Separated Oscillatory Field Measurement of the Lamb Shift in H, n=2*

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This paper reports a precision measurement of the Lamb shift in the n=2 state of hydrogen using separated oscillatory fields in conjunction with a fast atomic beam. Atoms in the $2^2S_{1/2}$ metastable state are produced through charge capture by protons in a gas target. The atoms pass thrugh two separated oscillatory fields whose relative phase is switched between 0 and π. A rf quenching field and a solar blind photomultiplier tube provide a monitor of the number of atoms in the $2^2S_{1/2}$ state that pass through the spectroscopy fields. The procedure used to take and correct the data is described and the major sources of residual error are discussed. The result of the measurement is compared with the current theoretical value. An experiment for further improvement in the measurement of the Lamb shift is outlined.

1. Introduction

The difference in the energy of the $2^2S_{1/2}$ and $2^2P_{1/2}$ levels in hydrogenic atoms is a purely electrodynamic effect due to the interaction of the bound electron with the quantized electromagnetic field. The measurement of this splitting was a major stimulus for the development of renormalization theory and still provides an important test of Quantum Electrodynamics. The precise measurement of this splitting is difficult because of the short radiative lifetime of the $2^2P_{1/2}$ state. The ratio of the linewidth to the transition frequency is roughly 1/10. Thus a high precision measurement requires a detailed understanding of the line shape and good control of the variables that shift and distort the resonance line.

The fast beam separated oscillatory field technique (SOF) provides a method through which one can obtain a series of lines whose widths are less than the natural line width with a good understanding of the factors which determine the line shape and the line center. This paper summarizes a separated oscillatory field measurement of the Lamb shift in hydrogen.[1]

*This work was carried out in collaboration with S. R. Lundeen and many of the innovative ideas which lead to the success of the experiment are due to him. His present address is Department of PHysics, University of Notre Dame, Notre Dame, IN 46556, USA.

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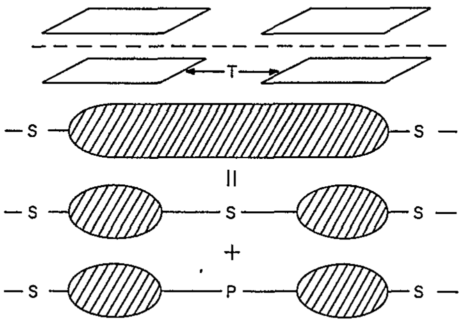
2. Description of Method

Figure 1 shows schematically the origin of the narrowed signal. An atom in the $2^2S_{1/2}$ state enters the first rf region where, in general, the rf field produces a superposition state in which the wavefunction for the atom has components in both the $2^2S_{1/2}$ and $2^2P_{1/2}$ states. The atom then passes through a free field region into a second rf region where the superposition state is changed further. The probability for the atom to emerge from the second rf field in the $2^2S_{1/2}$ state contains an interference term of the form shown in Fig. 1 whose frequency width depends on the separation in time T of the two rf regions rather than the natural linewidth. By changing the relative phase of the two rf regions from 0^0 to 180^0, one can isolate the interference signal.



$$|a_{s,OUT}|^2 = \cdots + Ke^{-\frac{\Gamma_p \cdot T}{2}} \cos[(\omega_0-\omega)T+(\delta_2-\delta_1)+f_-(\omega_0-\omega)]$$

Fig. 1 Schematic diagram showing origin of the interference signal

Since the interference term depends on the amplitude for an atom to make a transition to the $2^2P_{1/2}$ state in the first rf region and back to the $2^2S_{1/2}$ state in the second rf region, it essentially selects atoms in the $^2P_{1/2}$ state that live for a time T. As the time separation between the two SOF regions is increased, the frequency width of the interference signal decreases as 1/T and the size of the interference signal decreases exponentially with half the decay constant for the $2^2P_{1/2}$ state. One can trade signal size for a decrease in line width and still retain a high signal to noise ratio for the narrowed signal.

To carry out this scheme, a fast atomic beam ($v/c \simeq 0.01$) is used to translate the required nanosecond time intervals into convenient laboratory distances. To avoid complications due to motional electric fields, the entire experiment is performed in zero magnetic field and the resonance is tuned through directly by changing the frequency of the applied rf field. Other rf fields are used to select one hyperfine state so as to simplify the line shape.

3. Description of Measurement

Figure 2 shows a schematic diagram of the fast beam apparatus. The fast beam is obtained by charge capture from a 50-100 keV proton beam produced by a commercial 150 keV accelerator. The separated rf fields are produced by pairs of plates each of which is a section of a 50Ω transmission line. The two plates of each pair are driven 180^0 out of phase to insure that the midplane containing the beam axis remains at ground potential and that the rf electric field seen by an atom traveling along the axis is uniformly polarized transverse to its velocity.

