Separated-Oscillatory-Fields Measurement of the Lamb Shift in H, $n = 2$†

S. R. Lundeen and F. M. Pipkin
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 31 March 1975)

The separated-oscillatory-field technique has been used with a fast atomic beam to measure in zero magnetic field the $2\,^2S_{1/2} \rightarrow 2\,^2P_{1/2}$ Lamb-shift interval in hydrogen. Resonance lines narrower than the natural linewidth by a factor of 3 were used to obtain $S(\mathrm{H}, n=2) = 1057.893(20)$ MHz. This result has a factor of 3 increase in precision over earlier measurements.

Measurements of the Lamb shift in hydrogenlike atoms give one of the best low-energy tests of quantum electrodynamics.[1,2] The first, and still the most precise, of these measurements is for the $n = 2$ state of hydrogen. Figure 1 summarizes the direct and indirect measurements of this interval and a more recent value for the theory.[3-9] Only the single measurement of Robiscoe is in good agreement with theory; the overall agreement between experiment and theory is poor.

The precision of the past measurements has been limited by the 100-MHz natural linewidth of the transition. This paper reports a new measurement using the separated-oscillatory-field technique[10] and a fast atomic beam to obtain lines whose width is less than the natural linewidth.[11,12] We report in particular measurements with lines whose width is one-third the natural linewidth and an improvement by a factor of 3 in the precision of the experimental value for this interval.

Figure 2 shows the apparatus. A beam of 50–100-keV protons from a small accelerator is partially converted through charge capture to a fast excited hydrogen beam. Since the $2\,^2S_{1/2}$ state is metastable and the $2\,^2P_{1/2}$ state decays rapidly (1.6 nsec) to the ground state, decay in the drift region depopulates the $2P$ state and produces a beam of atoms predominantly in the $2S$ and $1S$ states. The $2S$ atoms normally reach the detection region where a continuously applied electric field quenches them and a photomultiplier views the emitted Lyman-α radiation.

If, before reaching the detection region, the beam passes through a region of rf electric field whose frequency is nearly resonant with the $2\,^2S_{1/2}$-$2\,^2P_{1/2}$ Lamb shift interval, some fraction of the $2S$ atoms will be quenched and lost from the beam. Such quenching is detected through the consequent decrease in the Lyman-α flux observed in the detection region. The quenching resonance is displayed by varying the frequency of the applied field while keeping its amplitude constant. At no time is an external magnetic field applied.

In the present experiment the spectroscopic rf field is applied coherently in two separated regions, with the relative phase of the fields in the two regions chosen to be either 0° or 180°. The 0° and 180° quenching signals are defined as

$$S(0°) = [N(\mathrm{off}) - N(\mathrm{on}, 0°)]/N(\mathrm{off}),$$

$$S(180°) = [N(\mathrm{off}) - N(\mathrm{on}, 180°)]/N(\mathrm{off}),$$

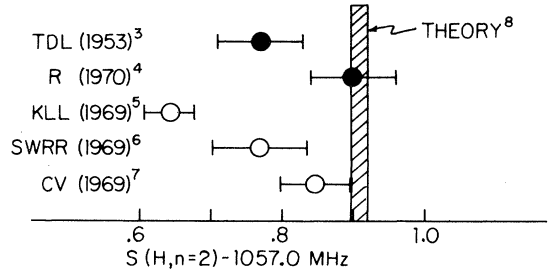

FIG. 1. Previous measurements of the Lamb shift in H, $n = 2$. Indirect measurements (open circles) *assume* $\Delta E = 10\,969.019(24)$ MHz $[\alpha^{-1} = 137.036\,12(15)]$ (Ref. 9).

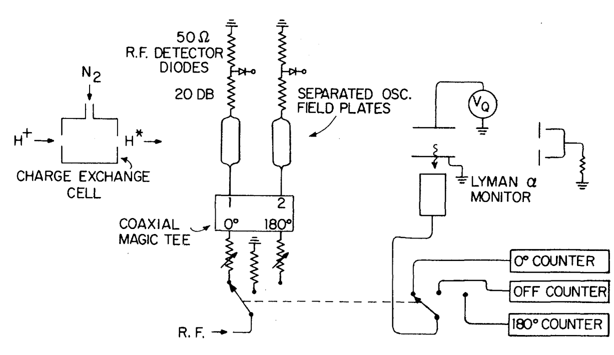

FIG. 2. Fast-beam, separated-oscillatory-field apparatus. The coaxial magic tee divides the rf power equally between the two separated rf regions with a relative phase of 0° or 180°.

