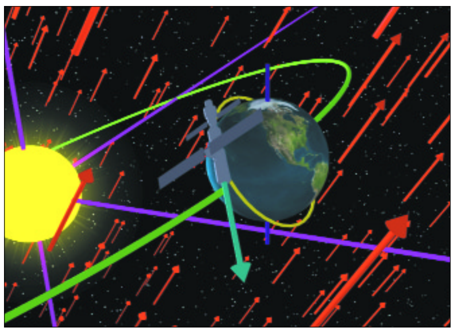
As physicists celebrate 100 years of Lorentz symmetry, some theorists and experimentalists are working hard to spoil the party

Breaking Lorentz symmetry

Robert Bluhm

IMAGINE you are about to create a universe. How would you do it? As soon as you say "let there be the laws of physics" you would immediately face a problem. Do the same laws hold for everyone in your universe regardless of where they are? Or do the laws change as you move about or face in different directions? Clearly the most equitable and fair way to proceed would be to make the laws of physics the same for all observers. To a physicist such equality and fairness of physical laws is called a symmetry, and the symmetry that requires the laws of physics to be the same for all observers is known as Lorentz symmetry.



Clocking the direction of space – the breaking of Lorentz symmetry can cause different points in space–time to have a preferred direction (red arrows). If the direction of space is the same at all points in the Earth's orbit, experiments on board the International Space Station (ISS) should be able to measure the magnitude of the Lorentz-breaking effect. For instance, the orientation of atoms in an atomic clock on board the ISS (blue arrow) will change with respect to the red arrows as the ISS orbits the Earth. This would modify the energy levels of the atoms and therefore cause the clock rate to change cyclically.

Symmetry is one of the most important concepts in physics, and it is closely linked to the conservation of quantities such as energy, momentum and charge. However, symmetry breaking is also incredibly important. The breaking of electroweak symmetry, for example, is responsible for the generation of mass in the Standard Model of particle physics.

It was Einstein who, in 1905, first used Lorentz symmetry to describe the laws of physics in our universe. He took Lorentz symmetry as a postulate of special relativity, whereby he assumed that the laws of physics – including the speed of light in a vacuum – are the same for all *inertial* observers. An inertial observer is anyone with a system of calibrated clocks and rulers that is at rest in a frame of reference that is not accelerating. Einstein worked out the consequences of Lorentz symmetry and came to the startling conclusion that measurements of length and time intervals are different when they are made by inertial observers moving relative to each other. The extent of this distortion of space and time is described by a set of equations that are now known as Lorentz transformations (see box on page XX).

These transformations had actually been discovered the previous year by Hendrik Antoon Lorentz when he was attempting to explain the null results of the Michelson–Morley experiment. Although the context in which he used them turned out to be incorrect (it appears that there is no ether), the equations themselves are the same as those Einstein derived in 1905 to describe transformations in space and time in relativity theory.

Lorentz symmetry has so far withstood the tests of time, but in recent years theorists have begun to question whether it is indeed an exact symmetry of nature. They are motivated primarily by one of the biggest unsolved problems in physics: how can we make gravity compatible with quantum physics (see "Welcome to quantum gravity" *Physics World* November 2003 pp27–47).

The leading contender for a theory of quantum gravity is string theory, which replaces point particles by 1D strings or by higher-dimensional objects known as branes. In addition to incorporating gravity in a quantum theory, string theory also attempts to combine the four forces of nature – the strong and weak nuclear forces, electromagnetism and gravity – into one unified theory. A different approach, known as loop quantum gravity, describes the gravitational interaction in terms of variables on a loop. Both of these theories allow for the possibility that Lorentz symmetry might not hold exactly.

The energy scale where gravity meets quantum physics is called the Planck scale. The Planck energy is defined as $(\hbar c^5/G)^{1/2}$, where $\hbar$ is Planck's constant divided by 2π, c is the speed of light and G is Newton's gravitational constant. The Planck energy is approximately equal to 10^{19} GeV, which is many orders of magnitude beyond the reach of even the most powerful particle accelerator. Some physicists have therefore concluded that physics at the Planck scale can never be tested. However, as we shall see, this view is short-sighted. A number of recent experiments that test Lorentz symmetry are already sensitive to physics at the Planck scale. Indeed, the search for Lorentz violation has become the main focus of recent work in quantum-gravity phenomenology.

