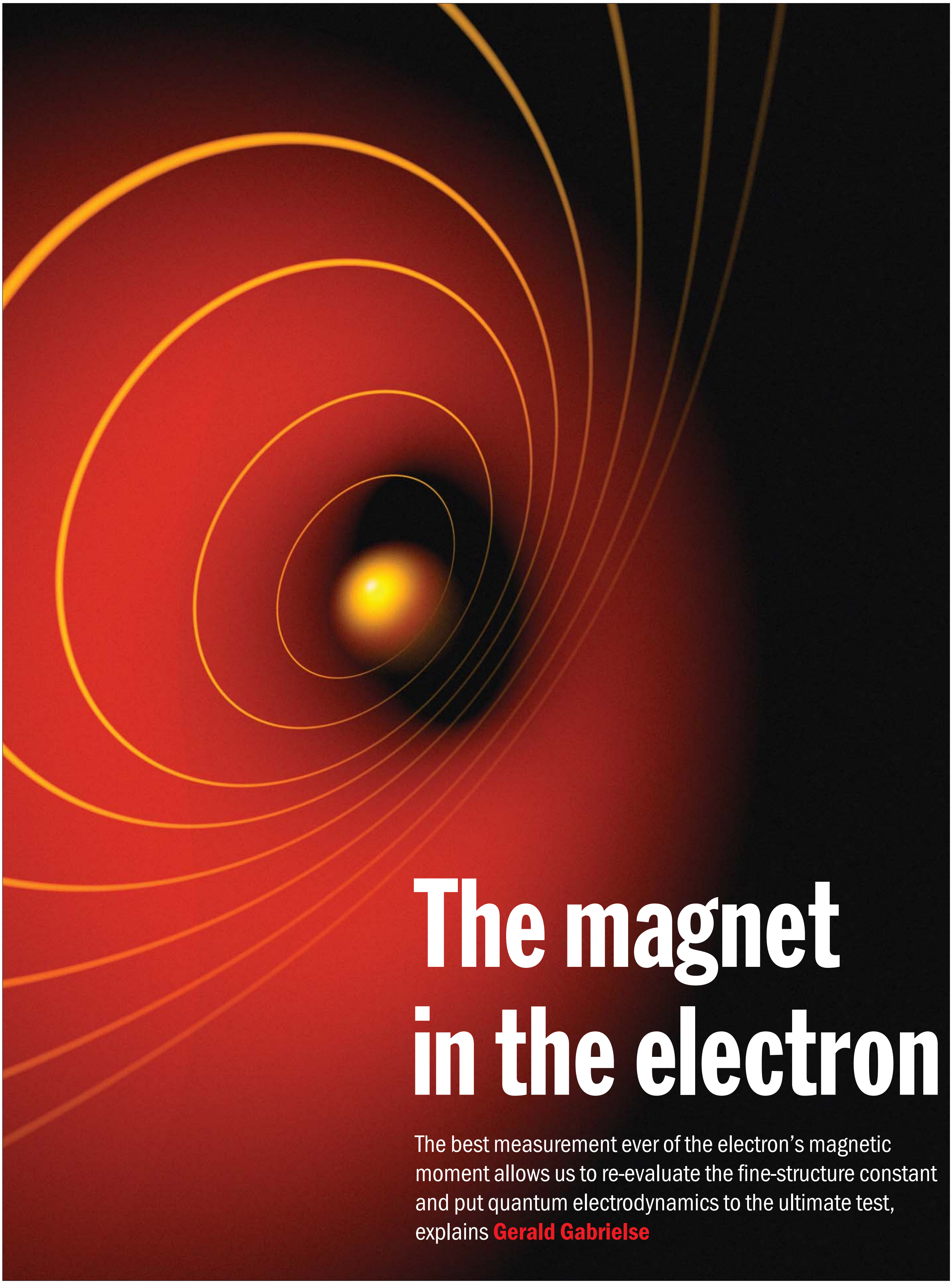

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The magnet in the electron

The best measurement ever of the electron's magnetic moment allows us to re-evaluate the fine-structure constant and put quantum electrodynamics to the ultimate test, explains **Gerald Gabrielse**

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What do the massive Earth and the tiny electron have in common? The unusual answer is that both act as if they have a magnet lurking inside them. For the Earth, the magnet is almost aligned with the axis of the Earth's rotation, while the magnet inside the electron seems to point precisely in the same direction as the electron's intrinsic angular momentum or spin. Measurements of the Earth's magnetism give us a glimpse into the inner structure of our planet, revealing dramatic changes in the otherwise unseen currents of molten iron that are thought to be responsible for the geomagnetic field. Now, after a 20-year quest, we have obtained a similar magnetic glimpse into another place we cannot travel to or see: a single electron.

