The frontier of particle physics is not the exclusive territory of high-energy accelerator laboratories and low-energy experiments on the electron now promise to probe new physics beyond the Standard Model of elementary particles

Electron dipole moments

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IT IS now one hundred years since J J Thomson showed that cathode rays are composed of electrons, the lightest of the known charged particles. Yet a century later, after many spectacular advances in particle physics, it is curious that the two most elementary properties of the electron, its mass and charge, remain a deep mystery. In the modern theory of elementary particles, the Standard Model, the mass and charge of the electron cannot be calculated from first principles. Rather, the values measured in experiments are inserted into the theory "by hand". Presumably at some time in the future these values will be understood from first principles, but at present no one knows why the charge and mass of the electron, or indeed any other elementary particle, have those particular values.

In 1925, almost 30 years after Thomson's discovery, George Uhlenbeck and Samuel Goudsmit proposed that, in addition to mass and charge, the electron had another intrinsic property known as "spin". This intrinsic angular momentum generated the magnetic moment that was needed to explain the behaviour of alkali atom spectra in magnetic fields. The idea of intrinsic spin was a surprise, but it had to be taken seriously because it explained the main features of the known spectra. The only problem was that the gyromagnetic ratio – the ratio of the magnetic moment, μ_e, to the spin, s – had to be roughly twice the value predicted by simple classical arguments to explain the spectra. This mysterious factor became known as the electron g-factor or g_e.

Two years later, Paul Dirac formulated his famous version of quantum mechanics that incorporated special relativity. The Dirac equation gave the electron the required spin and, miraculously, predicted a magnetic moment cor-

responding precisely to $g_e = 2$. In fact, the equation yielded an embarrassment of riches, causing Dirac to predict the existence of new particles with negative mass now known as antimatter. This rather unsatisfactory feature of the theory later turned into a triumph when the positron – the antiparticle of the electron – was detected in 1932.

The Standard Model and beyond

Despite its remarkable success, the Dirac equation was not the last word on the subject because it did not include the quantum nature of the electromagnetic field. The uncertainty principle allows the electromagnetic field to fluctuate, and these fluctuations "jiggle" the electron, even in the absence of any applied field. In other words, the quantum "vacuum" is not completely empty. These effects are accounted for in quantum electrodynamics (QED), the theory developed in the 1940s to explain electromagnetic interactions in terms of the exchange of photons between particles.

In 1947 Julian Schwinger used QED to show that the electron g-factor was not 2. Rather, Schwinger showed that $g_e = 2 + \alpha/\pi + c_2\alpha^2 + c_3\alpha^3...$, where α is a dimensionless ratio known as the "fine structure constant" and $c_{2,3}...$ are constants that are very difficult to calculate. Like charge, the fine structure constant measures the strength of electromagnetic interactions, but in units that are more natural for particle physics. The constant is defined as $\alpha = e^2/4\pi\varepsilon_0\hbar c \approx 1/137$, where e is the charge on the electron, ε_0 is the permittivity of free space, $\hbar$ is Planck's constant divided by 2π and c is the speed of light.

In the 50 years since Schwinger's discovery many
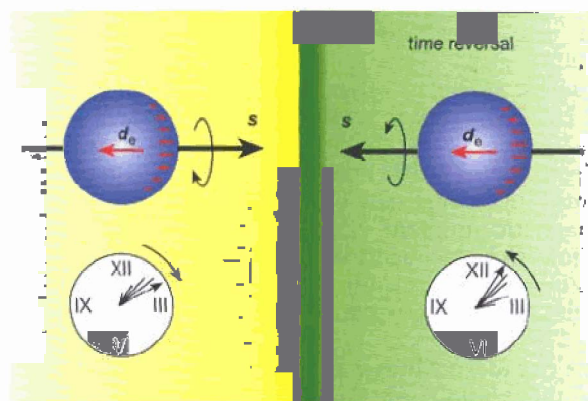
1 If time is reversed the spin, s, of the electron changes direction but the charge distribution, which determines the dipole moment, d_e, remains the same. This means that the product $d_e \cdot s$ is different in the normal and time-reversed worlds. Therefore, the existence of a permanent electric dipole moment would violate time-reversal symmetry and provide evidence for physics beyond the Standard Model.

groups have worked on evaluating g_e and all the terms up to α^4 are now known. Measurements of g_e-2 have improved to an accuracy of 4 parts in 10^9 over the same period. Both of these results are notable *tours de force*, but even more remarkable is the fact that theory and experiment agree at the level of 2 parts in 10^8, the accuracy with which α is known (from measurements of the quantum Hall effect).