Theory of Lorentz violation

For the past 15 years Alan Kostelecky and co-workers at Indiana University in the US have been pioneering the search for Lorentz violation as a signature of Planck-scale physics (figure 1). Their work has spanned a number of areas that include string theory, gravity theory, quantum field theory, cosmology and phenomenology, and they have uncovered a number of new ways to test Lorentz symmetry. Meanwhile, technological advances have led to an improvement in the sensitivity of

Lorentz and CPT symmetry

Lorentz transformations are continuous transformations consisting of relative motion at constant velocity (boosts) and rotations. A general Lorentz transformation involves both of these at the same time, which leads to a mixing of space and time intervals, and ultimately to a blurring of the distinction between space and time. What emerges in relativity is a 4D geometry, where the fourth dimension becomes the product of the time, t, multiplied by the speed of light, c (note: ct has units of length). In four dimensions an invariant notion of distance called a space–time interval can be introduced. Lorentz transformations between different co-ordinate frames ensure that the space–time interval and the value of the speed of light are the same for all inertial observers. Crucial to these equations is the Lorentz factor, $1/(1-v^2/c^2)^{1/2}$, where v is the relative velocity of the frames. A muon that is travelling at 99% of the speed of light, for example, will have a lifetime that is about seven times longer than a muon at rest.

Lorentz symmetry is closely linked to another symmetry called CPT symmetry. CPT is the combined discrete symmetry consisting of interchanging particles and antiparticles (C, or charge conjugation), reflection in space (P, or parity), and reversal of the direction of time (T, or time reversal). While violation of each of the individual transformations C, P or T and the combination CP have been observed in experiments, CPT violation has never been detected. A famous theorem, called the CPT theorem, proved independently by John Bell, Wolfgang Pauli and Gerhardt Luders, states that any Lorentz-invariant field theory describing point particles must be CPT invariant. More recently it has been shown that if CPT is broken in field theory, then Lorentz symmetry must also be broken.

experiments looking for Lorentz violation. As a result, several exceptionally accurate Lorentz tests have recently been conducted, and other experiments are currently under way.

To begin to understand Kostelecky's work on Lorentz violation it is important to realize that there are actually two ways to view Lorentz symmetry. The statement that the laws of physics are the same for all inertial observers is what is known as *observer* Lorentz invariance. This elegant symmetry simply says that nature's laws cannot depend on the perspective of an observer: a person on a moving train and a person waiting at a station, for example, obey the same laws of physics. But what happens if the person on the train gets up and starts to walk about? Giving a particle or object a motion with respect to a fixed inertial frame (the train in this case) is called a *particle* Lorentz transformation.

From the fixed perspective of a moving train, do a seated passenger and a moving passenger experience the same laws of physics? In the absence of Lorentz violation, the answer is yes. The moving passenger simply introduces a third observer frame, and the particle Lorentz transformation and the observer Lorentz transformation are basically the same. However, Kostelecky has shown that these two types of transformation are not equivalent if Lorentz symmetry is violated. In other words, the laws of physics experienced by the moving passenger can be different to those felt by the passenger who remains seated.

To get a better sense of this, imagine you are able to zoom inside a magnet. You would see that it is made of lots of small magnetic dipoles that are all aligned in a particular direction. The definition of observer Lorentz invariance states that a physical interaction cannot depend on how you orient yourself with respect to the magnet. Therefore, the motion of a charged object such as an electron will not depend on whether you stand with the dipoles pointing to your left or with the dipoles pointing straight ahead of you.

However, the force acting on a charged particle that is moving to your left will be different to that acting on a particle that is moving straight ahead of you. This is because the magnetic force depends on the direction of the motion with respect to the magnetic field. In this magnetic example, we say that the particle Lorentz symmetry is broken by the background magnetic field, while the observer Lorentz symmetry is not.