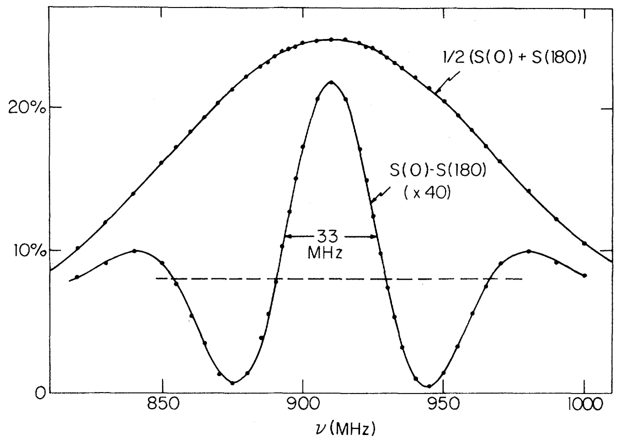

FIG. 3. Typical separated-oscillatory-field resonance line shapes.

where N is the rate at which photons are detected for the indicated states of the rf fields. The difference between these two signals gives the "interference signal." The frequency width of the interference signal depends upon the separation of the rf plates rather than the lifetime of the P state. It is this feature which enables one to reduce the linewidth.

Figure 3 shows a typical resonance profile for the $(2\,^2S_{1/2}, F=0)$ to $(2\,^2P_{1/2}, F=1)$ transition. The contributions of the other two hyperfine components have been eliminated through the use of an rf state-selection technique.[12] The experimental line profile is in good agreement with the expected profile calculated for the actual amplitude profile of the rf field by numerical integration of the Schrödinger equation. For uniformly polarized rf fields the theoretical interference curve is symmetric and, with the exception of small (<0.1 MHz) corrections, centered on the zero-magnetic-field separation of the resonant levels.

The uniformly polarized rf fields are produced by pairs of balanced rf plates in each of the separated rf regions. The rf phase is controlled automatically and reproducibly by a system of high-precision coaxial magic tees. With this system, the relative phase of the two rf fields is equal to its nominal value to within a few milliradians. The small effects of phase errors of this magnitude are canceled during data acquisition by physically interchanging the rf plates so that the atomic beam encounters the plates in reverse time order. A similar scheme is used to eliminate small Doppler shifts that may arise if the direction of propagation of the rf is not exactly perpendicular to the atomic beam. The amplitude of the rf field is held constant to within 0.1% over the frequency range used in these measurements.

In order to determine the Lamb shift the center of the interference resonance was measured by the method of symmetric points. Two independent measurements were made in each of three different geometrical arrangements of the apparatus. The results are summarized in Table I. The measurement errors shown in column 5 of Table I are inferred from the scatter of eight line centers within each data set.

As an experimental check of the line symmetry, measurements were made at three widely spaced positions on the line profile. For the line shown in Fig. 3, the pairs (890, 930), (886, 926), and (882, 922) MHz were used. To within the measurement uncertainty of 14 ppm, the line centers determined from the different pairs were the same.

A careful investigation was made of effects that

TABLE I. Summary of the six independent measurements of the $(2\,^2S_{1/2},F=0)\rightarrow(2\,^2P_{1/2},F=1)$ fine-structure transition.

Data set	Beam energy (keV)	Plate spacing (cm)	Linewidth (MHz)[a]	Raw line center (MHz)	Total correction (MHz)	$\nu_0((2S_{1/2},F=0)-(2P_{1/2},F=1))$ (MHz)
3	50	3.30	40	909.876(24)	0.058(19)	909.934(31)
4	50	3.30	40	909.957(35)	0.058(19)	910.015(40)
7	100	5.08	36	909.822(20)	0.117(16)	909.939(26)
8	100	5.08	36	909.776(19)	0.117(16)	909.893(25)
9	100	5.97	32	909.804(26)	0.136(18)	909.940(32)
10	100	5.97	32	909.780(20)	0.136(18)	909.916(27)
Average						909.940(20)

[a] Full width at half-maximum.