Obviously QED is an astonishingly accurate way to describe the effect of electromagnetic quantum noise on the value of g_e. If we did not know better, we might be tempted to think that QED is the correct theory of everything and that the magnetic moment of the electron has nothing more to reveal. However, the existence of nuclear matter tells us that nature is more complicated. In addition to electromagnetic interactions, which result from the exchange of photons over large distances, and gravity, there are also weak and strong interactions associated with higher energies and shorter length scales.

It is possible to generalize the ideas of QED to make a quantum field theory of all the fundamental forces except gravity. And in the quantum vacuum of this theory there are fluctuations of all the fields, not just those that are electromagnetic. This picture has been systematically tested by many experiments in atomic, nuclear and high-energy physics over the last 20 years and is now known as the Standard Model because of its great success. It predicts that the existence of heavier particles, in particular muons and the light quarks, starts to affect g_e-2 at the level of a few parts in 10^9, the current level of experimental accuracy.

Indeed, one could think of the electron as a small boat being tossed about by quantum noise in a rough sea of virtual particles and fields. The magnetic moment is a delicate sensor that records the whole rich spectrum of these fluctuations, with each successive digit probing higher masses and shorter length scales in the spectrum of fundamental interactions.

But what about physics beyond the Standard Model? Is it possible that this model contains the whole truth and that there is nothing more to know about fundamental interactions? Few physicists believe this. We need to explain why the known interactions have the strengths they do, why the fundamental particles have different masses, and how gravity fits into the whole picture. The evidence for the new physics is waiting to be seen in the value of g_e-2, but hidden in digits well beyond those we are currently able to measure and interpret. There is, however, another way to unlock these secrets – to measure the electric dipole moment of the electron.

Dipole moments and time

Whereas magnetic moments are caused by the angular momentum of charges, electric dipole moments are

2 Experiments on various atoms since the early 1960s have found the electric dipole moment of the electron (d_e) to be consistent with zero and the upper limit on d_e has moved steadily downwards as experimental precision has improved. The shaded curves show the range of predictions for d_e according to the main theoretical contenders for physics beyond the Standard Model. Supersymmetry (SUSY) theories include an angle, ϕ, whose value is unknown: SUSY theories with $\phi \sim 1$ are ruled out by experiment, but theories with $\phi \sim \alpha/\pi$ are not, although there is no particular reason for ϕ to be small. The ytterbium fluoride experiment at Sussex will be the first experiment to use a heavy paramagnetic molecule and will be able to detect dipole moments of the size predicted by the multi-Higgs and left–right theories.

associated with the distribution of charge. The electric dipole moment, d_e, of the electron is a measure of the average displacement of charge from the centre of mass. Only the displacement along the spin axis contributes to the dipole moment because the spin averages the other components to zero. Consequently, the spin and dipole moment are parallel (or antiparallel) and we may consider the scalar product, $s \cdot d_e$, to be a new intrinsic property of the electron.
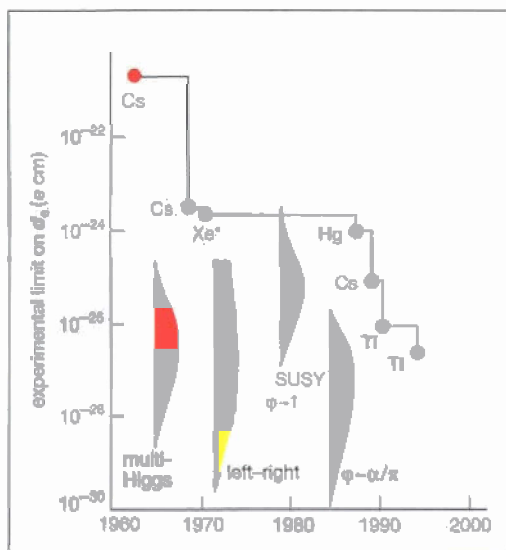
This quantity is closely related to time-reversal or T symmetry. To see how this works, imagine that we are able to make a movie of the spinning electron. It would be obvious whether the movie was running forwards or backwards because $s \cdot d_e$ would be positive in one case and negative in the other (figure 1). Such a difference is a violation of T symmetry, which can therefore only be true if the dipole moment of the spinning electron is exactly zero.