The alignment of a magnet is a classic example of what is called spontaneous symmetry breaking. The interactions of the individual dipoles in a magnet do not depend on any particular direction, and their dynamics are rotationally invariant. For the magnet to form, however, the dipoles must spontaneously align in some direction, which "spontaneously breaks" the rotational symmetry.

In 1989 Kostelecky and Stuart Samuel of the City University of New York showed that string theory allows forLorentz symmetry to be spontaneously broken in the early universe. If Lorentz symmetry is spontaneously broken, small relic background fields – which are called tensor-valued vacuum expectation values – would permeate the universe and point in spontaneously chosen directions. An elementary particle in the presence of one of these relic fields would then experience interactions that have a preferred direction in space–time. In particular, there could be preferred directions in 3D space in any fixed reference frame, such as an Earth-based laboratory (see figure on page XX).

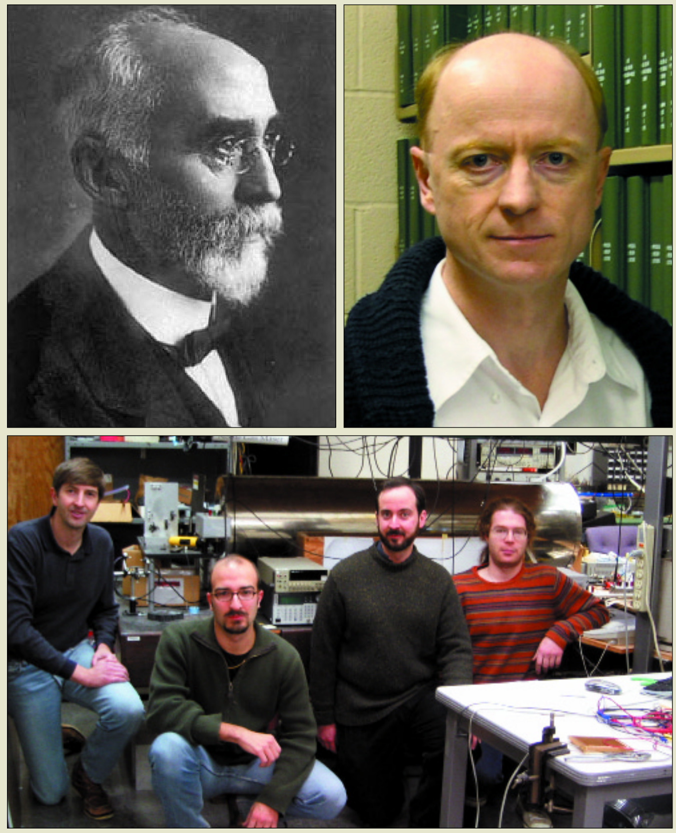
At a fundamental level, Lorentz symmetry would still hold dynamically, and all interactions would remain invariant under observer Lorentz transformations. However, the presence of the relic fields would break the *particle* Lorentz invariance, leading to variations in physical interactions as the motion or orientation of a particle changes with respect to the relic fields.

If Lorentz symmetry is broken by some mechanism originating at the Planck scale, is there any hope of detecting such an effect? Surprisingly, the answer is yes. Over the past decade Kostelecky and co-workers have been exploring how a violation of Lorentz symmetry might provide evidence for new physics arising at the Planck scale. However, rather than smash particles together at high energies to explore this, researchers are turning to ultrahigh-precision experiments at *low* energies to search for signs that Lorentz symmetry has been broken. The idea is that such low-energy effects are caused by corrections involving inverse powers of the Planck scale.

Possible violations of Lorentz invariance are an ideal signal of new physics because nothing in the Standard Model of particle physics permits the violation of special relativity. Therefore, no conventional process could ever mimic or cover up a genuine signal of Lorentz violation.

Since a viable theory of physics at the Planck scale remains elusive, it is difficult to make precise predictions for the small corrections that could occur due to Lorentz violation. However, we can obtain a rough estimate. The rest-mass energy of the proton, for example, is about 1 GeV, and the ratio of this energy to the Planck scale is about 1 part in 10^{19}. If an experiment with protons is sensitive to effects at or below this level, then it is effectively probing the Planck scale.