could shift the line center by more than 0.001 MHz from the true center of the single hyperfine transition being observed. The largest single such effect is relativistic time dilation [$\leq$ 0.107(4) MHz]. The Bloch-Siegert shift and an rf shift due to the $2\,^2P_{3/2}$ state produce small corrections [$\leq$ 0.0037(4) MHz]. Other effects considered include incomplete hyperfine state selection [$\leq$ 0.002(2) MHz], imperfections in the rf system [$\leq$ 0.063(8) MHz], line-shape distortions for off-axis beam trajectories [$\leq$ 0.004(10) MHz], stray electric and magnetic fields [$\leq$ 0.000(5) MHz], natural or induced population coherence [$\leq$ 0.000(7) MHz], and detection of cascade produced light [$\leq$ 0.000(1) MHz]. The total correction for each measurement is shown in Table I. The simple average of the six independent measurements is

$$\nu_0((2\,^2S_{1/2}, F=0) \rightarrow (2\,^2P_{1/2}, F=1)) = 909.940(20) \text{ MHz}.$$

With the values of the zero-field hyperfine-structure intervals measured for the $2\,^2S_{1/2}$ state[13] and calculated for the $2\,^2P_{1/2}$ state,[14] this gives for the Lamb shift

$$S_{\text{exp}}(H, n=2) = \nu_0 + 147.953 \text{ MHz} = 1057.893(20) \text{ MHz}.$$

This error is the quadrature sum of a 0.010-MHz measurement error and a 0.018-MHz error in the total systematic correction.

This result is consistent with the calculation of Erickson,[8]

$$S_{\text{theo}}(H, n=2) = 1057.912(11) \text{ MHz}.$$

More recently, Mohr has numerically evaluated the self-energy contribution to the Lamb shift for a range of nuclear charge $Z = 10 \rightarrow 110$. By extrapolation, he obtains for $Z = 1$,[15]

$$S_{\text{theo}}(H, n=2) = 1057.864(14) \text{ MHz}.$$

This result is also consistent with the measurement reported here, though it differs significantly from the calculation of Erickson.

Further improvements in the experimental precision by at least a factor of 3 should be attainable with the present technique through more careful control of systematic corrections and longer data acquisition times. Further work on the theory should resolve the discrepancy in the two calculations. Thus, it should be possible to make a more definitive test of quantum electrodynamics.

†Research supported by the National Science Foundation under Grant No. GP-43742X.

[1] S. J. Brodsky and S. D. Drell, Annu. Rev. Nucl. Sci. 20, 147 (1970).

[2] B. E. Lautrup, A. Peterman, and E. de Rafael, Phys. Rep. 3C, 193 (1972).

[3] S. Triebwasser, E. S. Dayhoff, and W. E. Lamb, Jr., Phys. Rev. 89, 98 (1953) [S = 1057.77(6) MHz].

[4] R. T. Robiscoe and T. W. Shyn, Phys. Rev. Lett. 24, 559 (1970) [S = 1057.90(6) MHz].

[5] S. L. Kaufman, W. E. Lamb, Jr., K. R. Lea, and M. Leventhal, Phys. Rev. Lett. 22, 507 (1969) [$\Delta E - S$ = 9911.38(3) MHz].

[6] T. W. Shyn, W. L. Williams, R. T. Robiscoe, and T. Rebane, Phys. Rev. Lett. 22, 1273 (1969) [$\Delta E - S$ = 9911.25(6) MHz].

[7] T. V. Vorburger and B. L. Cosens, Phys. Rev. Lett. 23, 1273 (1969) [$\Delta E - S$ = 9911.17(4) MHz].

[8] G. W. Erickson, Phys. Rev. Lett. 27, 780 (1971).

[9] E. R. Cohen and B. N. Taylor, J. Phys. Chem. Ref. Data 2, 741 (1973).

[10] N. F. Ramsey, *Molecular Beams* (Oxford Univ. Press, London, England, 1956), p. 124.

[11] V. W. Hughes, in *Quantum Electronics*, edited by C. H. Townes (Columbia Univ. Press, New York, 1960), p. 502.

[12] C. W. Fabjan and F. M. Pipkin, Phys. Rev. A 6, 556 (1972).

[13] J. W. Heberle, H. A. Reich, and P. Kusch, Phys. Rev. 104, 1585 (1956).

[14] S. J. Brodsky and R. G. Parsons, Phys. Rev. 163, 134 (1967).

[15] P. J. Mohr, Phys. Rev. Lett. 34, 1050 (1975).