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Plumbing the Electron's Depths

Careful observation of a single electron in an atom trap over a period of several months has resulted in the best measurement yet of the electron's magnetic moment and an improved value for alpha, the fine structure constant, the parameter which sets the overall strength of the electromagnetic force.

Electrons are of course a part of every atom and as such are a basic building block of the universe. And alpha is an important member of the system of fundamental constants used to describe nature.

The electron, much lighter than a proton and generally thought to be a pointlike particle, is about as fundamental an object for study as one can have in physics. Nevertheless, the electron's interaction with the vacuum is anything but simple. The theory of quantum electrodynamics (QED) predicts that an electron is perpetually grappling with virtual particles -- such as photons and electron-positron pairs -- emerging briefly from the surrounding vacuum.

In the absence of these interactions, the magnetic moment of the electron (referred to by the letter *g*), which relates the size of the electron's magnetism to its intrinsic spin, would have a value of 2. But direct measurements of *g* show that it is slightly different from 2. The finer these measurements become, the better one can probe the quantum nature of electrons and QED itself. Furthermore, if the electron had structure (in the way that protons, for instance, are made of quarks), this too would show up in measurements of *g*.

To gain the greatest possible control over the electron and its environment, Gerald Gabrielse and his students Brian Odom and David Hanneke at Harvard University create a macroscopic artificial atom consisting of a single electron executing an endless looping trajectory within a trap made of charged electrodes -- a central, positively-charged electrode and two negatively-charged electrodes above and below -- supplemented by coils producing a magnetic field. The combined electric and magnetic forces keep the electron in its circular "cyclotron" orbit. In addition to this planar motion, the electron wobbles up and down in the vertical direction, the direction of the magnetic field. The heart of the Harvard experiment is to explore these two motions -- the circular motion, which conforms to quantum rules, and the vertical motion, which conforms to classical physics -- in a new way.

First the quantum part. Like any real atom, this artificial atom is under the sway of quantum rules, and the captive electron can only possess certain permitted energies. Electrons have been bound in traps like this before, but this new experiment is the first to be laid out so that the electron can reside in its very lowest quantum-allowed cyclotron states. The apparatus does this by controlling stray energy, such as by inhibiting blackbody heating of the electron by cooling the central enclosure to a temperature of one-tenth of a degree above absolute zero and by inhibiting emission by the electron itself through clever design of the atom trap cavity. The whole setup is acting as a one-electron quantum cyclotron.

Second, the classical part. The Harvard experiment is the first to induce a microscopic object to adjust its own oscillations based on interactions with its environment (see their publication of a year ago: D'Urso *et al.*, Physical Review Letters, 25 March 2005). The electron, as it moves vertically, induces a very tiny voltage change in the external electrical circuit supplying the electrodes. Sensing this change, the circuit can adjust the electrode voltage to enhance or depress the electron's up-and-down excursions. This feedback-actuated self-excitation, if it's not too big or too small, allows the researchers to measure an oscillation frequency which in turn is related to the electron's quantum state.

It is this masterful control over the electron's motions and the ability to measure the energy levels of the electron's artificial quantum environment that allows the Harvard group to improve the measurement of *g* by a factor of 6 over previous work. The new uncertainty in the value, set forth in an upcoming article in Physical Review Letters, is now at the level of 0.76 parts per trillion.

No less important than *g* is alpha. By inserting the new value of *g* into QED equations, and thanks to improved QED calculations of very high accuracy, the experimenters and theorists together determined a new value for alpha, one with an accuracy ten times better than available from any other method. This is the first time a more precise value of alpha has been reported since 1987. The new alpha, published in a companion article in Physical Review Letters, has an uncertainty of 0.7 parts per billion.

The measured value of *g* can also be used to address the issue of hypothetical electron constituents. Such subcomponents, the new *g* measurement shows, could be no lighter than 130 gigaelectronvolt. On the basis of this experiment one can also place a corresponding limit on the size of the electron: it must be no larger than 10^{-18} meter across. These are not necessarily the best experimental limits on the size or structure of the electron, but this is, after all, work that is patently in the realm of low-temperature atomic physics and not the realm of high-energy particle accelerators, where fundamental particle properties are normally measured.

The Harvard atom trap effort has spanned twenty years and has yielded more than half a dozen Ph.D.'s. According to Gabrielse (gabrielse@physics.harvard.edu, 617-495-4381), an improved value for alpha should, among other things, contribute to the pending adjustment of fundamental constants aimed at redefining the kilogram in a way that avoids the use of an actual weight kept under glass in Paris.

Odom *et al.*, and Gabrielse *et al.*, two upcoming articles in Physical Review Letters
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