1 Lorentz figures



In 1904 the Dutch physicist Hendrik Antoon Lorentz formulated a set of equations that maintain the invariance of the laws of physics in relativity. For the past 15 years Alan Kostelecky of Indiana University has been exploring the theoretical and phenomenological implications of Lorentz violation. His work and that of others has enabled groups like that of Ronald Walsworth (left in bottom picture) at the Harvard-Smithsonian Center for Astrophysics to put Lorentz symmetry to the test in high-precision atomic experiments.

Standard Model extension

To test whether or not Lorentz symmetry is violated it is useful to have a general theoretical framework that incorporates Lorentz violation into the Standard Model. Some 10 years ago Don Colladay, Alan Kostelecky and Robertus Potting at Indiana University worked out such a theory and called it the Standard Model extension (SME). The SME describes all the particle interactions that maintain observer Lorentz invariance but not particle Lorentz invariance. The theory is also compatible with the Standard Model and any modifications that arise from a more fundamental theory, such as string theory.

Furthermore, the SME contains all the possible interactions that could arise from spontaneous breaking of Lorentz symmetry. In this case the SME coefficients become the constant background fields that permeate the universe and which lead to particle interactions that have preferred directions. This means that the physical properties of a particle, such as its energy and momentum, will change as the motion or spin orientation of the particle changes with respect to the background SME coefficients.

Each type, or "flavour", of particle in the SME can have different Lorentz-violating interactions. For instance, electrons might have Lorentz-violating interactions, while photons do not. This is analogous to the way in which electrons experience the weak force while photons do not. These interactions also behave differently under the individual space–time symmetries: charge conjugation (C), parity (P) and time reversal (T). Therefore, the SME includes a large number of parameters depending on the species of a particle; its C, P and T properties; and its direction in space and time.

One of the most attractive features of the SME is that it can incorporate the different theoretical ideas involved in different types of experiments. For example, the SME includes terms that break the combined symmetry CPT, as well as terms that preserve CPT. It has recently been shown by Oscar Greenberg at the University of Maryland that any field theory that breaks CPT must also break Lorentz invariance (see box on page XX). This means that any theory that contains CPT symmetry breaking and is compatible with the Standard Model must be contained in the SME. Therefore, CPT experiments that compare matter and antimatter can provide tight bounds on Lorentz symmetry that might not be attainable with only matter.

The generality of the SME also makes it an umbrella theory for other theoretical models of Lorentz violation. For example, a phenomenological model formulated in 1949 by Howard Robertson of the Californian Institute of Technology (and generalized in 1976 by Reza Mansouri and Roman Sexl of the University of Vienna) was based on the notion that a preferred frame of reference exists. A set of Lorentz-violating parameters was introduced, which is often used to analyse velocity-of-light experiments, but it can be shown that these parameters are directly related to a subset of SME parameters.