Over the last two decades, a series of seven graduate students and I at Harvard University in the US have developed new methods and apparatus with which to measure the intrinsic magnetism or "magnetic moment" of the electron. Recently, we announced the first fruits of our labour: a value with a precision better than 8 parts in 10^{13} that represents the best determination of the magnetic moment of the electron since a celebrated measurement in 1987.

The new measurement is important for testing quantum electrodynamics (QED), the remarkably successful theory that describes the way light and matter interact via the electromagnetic force. Furthermore, by combining our measurement with QED we have been able to determine the fine-structure constant – a fundamental constant of nature – with an accuracy about 10 times better than any rival method. Last, but not least, the precision of our magnetic measurement allows us to search for signs of new physical processes and to test whether or not the electron has any internal structure.

Quantum cyclotron

Anyone with a compass can detect the Earth's magnetism. But the electron's magnetism is much too small, and the precision that we desire much too high, for such an approach to work. Our solution has been to bind an electron within an artificial atom that we built, the lowest energy levels of which depend sensitively upon the electron's magnetism. We need the electron to be bound, rather than free, because only then will it stay in the apparatus long enough to allow us to make such a precise measurement. However, since we wish to measure the magnetism of a *free* electron, the electron must be bound weakly enough so that its magnetism is not significantly altered by the artificial atom.

In the simplest of ordinary atoms, the hydrogen atom, an electron is bound to a proton. But the binding of an electron that this ordinary atom manages with a single proton just 0.05 nm away takes us an apparatus the size of a small room. The "nucleus" with which we replace the proton is an electromagnetic trap (called a Penning trap) about 1 cm in size, which surrounds a single electron suspended in empty space (figure 1). Outside the trap is a large external magnetic field (generated by many amps of current in a superconducting coil) that orients the electron's internal magnet much like the Earth's magnetism does the magnetic needle of a compass. Further increasing the size or our home-made atom is a refrigerator, a large dewar, vacuum pumps, a microwave source and a lot of electronics.

Every student of physics is familiar with the quantized energy levels occupied by an electron in an atom. The energy levels in our artificial atom are essentially the same as the energy levels of a free electron in a magnetic field, which means we can describe them in terms of the electron's cyclotron frequency, f_c, and spin frequency, f_s. The cyclotron frequency specifies how many circular orbits per second an electron makes when it is in a magnetic field, while the spin frequency specifies how many times per second the electron's spin vector rotates about the direction of the field. The traditional measure of the intrinsic magnetism of the electron is the constant of proportionality between the spin and cyclotron frequencies, defined as $g/2$, so that $f_s = (g/2)f_c$ (see box on page 34).

The cyclotron motion of a charged particle in a magnetic field is the same as that used in particle accelerators to whip electrons or protons to near-light speeds. But while the goal in particle physics is typically to make particles move as fast as possible with the largest possible energy in a large, circular cyclotron orbit, we achieve the opposite limit – the lowest possible electron energy – by cooling our artificial atom to a temperature of just 0.1 K. Only certain circular cyclotron orbit radii are allowed by quantum mechanics, and each of these corresponds to a different possible energy level for the electron. The cold electron must therefore choose between a limited number of radii and energy options, just like an electron in an ordinary atom.