In the Standard Model, T is not an exact symmetry but is nearly exact in normal matter (electrons, protons and neutrons). Even when we allow for the vacuum fluctuations associated with all the particles of the Standard Model, d_e remains fantastically small; the displacement of charge in the electron is calculated to be less than 10^{-38} cm, which is far too small to be measured. This means that measuring d_e is a very powerful way of searching for new physics beyond the Standard Model. Once again, as in the case of g_e-2, a static property of the electron is probing quantum fluctuations of the vacuum, but this probe responds only to interactions that violate T symmetry and therefore it automatically picks out the new physics.

There are many proposals for physics beyond the Standard Model that involve new phenomena at high energies and short length scales. For example, most theories require Higgs particles to be in the energy range 100 GeV–10 TeV and the search for these particles is a central activity in high-energy physics today. Moreover, almost all of these theories violate T symmetry substantially, which leads one to expect that it might be possible to observe electric dipole moments in ordinary matter. The experimental upper limit on d_e has moved steadily lower since the first measurement in 1964. The most accurate measurement to date – by Eugene Commins and collaborators at the University of California, Berkeley in 1994 – set an upper limit of 5×10^{-27} e cm.

The most popular of these theories, known as supersymmetry (SUSY), predicts an electric dipole moment in the region of 10^{-25}–10^{-26} e cm. This prediction has now been more or less ruled out by the experimental upper limit on d_e. It is possible, though a bit less natural, to force the SUSY theory to give a smaller d_e. Other theories, such as those involving several Higgs particles or theories with left–right symmetry, also produce a value of d_e in the vicinity of the present experimental limit (figure 2). This situation provides a strong incentive to improve the accuracy of dipole measurements and many

groups around the world, including our group at the Sussex Centre for Optical and Atomic Physics in the UK, are rising to this challenge.

Electrons in atoms and molecules

If an electron is placed in an electric field, E, its electric dipole moment has an interaction energy $-d_e \cdot E$. The basic idea of any experiment to measure the dipole moment is to compare the energies when d_e is parallel and antiparallel to the field. The obvious difficulty with this strategy is that a free electron, being a charged particle, is accelerated by the field and quickly crashes into the field plates. At first sight it seems that we might circumvent this problem by using an electron in a neutral atom, which is not accelerated by the field. However, after a moment's thought we realize that if the electron has no acceleration, it must be experiencing no average force; it seems that the applied field is completely screened by the other charges in the atom.

But we are forgetting that the magnetic forces associated with relativity can be important when the electron is close to a heavy nucleus. In 1965 Patrick Sandars of Oxford University showed that these forces make the net electric field on the electron much larger than the electric field applied to the atom. Sandars calculated that this relativistic effect enhanced the field on an electron in a caesium atom by a factor of approximately 120.

This discovery triggered a series of experiments on caesium, some of which provided the experimental limits on d_e shown in figure 2. In the most recent experiment, Larry Hunter and co-workers at Amherst College in Massachusetts used a circularly polarized laser beam to orientate the electron spins along a direction perpendicular to an electric field in a cell of caesium vapour. If d_e is non-zero, the interaction with the applied field must make the spin precess at a rate that is proportional to the applied field strength and to d_e. (This is similar to the way gravity causes a gyroscope to precess around the vertical.) Absorption from a second laser beam, at right angles to the first, was used to probe the perpendicular component of the electron spin produced by the precession and hence to determine d_e. The uncertainty in the measurement corresponds to a precession frequency of approximately 2 µHz.