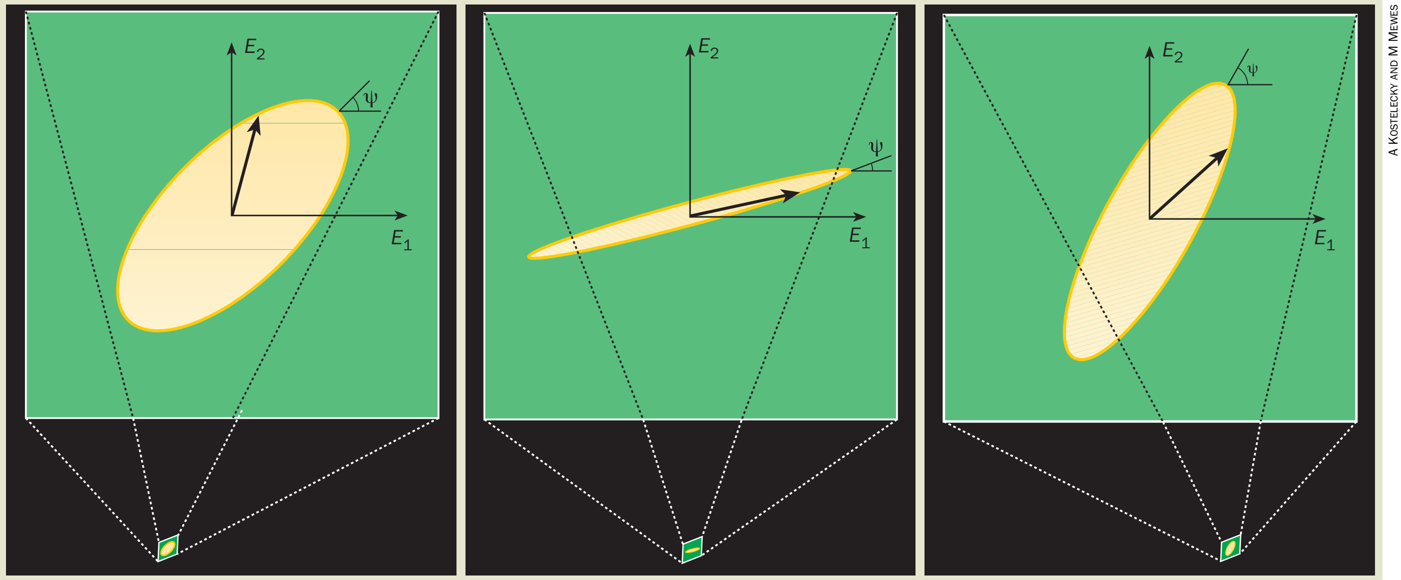
Similarly, in 1998 a set of Lorentz-violating interactions were used by Sidney Coleman and Sheldon Glashow at Harvard University to show that the apparent observation of cosmic rays above a high-energy threshold might be due to Lorentz violation. These interactions also turn out to be a limiting subset of SME coefficients. Being able to express these results in terms of the SME enables researchers to compare results from different types of experiments. A good illustration of this comes from the possibility of Lorentz breaking in loop quantum gravity, which was investigated by Daniel Sudarsky of the Universidad Nacional de Mexico and co-workers in 2002. They showed that Lorentz tests in atomic and nuclear experiments can provide tight bounds on any modifications to particle propagation with respect to the cosmic background radiation that are due to quantum-gravity effects.

This kind of crossover between the results of astrophysical, high-energy, nuclear and atomic experiments only becomes possible when the measurements are expressed in the common language of the SME.

Testing Lorentz symmetry

In discussing some of the recent experimental tests of Lorentz symmetry it is important to keep in mind that there is no single best test of Lorentz symmetry. This can be troubling for some people because they want to view Lorentz symmetry as a statement about the abstract nature of space and time in the absence of any particles or interactions. However, as relativity teaches us, Lorentz symmetry is really all about measurements, which ultimately must involve the interactions of elementary particles. Furthermore, since it is possible for one type of particle in the Standard Model to have interactions that violate Lorentz symmetry while another type does not, an exhaustive investigation of Lorentz violation involves a large

2 Astronomical propagation



One of the most precise ways to test Lorentz symmetry is to study light from astronomical sources. Conventionally the two perpendicular components of the electric field of a light beam, E_1 and E_2, propagate with the same velocity, and the total electric-field vector (black arrow) rotates in a plane with its tip tracing an ellipse. The polarization of the light is determined by the shape and orientation (given by the angle ψ) of the ellipse, which does not change during propagation. If Lorentz symmetry is broken, however, the rotational invariance is lost and the two polarization components of light can travel at slightly different speeds. This effect is called birefringence. In this case, the orientation and shape of the polarization ellipse changes as the light travels through space from a distant galaxy (left image) to the Earth (right). This effect has a characteristic frequency dependence that can be searched for in experiments.

number of experiments in order to probe every particle sector.