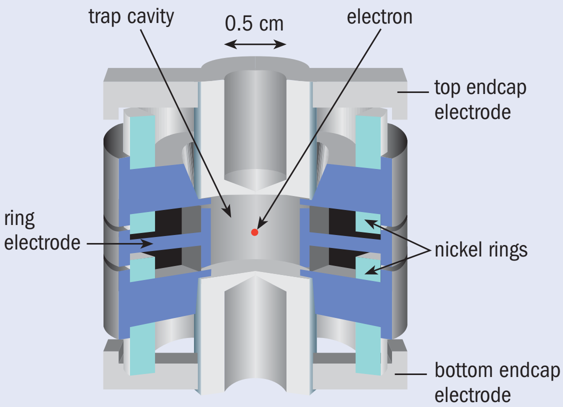
Our system is therefore sometimes called a quantum cyclotron, since the electron has a "ladder" of cyclotron energy levels that are equally spaced by the energy hf_c, where h is Planck's constant. These energy levels also depend on the spin of the electron, which can take just one of two values "up" or "down". If the electron's spin direction is flipped from pointing against the external magnetic field to pointing along it, for instance, then each of the cyclotron energy levels increases in energy by hf_s. As a result, there are two ladders of cyclotron energy levels open to the electron depending on whether the electron is spin-up or spin-down (figure 2).

An electron that is in one of the excited states will always spontaneously jump to a state directly below it, without changing its spin, by emitting a photon of light with an energy that corresponds to the difference in energy between the two levels. An important feature of our measurement is that our specially designed trap cavity inhibits this spontaneous emission. As a result,

At a Glance: Measuring the electron's magnetism

- The electron's intrinsic magnetism is similar to the Earth's magnetic dipole but is dictated by the rules of quantum mechanics
- If the quantum world operates as Dirac taught us, then the electron's intrinsic magnetism would have a value of $g/2 = 1$
- But quantum electrodynamics and other subtle physical processes conspire to make it about 1 part per 1000 larger than this value
- By making a quantum system comprising a single electron suspended in an electromagnetic trap, Harvard researchers have made the best measurement yet of the electron's magnetism
- This measurement provides a new value for the fine-structure constant, and places tight constraints on any internal structure of the electron

1 Artificial atoms



The Harvard experiment used by David Hanneke (left) and the author to measure the magnetic moment of the electron essentially creates a giant artificial atom, whereby a "Penning" trap simulates the electromagnetic field of a nucleus that binds a single electron very weakly in certain energy levels. A strong external magnetic field directed vertically through these trap electrodes, along with voltages applied to the electrodes, has suspended a single electron in the centre of a trap for up to 10 months.

The electron's magnetism

The traditional measure of the electron's intrinsic magnetism is a dimensionless constant typically referred to as "$g/2$". It comes from the definition of the electron's magnetic moment: $g(e/2m)S$, where e and m are the charge and mass of the electron, respectively, and S is the spin of the electron. The importance and meaning of $g/2$ is revealed most clearly by looking at the theoretical contributions to it (which also illustrates why we deal with $g/2$ instead of just g): $g/2 = 1 + a(\alpha) + \text{(small corrections)} + \text{(new physics)}$.

The "1" on the right-hand side of the equation is the value predicted by the Dirac theory of the electron, which is assumed to be a point particle, and is by far the largest contribution to the electron's magnetism. The contribution of the second term – the anomalous magnetic moment, $a(\alpha)$ – is about 1000 times smaller. This is a consequence of the interaction between the electron and the "virtual" particles of the vacuum (particles such as electron–positron pairs produced in accordance with the uncertainty principle and which then annihilate almost immediately). The surprisingly successful theory that describes such interactions between light and matter – quantum electrodynamics or QED – predicts the value of this anomaly in terms of the fine-structure constant, α. The "small corrections" are so small that we will not discuss them further here. They are due to strong and weak interactions, as opposed to the electromagnetic interactions responsible for the first two terms, and they can be accurately calculated using the Standard Model of particle physics.

Finally, one can never fully discount the possibility that there may be some new physical processes that cause the measured value of $g/2$ to differ from what is calculated. Measurements of $g/2$ for positive and negative muons – the heavier cousins of the electron – have recently been carried out precisely to look for such "new physics", and our measurement is needed to allow them to subtract away the QED contributions.

As well as allowing us to test QED with better precision than ever before, accurate measurements of the magnetic moment of the electron can tell us whether the electron is a point-like particle or whether it has an internal structure.

the electron takes more than 200 times longer to jump down to one of the two stable ground states, giving us time – about 10 s on average – to determine the state the electron was in before it made the jump. The time an electron spends in the excited states (the spontaneous-emission rate) increases as the frequency of the photon moves away from frequencies of the resonant modes of the cavity, which depend on its geometry. Since f_c is proportional to the strength of the magnetic field, we can adjust the spontaneous-emission rate simply by tuning the magnetic field.