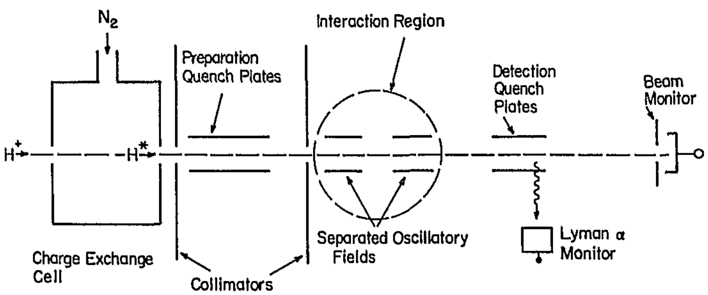


Fig. 2 A schematic diagram of the fast-atomic beam apparatus used in this measurement

To select one hyperfine state the preparation quench plates are driven at 1110 MHz and the detection quenching plates are driven at 910 MHz. Figure 3 shows the microwave system used to produce the two separated oscillatory fields. A high precision coaxial magic Tee drives the two rf regions so that they have relative phases of 0^0 or 180^0. Figure 4 shows the hyperfine state selection.

The signals are defined as the fractional decrease in the Lyman-α photocurrent N produced by a fixed amplitude rf electric field in the SOF region through the equations

$$S^0 = (N_{off} - N^0_{on})/N_{off},$$

$$S^\pi = (N_{off} - N^\pi_{on})/N_{off},$$

where N_{off}, N^0_{on}, N^π_{on} are the photocurrents when the rf is off, on with 0^0 relative phase, and on with 180^0 relative phase, respectively. In terms of these primary signals, the "interference" and "average quench" signals (I and $\bar{Q}$) are defined as

$$I = S^0 - S^\pi,$$

$$\bar{Q} = (S^0 + S^\pi)/2$$

Figure 5 shows the average quench and interference signals obtained with a 100 keV beam and increasing separation of the rf regions. The envelope of the interference signal is determined by the spatial distribution of the rf field in the two separated oscillatory field regions.

To eliminate the residual first order Doppler shift due to the failure of the direction of propagation of the rf field to be precisely perpendicular to the fast beam, measurements were taken with the rf drive on both the right and left sides of the beam. To eliminate the frequency shift due to phase errors in the rf drive system, measurements were made with the entire rf system, including the spectroscopy region, rotated 180^0 about an axis passing through the midpoint between the two

