Experimental Checks of Quantum Electrodynamics

The measurement that gave the impetus to the development of quantum electrodynamics (QED) was the measurement of the difference in the energy levels $^2S_{1/2} - {}^2P_{1/2}$ in the hydrogen atom by Lamb and collaborators (Lamb shift).[1] Such was the precision and quality of this work that it has taken nearly twenty years before anyone dared to repeat it. Now, just after the Nobel Prize for the theory, a repetition has been performed with a slightly different result.[2] There is a significant improvement over Lamb's measurement because Robiscoe used an atomic beam in a pure hyperfine-structure state. Thus the hyperfine structure is resolved in Robiscoe's work, whereas Lamb had a superposition of lines which were barely resolved. Since the quoted measurement accuracy is about 0.1% of the linewidth, this is important.

The actual measurement involves not the Lamb shift at zero field, but a transition between Zeeman components at finite field. In particular, Robiscoe was able to find transitions at zero frequency between hyperfine transitions by adjustment of the magnetic field. Two such transitions were measured—one in each paper—with results which agree. Since these are measurements made in full knowledge of the old, with an improvement, we must tentatively regard them as superior. The results for the zero-field Lamb shift are:

$$1057.77 \pm 0.10 \text{ MHz (Lamb)},$$
$$1058.05 \pm 0.10 \text{ MHz (Robiscoe)},$$
$$1057.50 \pm 0.11 \text{ MHz (theory)}.$$

The latest theory is due to Erickson and Yennie[3] with an unpublished improvement by M. Soto. The error is the estimate of uncalculated terms. We thus have a significant discrepancy of 1/2 MHz. There are three choices; the new experiments are wrong; the calculations are inadequate; or QED is basically wrong.

The fine-structure constant $\alpha(=e^2/\hbar c)$ has been determined by adding the $^2S_{1/2} - {}^2P_{1/2}$ level spacing to the $^2P_{3/2} - {}^2S_{1/2}$ obtained in a similar measurement. (Both measured in deuterium to get smaller linewidth.) In the least-squares adjustment of atomic constants[4] it is found that

other measurements of e (Millikan oil drop; x-ray measurement of N; x-ray measurements of h/e are too inaccurate to contribute. Pending a remeasurement of the $^2P_{3/2} - {}^2S_{1/2}$ transition, we may tentatively increase the fine structure by the 1/4 MHz found by Robiscoe—a change of 25 parts per million (ppm). This is an increase of about 12 ppm for α.

This goes a long way toward resolving another long-standing discrepancy—in the hydrogen hyperfine structure. This is the most accurate measurement in physics.[5] In a comparison with theory, we need α^2 and the g factors for the electron and proton. That for the electron is well known from calculations and measurements; that for the proton has been measured in oil or water and has been subject to a calculation[6] of a diamagnetic correction. Although few people doubted the calculation, it is good to have a new measurement of the g factor of the proton independent of the diamagnetic correction—and, thereby, checking the calculation. There is a new measurement[7] of g to an accuracy of 3×10^{-7} by inducing transitions between Zeeman components of the hyperfine structure of atomic hydrogen in a very stable high magnetic field.

Without the tentative new value for α there remains a discrepancy between theory and experiment of 40 ± 20 ppm. This discrepancy could have been due to a failure of QED (which physicists are reluctant to allow) or a correction due to polarizability of the proton (which physicists have been unable to calculate[8]). With the tentative change in α, the discrepancy becomes 15 ± 20 ppm, which is no longer troublesome.

Confirmation for this change in α comes from two sources. Firstly, muonium hyperfine structure which involves (we hope) no structure corrections gave a result for α in agreement with that of Lamb.[9] However, Ruderman[10] has now noted that in deducing α from this measurement, a value of the free μ meson magnetic moment was used which is probably incorrect. The μ meson magnetic moment is measured in water and the chemical shift must be calculated and it is somewhat uncertain. Ruderman suggests a change of 20 ppm also in the direction to resolve the proton hfs discrepancy.

Confirmation also comes from a completely different source. A group from Pennsylvania[11] has measured current jumps from superconducting Josephson junctions excited by microwave radiation. These occur at potentials according to the formula $h\nu = 2$ eV. The measurement seems particularly clean and resolves itself into a measurement of a frequency and a small voltage. They measure the emf in volts and this makes the measurement hc/e in the usual units.

Thus $2e/h = 4.83591$ Hz/volt (± 6 ppm), which yields a value of hc/e 38 ppm higher than given by the recent adjustment of atomic constants.[4] This, however, is the result which would be achieved by an increase of α by 19 ppm. This measurement is more accurate than the

direct determination of α. Thus it seems that the discrepancy in the hydrogen hyperfine-structure measurement has disappeared with only a small error for a possible polarizability correction. It is strange that a measurement in superconductivity should show that there is little polarizability of the proton, but the coupling of atomic constants in measurements leads to strange results.

The g factor of the electron has already been measured. Experiment and theory agree. Now the g factor of the free positron has been measured.[12] The quantity $g/2 - 1$ has been measured to an accuracy of 1 part in 10^5 and agrees with that of the electron as expected.

Other measurements on quantum electrodynamics concentrate on high momentum transfer and therefore on small distances. There are several new contributions in this productive past summer.

The most important of these contributions is the first result from the electron-electron scattering experiment with the Princeton-Stanford storage ring.[13] Four hundred scatters with center-of-mass angles between 40° and 90° were analyzed and compared with the calculations of QED. Only relative cross sections were determined.

The effect of a deviation from theory can be made semiquantitative by a Feynman regulator. The photon propagator $1/q^2$ is replaced in the calculations by $[1/q^2 - 1/(q^2 + K^2)]$ and the regulator (K) is derived from experiment. The electron-electron scattering experiment tells us that for the photon propagator $K \geqslant 0.8$ GeV/c.

There is a very precise (1%) measurement of positron-electron scattering from Orsay[14] at 300 MeV and 500 MeV at 180°. Complete agreement was found between theory and experiment. Using a Feynman regulator again, we find that $K \geqslant 0.4$ GeV/c. This is reassuring.

The new CERN μ-meson storage ring has begun operation and the difference of the gyromagnetic ratio (g) and the Dirac value ($g - 2$) for the free negative muon has been measured.[15] This new result agrees with the old for free μ^+ mesons with, so far, a factor of two improvement in accuracy. Thus the earlier conclusions are confirmed and we can anticipate better measurements soon.

A spectacular announcement at the International Conference on High-Energy Physics at Berkeley in September was that of a new experiment on the pair production of electron-positron pairs at wide angles. An earlier result[16] had found a cross section greater than theory by a factor of 2 at large momentum transfers—a result not easily described by the Feynman regulator, but involving momentum transfers about $(300 \text{ MeV}/c)^2$. The new measurement from DESY,[17] still not finally analyzed, gives results equal to theory to about 5% precision at this momentum transfer. Again, since this is a second measurement, per-

formed with full knowledge of the problems and difficulties of the first, we must tentatively accept it as superior.

There is also a result on photoproduction of muon pairs.[18] The authors give a limit for a regulator $K = 1.2_{-0.3}^{+1}$ GeV/c, being two standard deviations from no effect. The results are inconsistent with the earlier *electron*-pair results[16] but consistent with the new ones.

Thus, the last summer has opened up one discrepancy—the Lamb shift —and may have closed two others—hydrogen hyperfine structure and photoproduction of electron-positron pairs.

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