, the widths found by the program were within errors consistent with the same width for all three components. From the average of these measurements we obtain, after correcting for the Doppler shift for the Lamb shift in the $n=3$ state of atomic hydrogen, the preliminary value

$$\mathcal{S}(\mathrm{H}, n=3) = 315.11 \pm 0.89 \text{ MHz}.$$

The error is one standard deviation and it is based on the statistical error and the uncertainty in the Doppler shift correction.

This value agrees well with the only other measurement made on the $n=3$ state of atomic hydrogen. The other measurement was made by Kleinpoppen using an atomic-beam technique.[6] He obtained

$$\mathcal{S}(\mathrm{H}, n=3)_{\mathrm{K}} = 313.6 \pm 5.7 \text{ MHz}.$$

It also agrees well with the deuterium measurement of Wilcox and Lamb[7] when the theoretical ratio of the deuterium and hydrogen Lamb shifts is used to correct the measured deuterium value so as to obtain an equivalent value for hydrogen. The Wilcox and Lamb measurement gives

$$\mathcal{S}(\mathrm{H}, n=3)_{\mathrm{WL}} = 314.93 \pm 0.80 \text{ MHz}.$$

All three measurements agree satisfactorily with the theoretical value[8]

$$\mathcal{S}(\mathrm{H}, n=3)_T = 314.895 \pm 0.025 \text{ MHz}.$$

The success of this experiment in making fine-structure measurements using a fast hydrogen beam indicates that double oscillatory field techniques can be used to select those atoms which live a long time and thus the resonance lines can be significantly narrowed. This will make possible more precise measurements and enable one to resolve some of the disagreements and inconsistencies in the present fine-structure measurements.[1]

We wish in particular to acknowledge the aid of Mr. Robert Brown in constructing the accelerator and for numerous stimulating discussions of the technique. Mr. Mark Silverman contributed significantly to the reduction of the data and to the least-squares fitting program.

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HIGH RESOLUTION PHOTODETACHMENT OF S⁻ NEAR THRESHOLD*

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A tunable dye laser has been used to measure the fine-structure splitting of the ^2P state of S⁻ in a crossed-beam photodetachment experiment. These measurements verify photodetachment threshold laws and provide the most accurate experimental determination of any electron affinity.

The vastly increased resolution obtainable with continuously tunable dye lasers over conventional light sources offers a unique opportunity to make precise threshold measurements in photodetachment of negative ions. This paper reports the early measurements of the relative cross section for the process $\mathrm{S}^- + h\nu \rightarrow \mathrm{S} + e^-$ in the first 1200 cm^{-1} above threshold. These measurements provide the first experimental verification of the theoretical threshold law for p-electron photodetachment, on which some doubt has recently been cast,[1] and the first photodetachment measurement of negative-ion fine structure (the doublet splitting in O⁻ has been obtained previously be examination of the radiative attachment continuum[2]).

The theoretical threshold behavior of photodetachment cross sections of atomic negative ions is proportional to k^{2l+1}, where k is the momentum of the outgoing electron and l is its orbital angular momentum.[3] In the case of p-electron detachment, the outgoing electron is either s wave or d wave, and the threshold dependence is given by the s-wave contribution. Calculations on O⁻ photodetachment[4] indicate that the amplitude of the d-wave part is very small in the energy range studied here. Following the discussion in Branscomb et al.[3] the threshold dependence of the S⁻ photodetachment cross section is expected to be of the form

$$\sigma = \sum_{j=1}^{6} \alpha_j k_j,$$

where k_j is the momentum of the ejected electron in the jth transition. The six photodetachment transitions are those which connect the doublet S⁻ state with the triplet S state. One expects, therefore, six thresholds as a function of photon energy, each one incrementally $\sigma_j = \alpha_j k_j$.

The effect of the fine structure has been considered previously[3] in O⁻, but primarily to establish an upper limit for the broadening of the threshold. In that paper and elsewhere,[1] the strengths of the individual fine-structure transitions have been taken to be the products of the statistical weights of the initial O⁻ states and