Careful magnetic shielding is required because magnetic fields can couple to the electron's magnetic moment, which also causes the spin to precess. Even with perfect shielding, the motion of the atoms through the applied electric field still generates a magnetic field on the electron. One great virtue of the Amherst experiment is that this effect averages to zero because the atoms are all moving in different directions. The down side is that the cell can only support a relatively small electric field (about 4 kV cm^{-1}) before insulation breaks down, which limits the size of the precession angle for a given d_e. Life is full of compromises.

The most recent measurement – in which the Berkeley

group fire a beam of thermal thallium atoms through a vacuum chamber – makes the opposite compromise. The atoms are moving at several hundred metres per second, which leads to a large motional magnetic field that must be controlled very carefully. The advantage is that they are able to apply a much larger electric field (about 100 kV cm^{-1}) in the vacuum, which makes the precession angle more sensitive to the electric dipole moment. Moreover, thallium has the largest known relativistic enhancement factor of any atom – about 600 compared with 120 in caesium – so the net field on the electron spin is 60 MV cm^{-1}. This helps to make the Berkeley experiment the most accurate to date.

A few years after Sandars discovered the atomic enhancement, he pointed out that polar molecules (molecules with strong ionic bonds) have a great advantage over atoms. For example, suppose we apply a modest field, E, to some heavy fluoride, X^+F^-, which then becomes polarized. The electric field experienced by the X^+ ion is the sum of E and the huge field of the fluorine ion, which is only a few tenths of a nanometre away. As a result of this, the field experienced by the electron spin in the X^+ ion can be as much as a thousand times larger than is possible in a neutral atom.
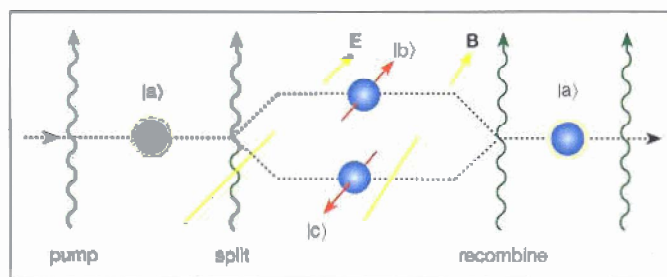
The ytterbium fluoride experiment

The most suitable molecules for measuring d_e are heavy, polar and have an unpaired electron (i.e. are paramagnetic). However, these requirements limit the candidates to a relatively small number of molecules. In the 1980s the physical chemistry community began to overcome the practical difficulties of working with these molecules, developing techniques to produce paramagnetic molecular beams and high-resolution spectroscopic methods to study them. Although the techniques were developed using lighter molecules, we have been able to extend them to the molecules of interest for measuring d_e. Thus it has now become possible to make the unusual marriage of physical chemistry with ultrahigh-resolution atomic physics and elementary particle physics that was envisaged by Sandars 25 years ago. The molecule we have chosen is ytterbium fluoride (YbF).

Detailed calculations have shown that the effective field strength, E_{eff} on the electron spin in YbF is 30 GV cm^{-1}. Although this is a very strong field, if d_e is less than


3 The heart of the YbF experiment at Sussex is an interferometer for electron spin. First, the molecule is pumped by laser light into state |a). This is then split into a coherent superposition of |b) and |c) that have opposite electron spin. In the presence of electric and magnetic fields these states acquire a phase difference that depends on the electric dipole interaction energy, $-d_e \cdot E_{\text{eff}}$. A further interaction with laser beams recombines the two parts of the wavefunction and causes them to interfere; the resulting amplitude in state |a) depends on the phase difference along the two paths. Finally, a probe laser measures the population in state |a), from which we can determine the electric dipole moment d_e.

5×10^{-27} e cm, as the latest Berkeley experiment tells us it is, then the interaction energy that we must measure is less than 2×10^{-16} eV. In frequency units this energy corresponds to about 40 mHz, which is much too small to be detected by the standard techniques of molecular spectroscopy.