The most famous tests of Lorentz symmetry – the Michelson–Morley experiments – use photons. A beam of light is split into two beams that travel at right angles to each other, are reflected by mirrors and then recombined with each other to produce an interference pattern. The pattern that is produced depends on the different lengths of the two paths. Researchers look for a change in this pattern as the interferometer is rotated. This effectively acts as a test of Lorentz symmetry because it is sensitive to any dependence of the speed of light on direction in space. Closely related to Michelson–Morley experiments are Kennedy–Thorndike experiments, which use an interferometer that is held fixed in the laboratory. Here, researchers look for a change in the interference pattern over time due to the Earth's motion around the Sun. This acts as a test of Lorentz symmetry because it is sensitive to any dependence of the speed of light on velocity.

Modern-day versions of these laboratory experiments with light have recently been performed. The most sensitive of these look for small changes in the resonant frequency of a microwave cavity as it rotates and moves due to the Earth's orbit around the Sun. In 2003 John Lipa and co-workers at Stanford University compared the resonant frequencies of two orthogonal cyrogenic optical resonators over the course of several months. In a similar experiment, Achim Peters and colleagues at Humboldt University in Berlin compared the resonant frequencies of two orthogonal resonators constructed from crystalline sapphire over a period of a year. The signal for Lorentz violation in these experiments would be a difference between the two resonator frequencies that varies with the same periodicity as the Earth's motion.

In a third experiment, Peter Wolf and co-workers at the Observatoire de Paris compared the frequencies of a sapphire crystal resonator and a hydrogen maser over a period of nearly a year. In this case it is the difference in the sensitivities of the crystal and the hydrogen maser that would provide a Lorentz-violating signal. Together these experiments showed that any violation of Lorentz symmetry must be smaller than 1 part in 10^{11} for a number of different SME parameters in the photon sector – and smaller than 1 part in 10^{15} for some of these parameters (see Lipa *et al.*, Muller *et al.* and Wolf *et al.* in further reading).

Some alternatives to these laboratory-based experiments – which yield bounds on a different subset of the SME coefficients for the photon – use light from distant astrophysical sources. These experiments have a much higher precision than laboratory-based experiments because the light travels across vast regions of space. The long propagation time can magnify any small differences in the properties of the light – such as its wavelength or polarization – due to Lorentz violation (figure 2).

In 1990 Roman Jackiw of the Massachusetts Institute of Technology and co-workers showed that SME parameters that violated CPT symmetry could be tested with a precision of 1 part in 10^{42} in measurements of light from distant galaxies. In the CPT-preserving photon sector, on the other hand, a sensitivity of one part in 10^{32} was obtained by Kostelecky and Matthew Mewes at Indiana. By analysing infrared, visible and ultraviolet light from distant galaxies, they studied a Lorentz-violating effect that causes the polarization of light to change in a way that depends on its wavelength (see Kostelecky and Mewes in further reading).

Atomic precision

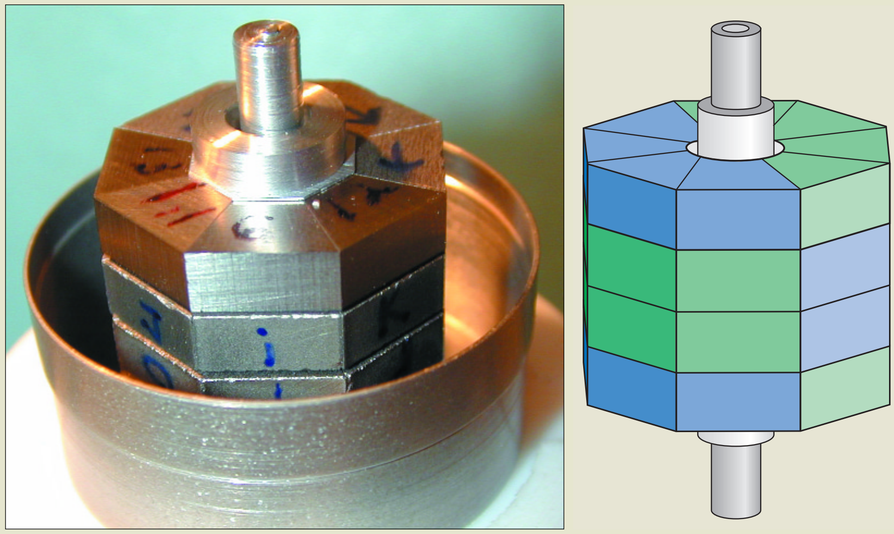
When it comes to investigating Lorentz violation in matter, it is atomic physicists who are able to make the most precise measurements. This is because small frequency shifts that depend on the state of a nucleus can be measured with exquisite accuracy in atomic experiments. Resolutions of 1 mHz or better are common, which corresponds to a sensitivity of about one part in 10^{27} relative to the proton-mass scale. Such accuracy means that these experiments are highly sensitive to small corrections that could originate from the Planck scale.