Confining a single electron within a home-made atom has allowed us to measure the electron's magnetic moment to a remarkable accuracy of 7.6 parts in 10^{13}

Measuring the magnetism

Inhibiting spontaneous emission gives us the time we need to determine the quantum cyclotron state of the electron. The signal we actually measure is produced by the electron's oscillatory motion along the direction of the vertical magnetic field that is produced by the external superconducting coil. Small nickel rings that encircle the trap cause the frequency of this oscillation to shift by a small but detectable amount when the electron jumps between the three lowest energy levels. If we can measure two of the three frequencies that correspond to the separation of the lowest states, we can determine the strength of the electron's intrinsic magnetism, $g/2$, from their ratio. In fact, we measure the frequency difference, $f_a = f_s - f_c$, instead of f_s, along with f_c, to determine $g/2 = 1 + f_a/f_c$.

To measure the cyclotron frequency, f_c, we use a technique called quantum-jump spectroscopy. We start with the electron in the lowest energy level, introduce microwave photons with a particular frequency into the trap cavity for a short time and then turn on a detector that reveals whether these photons have excited the electron in our artificial atom from its ground state to its first excited state (figure 3, left). The highest number of "quantum jumps" takes place when the frequency of the photons that we send into the trap cavity matches that of the cyclotron frequency, thereby revealing the value of f_c that we need to determine $g/2$.

We use a similar procedure to measure the other frequency we need, f_a. Here, we begin with the electron in the upper of the two ground states and make it jump to the energy level closest to it, a transition which requires both a spin-flip and a cyclotron excitation. We then wait until the spontaneous emission of a photon causes the electron to drop into the lowest ground state and detect whether the spin has flipped (figure 3, right).

Once we have measured the two frequencies f_c and f_a, then $g/2$ follows. Writing out all the digits for our result, $g/2 = 1.001\,159\,652\,180\,85 \pm 0.000\,000\,000\,000\,76$, may make it easier to appreciate the accuracy of 7.6 parts in 10^{13}. Our measurement almost agrees with the last measurement of $g/2$ made way back in 1987, which involved using one electron as we do but without resolving the individual quantum states of the electron's motion (figure 4). Taking the discrepancy and the smaller claimed uncertainties into account, the new result is nearly 10 times more accurate than what has been used for the last 20 years.

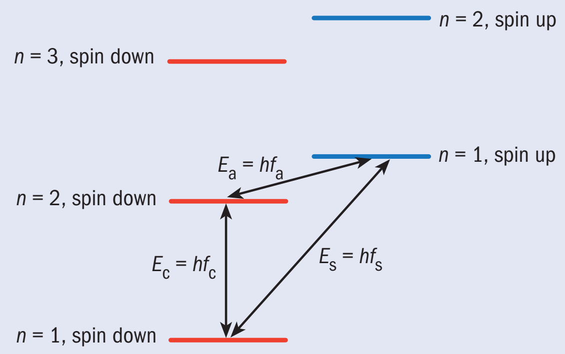
Much of the effort involved in arriving at this new result lies in evaluating the size of the uncertainty that shows up as the error bar. Some of the uncertainty is statistical, arising from the limited number of measurements done in the time available, but this is not a large contribution. Most of the uncertainty comes from things that we do not yet understand as well as we would like, and which potentially can affect the result.

One such "systematic uncertainty" is the effect of the interaction of the electron with the cylindrical cavity that surrounds it. Whenever two oscillators with slightly different oscillation frequencies interact, the frequencies of both oscillators shift slightly. In the case of our single-electron cyclotron, the electron interaction with the resonances in the cavity (the same resonances that modify the spontaneous-emission rate) shifts the cyclotron frequency by a tiny amount. Key to the success of the experiment was thus our invention of a cylindrical trap cavity that interacts with the electron in a way that can be calculated reliably. With more work this "cavity shift" uncertainty will be reduced.

