Part 8  Fine Structure Constant

Review of Spectroscopic Data for Determining the Fine Structure Constant*

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1. Introduction

The Sommerfeld fine structure constant $\alpha$ has played an important role in atomic spectroscopy ever since its introduction by Arnold Sommerfeld in 1916 (1). It originated in Sommerfeld's theory of the fine structure of the optical spectrum of atomic hydrogen. In a relativistic treatment of the Kepler problem in the Bohr theory, the quantity $v_{L}/c$ (where $v_{L}$ is the velocity of the electron in the first Bohr orbit, and $c$ is the velocity of light) was denoted by $\alpha$. But its utility goes far beyond this particular case. We note the following features regarding $\alpha$:

1. Dimensionless fundamental constant.
2. $\alpha = e^2/hc \approx 1/137$, or, in SI units, $\alpha = (e/c^2/4\pi)(e^2/hc)$.
3. Basic coefficient in the electromagnetic interaction.
4. Expansion parameter in quantum electrodynamics (QED).
5. Cosmological significance? Group-theoretical interpretation?

To set the stage for a review of experimental measurements of $\alpha$, Fig. 1 reminds us of the way experiment and theory are related. This figure shows the comparison between an experimentally measured quantity and the theoretically calculated value for that quantity. The experimental result depends on various standards, against which the measuring equipment is calibrated. The theoretical expression is of course dependent on the underlying principles of physics, such as the electromagnetic interaction and quantum electrodynamics, and also on numerical values of the fundamental constants, chief among which is $\alpha$ for the present discussion. The result of the comparison may lead to one of two conclusions: (i) "agreement," which is interpreted as experimental confirmation of theory and of the input value of $\alpha$; or (ii) "disagreement," which implies a failure in one or more boxes. In this predicament, one course of action is to remove the disagreement simply by changing the value of $\alpha$, i.e. deriving a new value for $\alpha$. Indeed, an analysis of a considerable array of experimental data, via the implied value of the fine structure constant, was undertaken by Taylor, Parker, and Langenberg (2), in tables 28 and 29 of their comprehensive review article. Today, however, I shall adopt that value for $\alpha$ which they obtained from data independent of quantum electrodynamics theory known as $\alpha^{-1}_{\text{QED}}$, where $\alpha^{-1}_{\text{QED}} = 137.03608(26)$. Experimental results

will then be compared with theoretical numbers based on this "standard" value for \( \alpha \). Where discrepancies exist, it now appears likely that their origin lies not in the value for \( \alpha \), but rather in failures in other areas. In fact, the record of the past decade in this field shows discrepancies appearing and disappearing, with attempts being made to remove them at the various levels of boxes 2, 3, 4, and 5.

2. Methods of Measuring \( \alpha \)

When we focus on experiments aimed at measuring \( \alpha \), we find that the methods of optical spectroscopy have long been dominant, giving way to microwave spectroscopy, as those techniques were developed. In the last few years, still other methods have come to the fore. Some of these different approaches are tabulated in the first column of Fig. 2. This list makes no claim to be exhaustive. The first three items, Lamb shift, fine structure, and hyperfine structure, comprise the subject I shall discuss shortly. Only a very brief mention will be made here regarding the remaining four entries in Fig. 2 which are really the province of other speakers at this conference.

The electron spin magnetic moment differs from the value of 1 Bohr magneton by a small amount (about 1 part in \( 10^3 \)). This so-called "anomaly" is a quantum-electrodynamic effect, and can be calculated as a power series in \( \alpha(3) \). Experimental measurements of the anomaly have been made on the charged leptons to as high a precision as 3 ppm (parts per million) in the case of the electron(4). These experiments may be interpreted as a measurement of \( \alpha \), in which case excellent agreement is found with the "standard" \( \alpha \).

The ratio \( 2e/h \) is obtained from measurements of the current-voltage characteristic of a superconducting junction irradiated by microwave radiation. Using this a.c. Josephson effect, measurements of \( 2e/h \) have been made to a precision of 0.46 ppm (5). By a suitable combination of this result for \( 2e/h \) with other fundamental constants, a value for \( \alpha \) has been derived good to 1.6 ppm. Here the precision is mainly limited by that of the other constants which enter the functional relationship between \( \alpha \) and \( 2e/h \), in particular the value of \( \gamma_p \), the gyromagnetic ratio of the proton.

The use of a Josephson device in a superconducting ring which is physically rotated in a magnetic field is the basis of a method for measuring \( h/m \) (6). A precision of 6 ppm anticipated in the measurement of \( h/m \) will permit a determination of \( \alpha \) to about 3 ppm, via the relation given in Fig. 2.

In an experiment under development at the NBS (7), the Compton wavelength of the electron is to be obtained by measuring the wavelength of the two-photon annihilation \( \gamma \)-rays of positronium. If the annihilation line can be measured to 1 ppm, then \( \alpha \) can be derived to 0.5 ppm by means of the relation indicated in Fig. 2.

Returning to the earlier items on the list, namely Lamb shift,