Signals of Lorentz violation in matter can occur due to the coupling of the atomic constituents – protons, neutrons and electrons – to the background fields in the SME. In particular, the spin orientation of the constituent particles relative to the fixed background fields would vary as the Earth moves, leading to small frequency variations that can be measured.

The current record holder for Lorentz tests with both neutrons and protons is Ronald Walsworth's group at the Harvard-Smithsonian Center for Astrophysics (figure 1). In one experiment, the frequencies of helium and xenon masers operating within the same cavity are compared. The energy-level corrections in these atoms depend sensitively on how the neutrons within the nuclei are oriented with respect to the background SME coefficients. As the Earth rotates, these orientations change and the small difference between the helium and xenon frequencies would therefore change with time. In 2000 the Harvard team achieved a sensitivity to Lorentz violation of about one part in 10^{31} for the neutron by monitoring this frequency difference for sidereal time variations, i.e. variations as the Earth moves with respect to the fixed stars (see Bear *et al.* in further reading). A similar approach is to compare two hyperfine Zeeman transitions in a hydrogen maser, and this has produced a sensitivity of one part in 10^{27} for the proton.

Interestingly, the sharpest bounds on Lorentz violation for the electron do not come from measurements of atomic transitions, but from experiments with a spin-polarized torsion pendulum (figure 3). This remarkable device consists of a torus of alternating magnetic materials that are chosen so that the torus has a huge net spin – 10^{22} aligned electron spins – yet produces no magnetic field. It can therefore be used to measure anomalous spin couplings without the usual accompanying magnetic-dipole effects. The pendulum is placed on a rotating turntable so that the collective motion of the electron spins with respect to the background SME coefficients induces a small but measurable torque. Eric Adelberger and Blayne Heckel at the University of Washington have reached sensitivities to Lorentz violation for the electron of one part in 10^{29} using this experiment.

3 Torsion balance



Researchers at the University of Washington have used a spin-polarized torsion pendulum to carry out highly sensitive tests of Lorentz symmetry. The actual device (left) measures about 3 cm in diameter and is shielded by a metal cylinder. The pendulum consists of a stack of flat-faced toroids, which are formed by segments made from different magnetic materials (blue and green in the schematic). This results in a large total spin – due to some 10^{22} aligned electron spins – but a negligible magnetic field. The pendulum is suspended by a wire, and the whole device is rotated on a turntable. If Lorentz symmetry is broken, then anomalous spin-dependent interactions can cause small variations in the torque that can be measured with very high precision.

Clocks in space

As spectacular as these sensitivities are for Lorentz violation in ordinary matter – i.e. protons, neutrons and electrons – most of the SME coefficients for these particles escape detection in the experiments. One reason is that experiments looking for sidereal time variations are insensitive to SME coefficients that are aligned along the Earth's rotation axis. Another reason is that stationary Earth-based experiments do not typically involve Lorentz boost effects, which involve relative motion at a constant velocity. Both these limitations can be overcome by performing clock-comparison experiments in space, and there are plans for a number of missions – ACES, PARCS, RACE and SUMO – that will place atomic clocks on board the International Space Station (ISS). The tilt of the ISS orbit allows all spatial directions to be sampled, and its velocity – orbiting the Earth every 92 minutes – also allows for boost effects to be tested.

A clock-comparison experiment on board the ISS would compare two co-moving atomic clocks that use different atomic species and that therefore have different sensitivities to Lorentz violation. The difference in the clock frequencies would be monitored for time variations corresponding to those of the orbiting spacecraft, which would provide sharp sensitivity to many of the SME coefficients that are currently not tested.