Our approach at Sussex is to make a molecular interferometer. First, the internal motion of the molecule (vibration, rotation, hyperfine interaction, etc) is prepared by a laser, called the pump beam, into a single quantum mechanical state (labelled |a) in figure 3). Next, a second laser is used to split the wavefunction in a coherent superposition of two states, |b) and |c), that are exact time-

reverses of each other. These have opposite electron spin and hence opposite dipoles, $\pm d_e$. In the absence of external fields the states have exactly the same energy. When an electric field is applied, however, the two parts of the wavefunction experience opposite electric dipole interactions, $\pm d_e E_{\text{eff}}$, and after a time, t, a phase difference, $\varphi_d = 2d_e E_{\text{eff}}/\hbar$, accumulates between them. Another set of laser beams recombines the two parts of the wavefunction and returns them to $|a\rangle$. The amplitude of this state depends on φ_d because of interference between the two paths. Finally, a probe laser allows us to measure the population in state $|a\rangle$, which is proportional to $\cos^2\varphi_d$ as in any interferometer.

This technique as we have described it would not work very well because the phase angle, φ_d, is liable to be very small and the cosine of a small angle is not very sensitive to the angle itself. The experiment becomes more sensitive when we add a magnetic field, B, to the interferometer, which interacts with the magnetic moment of the electron to produce an extra, controllable phase shift, $\varphi_\mu = 2\mu Bt/\hbar$. The interferometer fringes are now proportional to $\cos^2\varphi$, where $\varphi = \varphi_d + \varphi_\mu$ is the total phase angle (figure 4).

The most sensitive places to look for small changes in angle are those with large slopes, so we set φ_μ equal to $\pi/4$. This gives $\varphi = \pi/4 + \varphi_d$ when the applied electric field points in one direction, and $\varphi = \pi/4 - \varphi_d$ when it points in the opposite direction. The change in the absorption of the probe laser between these two directions of the electric field is directly proportional to d_e. As a check, we can also reverse the magnetic field and make the total phase $\varphi = -\pi/4 \pm \varphi_d$. In short, the signal we look for is proportional to the sign of $E \cdot B$. If time could be reversed the magnetic field would reverse but the electric field would not, so this signature is clear evidence of the violation of T symmetry.

We have now built a beam apparatus designed to carry out this experiment. Our interferometer is a molecular beam approximately 1 m long in which the molecules accumulate their phase for about 3 ms, determined by their time of flight between splitter and recombiner. We have also developed the laser techniques needed to control the molecular states and are working towards control of the electric and magnetic fields at the required level of precision. Given the present upper limit on the electric
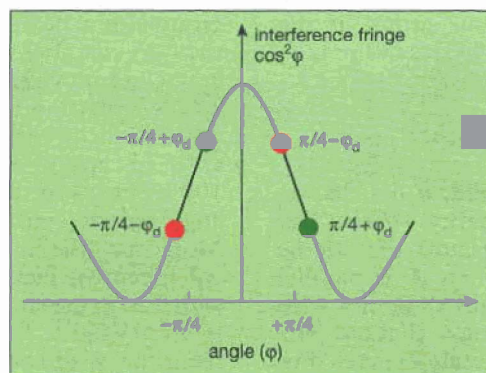
4 To measure d_e in an interferometer, the signal is measured at four angles, $\varphi = \pm\varphi_\mu \pm \varphi_d$, as indicated by the red and green circles. The applied magnetic field is chosen to set $\varphi_\mu = \pm\pi/4$, where the slope of the fringe pattern ($\cos^2\varphi$) is greatest. The very small angle φ_d, which is proportional to d_e, is measured by reversing the direction of the applied electric field and measuring the difference in the signals. This difference is positive on one side of the fringe and negative on the other.

dipole moment of the electron, we expect that the phase angle φ_d will be less than 1 mrad. Although this is not a large angle, the signal-to-noise ratio of our fringes will be good enough to see such an effect in less than an hour of integration time. Poised on the edge of the first molecular determination of d_e, we are full of hope that we will soon have our first glimpse of the new physics beyond the Standard Model.

If the experiment proves more difficult than anticipated, as experiments often do, we will nevertheless persist, recalling Steven Weinberg's remark in his summary talk for the 26th International Conference on High Energy Physics at Dallas in 1992: "…it may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments…seem to me to offer one of the most exciting possibilities for progress in particle physics."

Further reading

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