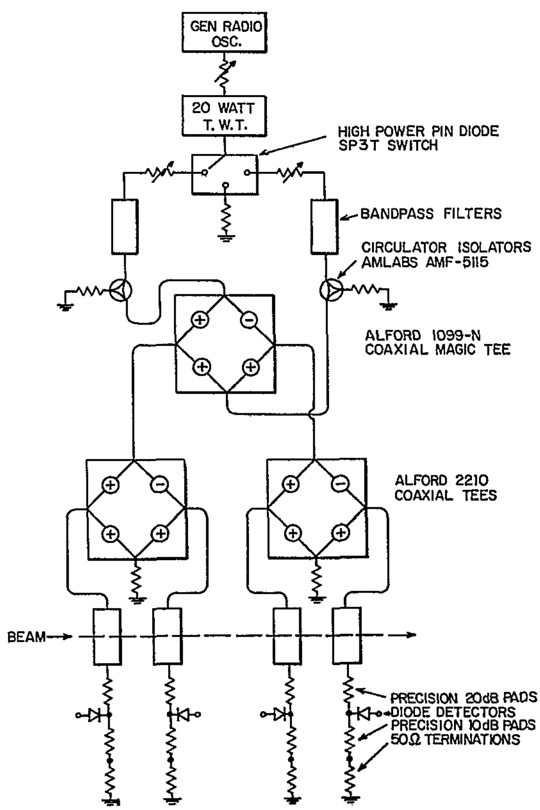


Fig. 3 The system used to power the separated oscillatory fields

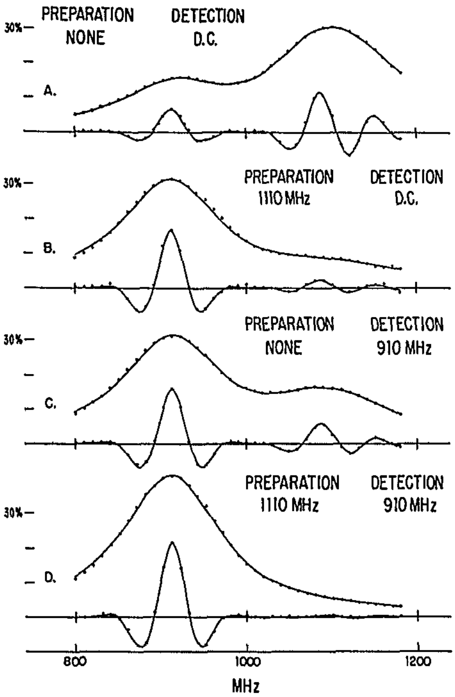


Fig. 4 A series of plots of the average quench and interference signals showing the hyperfine state selection due to the continuous rf fields in the state selection region and in the quench region.

SOF regions and parallel to the direction of propagation of the rf field. This exchange reverses the order in which an atom encounters the two rf regions and thus cancels phase errors.

Power monitoring diodes were used to set the rf power so the rf electric field did not vary as a function of frequency. The diodes were calibrated using a Hewlett Packard 432A Power Meter with a 8478B thermistor power sensor and calibrated attenuators. The power measurement was used in conjunction with slotted line studies of the rf interaction regions to determine the rf electric field at each frequency.

The method of symmetric points was used to determine the center of the interference curve. Extensive calculations showed that the line profile should be symmetric about the center frequency. The line center was then corrected for the second order Doppler shift, The Bloch-Siegert and rf Stark shifts, coupling between the rf plates, the residual F=1 hyperfine component, and distortion due to off axis electric fields. A small residual asymmetry in the average quench curve was attributed to a residual variation of the rf electric field across the line and corrected for on the assumption this was the correct explanation. Table 1 shows the measured interval and the corrections for one of the 8 data sets used to determine the final result.

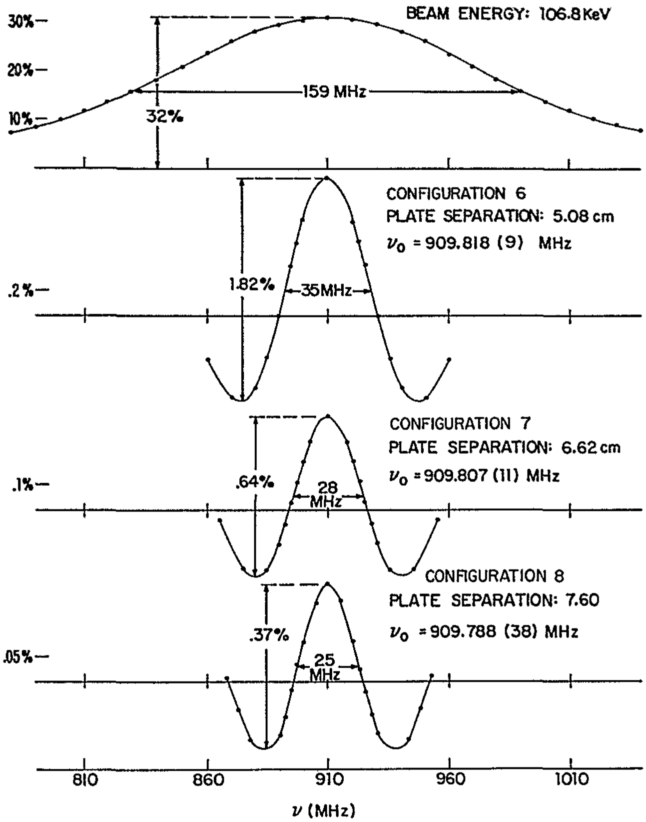


Fig. 5 Samples of the average quench and interference signals obtained in this experiment with increasing separation of the two rf regions

Table 1 The measured value and corrections for data point 6. The energy was 100 keV, the field separation 5.06(5) cm and the full width at half maximum 40.1 MHz. All the entries are in MHz.

Raw Center	909.818(9)
Corrections	
1) Time dilation	+0.104(4)
2) Bloch-Siegert & rf Stark shift	-0.027(2)
3) Plate coupling	0.000(0)
4) Residual F=1 component	0.001(0)
5) Incomplete $\bar{Q}$ subtraction	0.000(4)
6) Off-axis distortion	-0.003(2)
7) Variation of rf field	-0.001(1)
8) Additional rf field variation	-0.005(2)
$\nu[2^3S_{1/2}$ (F=0) $\leftrightarrow$ $2^2P_{1/2}$ (f=1)]	909.887(11)
Hyperfine structure	147.958
S(n=2)	1057.845(11)

4. Results

Figure 6 shows in graphic form the values obtained for the eight points at which data were taken. The final value for the Lamb shift is

$$S(H,n=2) = 1057.845(9) \text{ MHz}$$

Figure 7 shows a plot of all the reported direct measurements of the Lamb shift in the n=2 state of hydrogen.

