

If we want a theory of everything, we might have to break a few rules, says **Amanda Gefter**

IT'S not every day that respectable scientists challenge Einstein. But that's what Nobel prizewinner Sheldon Glashow and his colleague Andrew Cohen, both of Boston University in Massachusetts, have dared to do. They believe it is time to rewrite the rules of Einstein's special theory of relativity, our best description of the nature of space and time for over a century.

They call their theory very special relativity, or VSR. If Glashow and Cohen are right, it could tell us something profound about the fabric of the universe. It could solve a troubling mystery in particle physics. And it might get us a little closer to solving the problem at the top of most theorists' wish-lists: how to find a theory of everything.

The crucial evidence supporting Glashow and Cohen's theory may be right in front of your nose. Or, more accurately, passing right through it. For as you read this sentence, trillions of tiny particles called neutrinos are sailing through your body, imperceptible and undisturbed by the atoms that give you substance. Experiments conducted throughout the past decade have shown that neutrinos have mass, even though our best theory of matter claims that they ought to be massless. While formulating their new theory, Glashow and Cohen realised that a neutrino's mass may actually be a clue to an irregularity in space-time itself.

Einstein's theory of special relativity revolutionised our conceptions of space and time by exposing the symmetries that underlie the reality we see around us. Symmetries are those aspects of the world that do not change when we view them from different perspectives. No matter how we rotate a circle, for instance, its geometry always looks the same, so we can say that a circle has 360-degree rotational symmetry.

Einstein began with two basic postulates from which the special theory of relativity spilled forth. The first is that the speed of light is always the same regardless of how the light source is moving; the second, that the laws of physics are the same for all observers who are moving at a constant speed.

For these two postulates to hold, space-

time must have certain symmetries which, taken together, form the so-called Lorentz symmetry group, which concerns rotations and changes in velocity. If you were conducting a physics experiment, and your laboratory flipped upside down or began moving at a different speed, the fundamental laws of nature would not change, thanks to Lorentz symmetry.

Add to the Lorentz group the symmetry of space-time translations – meaning that you could move the laboratory, say, 50 metres to the west or forward three years in time without changing the results of your experiment – and you have the full set of symmetries encompassed by special relativity. You also have the full weirdness that it implies: the speed of light remains the same no matter how fast the light source is moving, time slows and distances contract at near-light speeds, energy and mass are interchangeable, and events that appear simultaneous to one observer do not to another.

Today, however, many physicists wonder whether Lorentz symmetry is a true

“Very special relativity could tell us that space-time treats some directions differently”





symmetry, or if in fact it might be broken at extremely small distances or enormously high energies. They are motivated by the search for a theory of everything, something that can unite the seemingly incompatible theories of quantum mechanics – which describes the behaviour of subatomic particles – and general relativity, Einstein's extension of the theory to include gravity.

One-way universe

Various approaches to creating such a theory of everything have all suggested that Lorentz symmetry might be broken at the so-called Planck scale, around 10^{-35} metres, where both quantum mechanics and gravity come into play. Two such theories, string theory and loop quantum gravity, hint towards broken Lorentz symmetry. Another approach called non-commutative geometry explicitly calls for it. "If Lorentz violations are discovered, they would provide an experimental handle on the underlying unified theory combining gravity and quantum physics – a handle that is sorely lacking to date," says Alan Kostelecky, a physicist at Indiana University in Bloomington.

Dozens of experiments looking for signs of broken Lorentz symmetry have been carried out. Not one has found any. That doesn't mean Lorentz symmetry is safe and sound, though. It just means that experiments have not been sensitive enough so far, or that physicists are looking in the wrong place.

Until now, physicists have searched for violations of Lorentz symmetry by picking away at well-tested consequences of special relativity such as the slowing of time or the constancy of the speed of light, which has led to experiments with light streaming in different directions or clocks flying at daredevil speeds. Glashow and Cohen, however, have found a way to break Lorentz symmetry without disturbing any of those cherished relativistic effects. They modified the special theory of relativity to reduce the amount of symmetry and so formulated very special relativity.

In this new theory, Lorentz symmetry is not fully intact, yet the key effects of special relativity remain unaffected. "People are shocked," says Cohen. "I don't believe anyone ever contemplated that there could be Lorentz violation while one of the basic ideas of special relativity, the constancy of the speed of light, could still be preserved."

What is lost in VSR, however, is the full rotational symmetry of space-time. "Not all directions are the same in VSR," says Glashow. "There's a preferred direction in space." Here on Earth, for instance, the preferred direction is down. That's because the mass of the planet breaks the symmetry of the surrounding space-time and gravity selects a unique

direction. But that's merely circumstantial – the underlying laws of physics see every direction as equal. Or so we thought. Cohen and Glashow are suggesting that maybe, even in the absence of a planet or anything else, space-time itself treats some directions differently from others.

According to VSR, the break in rotational symmetry should be extremely small and therefore unnoticeable at everyday scales. That's why, if such asymmetry exists, it has gone undetected for so long. "Rotational invariance is one of the additional postulates included in special relativity," Cohen says, "because people just have this intrinsic prejudice for it. What we said is, if you give up rotational invariance, there are these other possibilities." In other words, accept that space-time is even more counter-intuitive than we thought, and you might get a little closer to a theory of everything.

Although we have tested rotational invariance to a very high degree of accuracy, there is still wiggle room. "What's surprising is that if you give it up, these other possibilities nevertheless look very nearly rotationally invariant – just not exactly," Cohen says.