Why is our new measurement so much more accurate than what was possible in the past? Part of the answer lies in the success of the cylindrical trap. Another reason is that our electron resides only in the lowest quantum levels of the artificial atoms that we create and not in an unknown classical distribution of these states of the sort that took place in all earlier measurements. Furthermore, the cooling of the trap cavity to such a low temperature prevents black-body photons from disrupting the measurements. At higher temperatures the cavity would emit photons that would undergo quantum transitions between the lowest quantum states all the time, making it difficult for us to distinguish the effect of the photons that we introduce into the cavity for the quantum-jump spectroscopy.

Novel detection methods are also crucial for the new measurement of $g/2$. We have already described how

2 Energy levels and frequencies



The energy levels available to an electron in a quantum cyclotron are spaced almost equally like the rungs of a ladder, only there are two ladders because of the two different spin states of the electron. The "spin down" states (red) have electron spins directed in the opposite direction to the magnetic field, while the opposite "spin up" states (blue) have the electron spin directed along the magnetic field. Measuring the frequency of photons that make the electron jump between the lowest spin and cyclotron energy levels of this "home-made atom" allow researchers to deduce the intrinsic magnetism of the electron.

the frequency of the oscillatory motion of the electron along the direction of the external magnetic field reveals the cyclotron and spin states. We amplify the tiny signal from this motion with very sensitive transistor amplifiers that we built ourselves. One innovative feature is that some of the signal derived from the electron motion is sent back into the trap to force the electron to make bigger oscillations that are easier to detect. This "one-particle self-excited oscillator" works so well that it is now the centrepiece of a new experiment at Harvard in which student Nick Guise and I hope to detect the spin-flip of a single antiproton – a signal that is about 500 times smaller and more difficult to detect than the spin-flip of an electron.

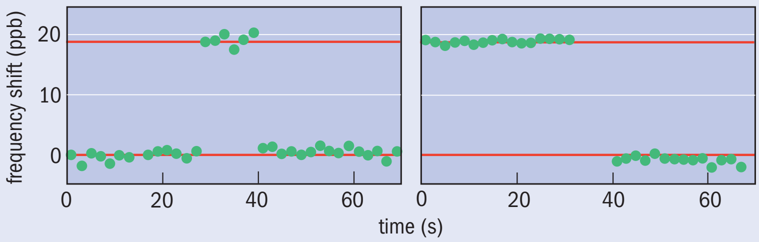
Fine structure

We can use our precise measurement of the electron's magnetism to determine the fine-structure constant, α. Defined essentially as the ratio $e^2/4\pi\varepsilon_0 c\hbar$, where e is the charge of the electron, ε_0 is the permittivity of free space, c is the speed of light and $\hbar$ is $h/2\pi$. This dimensionless constant appears in many contexts, from dictating the strength of the fundamental interaction between photons and charged particles to giving the electrical resistance of certain materials in a strong magnetic field. The "fine" comes from its role in explaining the small splittings, or fine structure, in the energy levels of hydrogen and other atoms.

A QED formula $g/2 = 1 + C_2(\alpha/\pi) + C_4(\alpha/\pi)^2 + C_6(\alpha/\pi)^3 + C_8(\alpha/\pi)^4 + \ldots$ relates the electron's magnetism to the fine-structure constant. As α/π is much less than one, each successive term in this infinite series is much smaller than its predecessor. The coefficients C_1, C_2, etc are numbers that come from remarkably difficult QED calculations that have been carried out over many years by many skilled and dedicated theorists. Worthy of special mention is Tom Kinoshita of Cornell University in the US, who has dedicated decades of his professional life to such calculations. Almost negligible

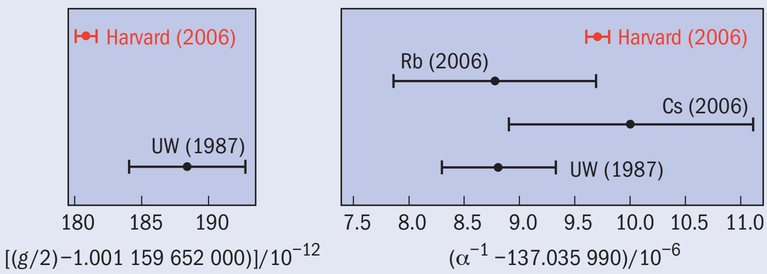
Basic wisdom
Measuring the electron's magnetic moment provides a value for the fine-structure constant using the theory of quantum electrodynamics that was co-invented in the 1940s by Freeman Dyson.