Another important test of Lorentz symmetry is to perform experiments with antimatter. This is because the experiments on matter particles alone typically have sensitivity to a combination of CPT-preserving and CPT-breaking forms of Lorentz violation, while comparisons of particles and antiparticles are directly sensitive to interactions that violate CPT. As a result, high-precision CPT tests with antimatter complement those performed on matter.

A number of such high-precision CPT experiments have been conducted in recent years. These include comparisons of the anomalous magnetic moments of electrons and positrons in Penning traps by Hans Dehmelt's group at the University of Washington, and proton–antiproton experiments at CERN performed by Gerald Gabrielse of Harvard and co-workers. Experiments are also under way at CERN that intend to make high-precision spectroscopic comparisons of hydrogen and antihydrogen, such as the ATHENA, ATRAP and ASACUSA collaborations (see *Physics World* March 2003 pp25–26).

Party on

This brief survey of recent Lorentz tests only lists those experiments involving light, ordinary matter, and antimatter. However, a number of additional experiments – many of which have exceptional sensitivity – are searching for Lorentz and CPT violation using other particles, such as mesons, muons, cosmic rays and neutrinos. Each of these tests provides a broad range of sensitivities for second-generation quarks and leptons in the Standard Model.

One particularly noteworthy result involves the neutrino sector, where recent experiments have shown that neutrinos can oscillate between different flavour states as they propagate. Recently, Kostelecky and Mewes showed that the observed neutrino oscillations can actually be explained by Lorentz violation rather than the neutrino having mass. Proposals have been put forward for experiments that will be able to test the unique signals of Lorentz violation in the neutrino sector.

There is no question that the coming years will remain an active and exciting time for Lorentz symmetry, especially in its role in quantum-gravity phenomenology. Theoretical and technological advances will lead to new tests that will continue to challenge the robustness of this symmetry at all levels.

Throughout the coming year, as physicists gather to celebrate 100 years of Lorentz symmetry, they will commemorate its illustrious history as one of the greatest discoveries of the 20th century. But just as relativity arose out of inconsistencies between Newtonian mechanics and electromagnetism, it could well be that resolving the incompatibility between gravity and quantum theory will lead to an even more elegant theory in which Lorentz symmetry is broken. In this respect, far from spoiling the party, the discovery of a tiny blemish in Lorentz symmetry would instead set the stage for even better parties yet to come.

Further reading

D Bear *et al*. 2000 Limit on Lorentz and CPT violation of the neutron using a two-species noble-gas maser *Phys. Rev. Lett.* **85** 5038

R Bluhm *et al*. 2002 Clock-comparison tests of CPT and Lorentz symmetry in space *Phys. Rev. Lett.* **88** 090801

S Carroll, G Field and R Jackiw 1990 Limits on a Lorentz- and parity-violating modification of electrodynamics *Phys. Rev.* D **41** 1231

O Greenberg 2002 CPT violation implies violation of Lorentz invariance *Phys. Rev. Lett.* **89** 231602

V Kostelecky and M Mewes 2002 Signals for Lorentz violation in electrodynamics *Phys. Rev.* D **66** 056005

S Lamoreaux 2002 Relativity: testing times in space *Nature* **403** 62

J Lipa *et al*. 2003 New limit on signals of Lorentz violation in electrodynamics *Phys. Rev. Lett.* **90** 060403

H Muller *et al*. 2003 Modern Michelson–Morley experiment using cryogenic optical resonators *Phys. Rev. Lett.* **91** 020401

N Russell 2003 The arrow of space–time *New Scientist* August 16 p22

D Sudarsky, L Urrutia and H Vucetich 2002 Observational bounds on quantum gravity signals using existing data *Phys. Rev. Lett.* **89** 231301

P Wolf *et al*. 2003 Tests of Lorentz invariance using a microwave resonator *Phys. Rev. Lett.* **90** 060402

Robert Bluhm is Sunrise Professor of Physics at Colby College in Waterville, ME 04901, US, e-mail rtbluhm@colby.edu