

The 64th Compton Lecture Series

Unsolved Mysteries of the Universe: Looking for Clues in Surprising Places

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Lecture 5: Using the Fine Structure Constant to Push on the Standard Model

Introduction to the Fine Structure Constant

- **The symbol used to represent the fine structure constant is the Greek letter α (alpha).**
- $\alpha = e^2 / \hbar c$, where e is the electron charge, \hbar is Planck's constant, and c is the speed of light .
- The fine structure constant first appeared in physics to quantify the “fine structure”, i.e. the splitting, of frequencies of light emission from atoms.
- Since then, α has been recognized as being of more general importance, but the name “fine structure constant” stuck.
- The fine structure constant is a *coupling constant*. It describes the strength of the interaction, or coupling, between light and matter
- $\alpha \approx 1/137$, but not exactly. This approximation is more conveniently written as $\alpha^{-1} \approx 137$. The most accurate experiment, discussed below, yields $\alpha^{-1} = 137.035\,999\,710$ (96).
- Although several interesting attempts have been made, we have no way to predict what the value for α should be. It is one of the free parameters of the Standard Model.
- **Regarding α , Richard Feynman said, “It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it.”** *QED: The Strange Theory of Light and Matter*, Princeton University Press 1985, p. 129.
- Its value is very important for the development of the universe. Several processes of element production depend very sensitively on α . This leads to speculation on its the relationship to the *anthropic principle*.

Running Coupling Constants

- Quantum Field theories must be *renormalized* before they give sensible results. Renormalization is the well-defined process of subtracting one infinity from another to end up with a finite answer.
- Renormalization yields a correction to the coupling constants which depends on energy. So, the coupling constants “run”, i.e. change with energy.
- We expect that if the four forces are unified, the running coupling constants will converge at some high energy. (This is one of the motivations for supersymmetry, discussed last lecture.)
- **For the rest of the lecture, we will discuss tests of the Standard Model using the low-energy value of the fine structure constant.**

Is it Really a Constant?

- Physicists generally assume that the constants of nature, such as α , do not vary with time or space.
- However, various theories say this might not be the case, and all such assumptions must be tested experimentally.
- There are two approaches to looking for time-variation of α .
 - Precision measurement can be performed in a laboratory over the course of a few years. These experiments generally do not yield accurate determination of α itself, but they are very sensitive to its variation with time.
 - We can look back at physics that happened a long time ago which depended on α , and ask whether it points to a different value. A few examples:
 1. The Oklo nuclear reactor was a natural, self-sustaining fission reactor that occurred in Gabon, Africa 1.5 billion years ago. The leftover abundance of certain isotopes depends sensitively on the value of α .
 2. Quasars act as bright, distant sources of light. Intervening gas clouds absorbed light at certain frequencies, and the frequencies of absorption depend on the value of the fine structure at that time. All absorption frequencies will be redshifted, but we can ask whether there are other unexpected shifts of one frequency relative to another, which would result from a different α .
- **There is an interesting trade-off in those two approaches. One leverages exquisite laboratory control and high precision (but short times), the other leverages very long timescales (but low precision).**

- So far, both precision tests and examination of ancient physics do not indicate time-variation of α . (Excitement from a few years ago about a non-zero effect in the quasar data seems to have been overturned by more recent observations.)

The Electron g-Factor and Precision Tests of the Standard Model

- **Circulating electrical charges create a magnetic field, which is proportional to the rate of circulation.**
- **The constant of proportionality is called the g-factor. Precisely, it is the ratio of magnetic moment (in units of the Bohr magneton) to the angular moment (in units of Planck's constant).**
- There is an interesting story for the electron g-factor theory.
 1. If the electron were a ball of charge with finite spatial extent, spinning non-relativistically, it would have $g = 1$.
 2. The first attempt to combine special relativity and quantum mechanics yielded the prediction that $g = 2$.
 3. Quantum Electrodynamics (QED), the theory which successfully combines special relativity and quantum mechanics, predicts $g = 2.002\ 319\ 304 \dots$
- The part-per-thousand sized corrections of QED arise from interaction of the electron and virtual particles in the vacuum. This is called the “anomalous magnetic moment.”
- **If the electron is truly a point-particle, then Quantum Electrodynamics and other parts of the Standard model allow us to predict its g-factor precisely, so long as we know α .**
- So, a measurement of the g-factor can be used to test the Standard Model. We follow this procedure:
 1. Measure g .
 2. Invert the QED calculations in order to extract a measurement of α .
 3. Compare this value of α with that obtained from other experiments.
- What are the possibilities for new physics if these values obtained for α disagree?
 - The electron is not really a point particle. It is made of other constituents.
 - There are new particles we don't know about yet. Then the corresponding virtual particles show up in the vacuum and shift g .
 - Something is wrong with QED itself. After all, to many people it is surprising that it works as well as it does.

The Harvard g-Factor Measurement

- This measurement represented 20 years of work to improve on the previous electron g -factor measurement performed at the University of Washington.
- When combined with existing QED theory, it provides a measurement of α that is 10 times more accurate than that from any other technique.
- In the Harvard experiment, we trap a single electron in a Penning trap, which is a clever combination of electric and magnetic fields.
- We cool the Penning trap to 0.1 K, just above absolute zero, so that the various motions of the electron are slowed.
- The electron's *cyclotron* motion is actually forced to be in its ground quantum state by this low temperature.
- We detect the electron's oscillations in the trap by the electrical signal it creates in a special amplifier.
- By carefully measuring the frequencies of the electron's spin-precession and cyclotron orbit, we are able to make the best measurement of the electron g -factor.
- **So far, no disagreement between this measurement of α and others has surfaced, but we badly need the other measurements to get better for a more interesting test!**