3 Quantum cyclotron jump and spin-flip



To measure the magnetism of an electron suspended in a Penning trap, the Harvard team looks for tiny changes in the electron's oscillation frequency that signal a quantum jump up to an excited cyclotron state and back down (left) or signal a spin-flip (right). Both shifts are measured in parts per billion of the oscillation frequency.

4 Fine measurements



The new measurements of the electron's magnetism (left) and, consequently, the fine-structure constant (right) are dramatically more precise than previous measurements.

"strong" and "electroweak" corrections to this formula, well understood within the Standard Model of particle physics, are not shown here.

If we assume that the theory is correct, we can use this formula along with our new measurement of $g/2$ to determine the fine-structure constant as $1/\alpha = 137.035\,999\,710 \pm 0.000\,000\,096$. (The reciprocal of α is traditionally quoted rather than α itself so as to produce a number that is close to 137.) This value of the fine-structure constant is about 10 times more accurate than that produced by any other method (figure 4). Furthermore, we can use our value of $g/2$ to test whether the formula itself is an accurate description of reality. In other words, does the measured magnetism of the electron agree with the value that can be calculated if an independently measured value of the fine-structure constant is plugged into the formula?

In fact, within the measurement uncertainties, this exercise yields a level of agreement that those who invented QED never imagined. Indeed, one of the inventors – Freeman Dyson – sent me a congratulatory letter after reading the report of our new measurement last year. "I remember that we thought of QED in 1949 as a temporary and jerry-built structure, with mathematical inconsistencies and renormalized infinities swept under the rug. We did not expect it to last more than 10 years before some more solidly built theory would replace it. Now, 57 years have gone by and that ramshackle structure still stands...It is amazing that you can measure her dance to one part per trillion and find her still following our beat," he wrote.

Finally, we can use our measurement of $g/2$ to probe the structure of the electron itself. The QED formula that relates $g/2$ and α would not be correct if the electron has internal structure, rather than being a point particle. The internal quark structure of the proton, for example, makes its magnetism take a very different value from simply $g = 2$. The same good agreement between our measurement and theory as that mentioned above allows us to estimate that if the electron does have some size, then it must be smaller than 10^{-18} m. Normally, such stringent limits can only be set using huge particle accelerators that can smash particles together at the incredible high energies required to penetrate to such small distances. Indeed, a smaller size limit has recently been set by measurements at the now-dismantled Large Electron–Positron collider (LEP) at CERN. Still, it very unusual to be able to set such a limit using one of the lowest energy measurements ever carried out.

Measurement of the moment

The measurements of the electron's magnetism described here are the result of many talented individuals – Joseph Tan, Ching-Hua Tseng, Kamal Abdullah, Daphna Enzer, Steve Peil, Brian D'Urso, Brian Odom and David Hanneke – working with me for two enjoyable decades. Each developed a new technique and/or part of the apparatus that we hoped would allow us to probe the electron much more accurately than had ever been possible – a quest that has now succeeded.

Confining a single electron within a home-made atom and probing the quantum structure of this artificial atom has allowed us to measure the electron's intrinsic magnetism to a remarkable accuracy of 7.6 parts in 10^{13}. We can use this measurement, along with very precise QED calculations, to determine the fine-structure constant to an accuracy that is about a factor of 10 better than achieved with any rival method. There is so far no evidence that QED is not an accurate description of the interaction of light and matter, and there is also still no evidence that the electron has internal structure.

Better measurements should be forthcoming. We expect to be able to measure $g/2$ even more accurately as we refine our technique and incorporate some new ideas. We also plan to measure $g/2$ for a positron – the antimatter partner of the electron – to see if it is the same as that for the electron. Finally, we hope to use our new experimental methods to measure $g/2$ for a proton and an antiproton, again to see if they are the same. Perhaps nature has new surprises waiting for us, to add to the amazement that our mathematical description of the interaction of light and matter works so remarkably well.

More about: Measuring the electron's magnetism

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