The principal uncertainty in the theoretical value for the Lamb shift is due to the radius of the proton. The radius determined by the early measurements by workers centered around Stanford [1] is

$$\langle r_p^2 \rangle^{1/2} = 0.805(11) \text{ fm.}$$

The radius determined more recently by the German scientists [1] is

$$\langle r_p^2 \rangle^{1/2} = 0.862(12) \text{ fm.}$$

If one includes the recently calculated recoil correction of BHATT and GROTCH [2] the theoretical value for the Lamb shift is

$$1057.852(11) \text{ MHz if } \langle r_p^2 \rangle^{1/2} = 0.805(11) \text{ fm,}$$

$$1057.870(11) \text{ MHz if } \langle r_p^2 \rangle^{1/2} = 0.862(12) \text{ fm.}$$

The experiment and theory are in excellent agreement if the old value for the proton radius is used; the agreement is poor if the new value of the proton radius is used. Because of the discrepant values for the proton radius, one cannot say how well experiment and theory agree. There are also uncalculated theoretical contributions which could be as large as 10 kHz.[3]

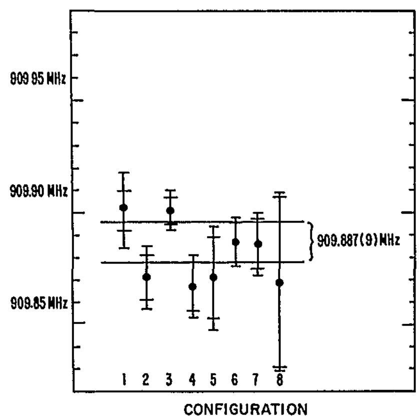


Fig. 6 A plot of the final line centers for the 8 configurations in which data were taken. The smaller error bars are the statistical uncertainties. The outer error bars include the systematic uncertainties

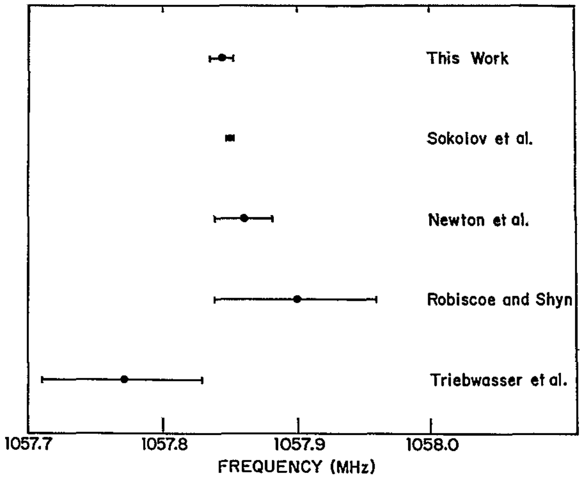


Fig. 7. A plot of all the direct precision measurements of the Lamb shift in the n=2 state of hydrogen

5. Prospects for Higher Precision

The principal limitations in the precent measurement are due to the line width and the uncertainty in the rf field as a function of frequency. A large solid angle detector such as the Lyman alpha detector [4] that has been used for measurements on He^+(n=4) could be used to provide an increase in signal by a factor of a hundred and thus make feasible measurements at wider separation with a line width of 20 MHz. The uncertainties in the rf field strength could be reduced by measuring the $2^2S_{1/2}$ - $2^2P_{3/2}$ transition near 10,000 MHz. At this frequency, one could use waveguides for which the microwave properties are more readily measurable and simpler to understand. At this frequency the necessary bandwidth required to study the transition is also a smaller fraction of the transition frequency. It is estimated that using this transition one could determine the Lamb shift to 1 in 10^6.

The uncertainty due to the nuclear radius could be reduced by making measurements on both hydrogen and deuterium. The ratio of the two radii is known better than the individual radii and the two measurements could be combined to reduce the uncertainty due to the nuclear radius.[5]

6. Conclusions

The fast beam separated oscillatory field method has been used to measure with high precision the Lamb shift in the n=2 state of hydrogen. The agreement between the measured value and the theoretical value is obscured by the discrepant values for the nuclear radius. This technique could be used to improve further the precision and to reduce the uncertainty due to the nuclear radius.

7. Acknowledgements

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8. References

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