So at how small a scale would we find VSR's Lorentz violation? The answer lies with the neutrinos that are sailing through your body. Those ethereal little ghosts are hardly of this world, interacting with matter only through gravity, which barely notices them, and the so-called weak force, which exerts itself only in

the cores of atomic nuclei. They are the least understood particles in the otherwise explicit framework of the standard model, our best description of the building blocks of matter and the forces that glue them together. Now, however, new explanations of the strange qualities of neutrinos are paving the way toward a deeper comprehension of the universe than the standard model offers.

Spinning neutrinos

It has been eight years since physicists first found conclusive evidence that neutrinos have mass, contrary to the predictions of the standard model. The 1998 discovery was made in Super-Kamiokande, a neutrino observatory located 1 kilometre below ground in a mine in Kamiokande, Japan. Neutrinos come in three distinct types or "flavours", but the Super-K experiment found that they were morphing from one flavour into another as they fell from the sky. It was as if you ordered a scoop of chocolate ice cream that transformed into strawberry on its way toward your lips and settled into vanilla upon your tongue.

The laws of quantum mechanics dictate that only particles with mass can change from one flavour to another. And so neutrinos, it seemed, must have a mass, albeit an incredibly tiny amount: a neutrino seems to be 100,000 million times lighter than a proton. The discovery was the first glimpse of physics beyond the standard model.

Physicists, however, still have no idea how neutrinos can have mass. It is the way that neutrinos spin that is so puzzling. Researchers have observed that some particles are "ambidextrous" – they can spin either to the right or to the left – while others are strictly one-handed.

Every neutrino ever observed has been left-handed. Yet only massless particles can be one-handed, and here's why. Imagine you are watching a particle travelling along and spinning to the left. You start running and soon you are running faster than the particle. As you sprint ahead of it, you look over your shoulder and see the particle spinning the other way round (see Graphic).

In other words, for any particle that spins to the left, there is some reference frame from which a faster-moving observer can look back and see the particle spinning to the right, making it ambidextrous. That is, unless the particle is moving at the speed of light, the fastest possible speed, in which case there's no way that any observer can outrun it. And only massless particles can move at light speed.

If neutrinos are always observed to be spinning to the left, then no observer must be able to outrun them, which means they must be travelling at light speed and they must be

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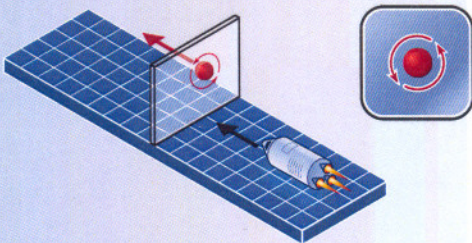
NEUTRINO PARADOX

According to standard theory, neutrinos cannot have mass and always spin in the same sense relative to their direction of travel, like a left-handed corkscrew (case 1). But they do both (case 2). Very special relativity solves the paradox (case 3)

CASE 1: MASSLESS NEUTRINO

With zero mass, the neutrino always travels at the speed of light

The spacecraft can never catch it up, so is always lagging behind



View from spacecraft

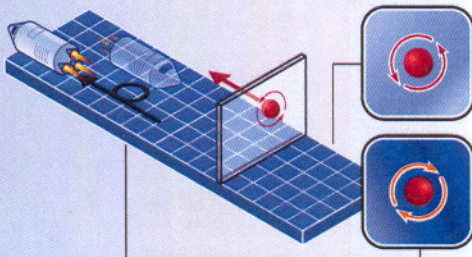
Neutrino always appears to be spinning anticlockwise because spacecraft is always behind neutrino

Agrees with standard model, but does not agree with experiments – neutrinos do have mass

CASE 2: NEUTRINO WITH MASS

Neutrino travels slower than light speed because it has mass

Spacecraft can overtake the neutrino and turn round to look back



View from spacecraft

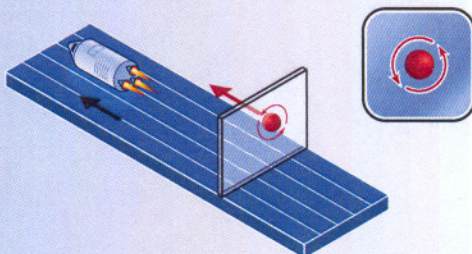
Neutrino is ahead and appears to be spinning anticlockwise

Spacecraft has overtaken neutrino and looks back to see neutrino spinning clockwise and travelling backwards in relation to the spacecraft. Forbidden by standard model – neutrinos are always left-handed

CASE 3: VERY SPECIAL RELATIVITY

Space-time has a preferred direction that prevents the spacecraft from turning round

Neutrino has mass. Spacecraft can overtake the neutrino but is forbidden from turning round to see it because space-time is not symmetric



View from spacecraft

Neutrino always appears to be spinning anticlockwise. Agrees with experiments and standard model

massless. Yet the Super-K results clearly showed that neutrinos have mass. How can a particle be both left-handed and massive?

Glashow and Cohen's theory can solve the paradox. It just so happens that the scale of VSR's Lorentz violation is right around the scale of the neutrino's tiny mass. "Suddenly we realised that within the context of very special relativity, neutrinos can acquire mass," says Glashow.

A left-handed neutrino with mass will appear right-handed if you run past it, turn around and look back at it. But that's exactly what VSR doesn't allow you to do. Although you can run faster than the neutrino, you can't turn back around to see it spinning the other way. Turning around is forbidden by VSR, because according to the theory, the rotational symmetry of space is broken, so the laws of physics forbid certain rotations. What emerges is an elegant explanation for what seemed like an impossible paradox. Neutrinos do move more slowly than the speed of light – on account of their mass – but no observer can ever see them spinning the other way. Neutrinos in a VSR universe can be exclusively left-handed and have mass at the same time.

True, other explanations have been

proposed for the origin of neutrino mass.

"They don't invoke something as dramatic as violating Lorentz invariance," says physicist Sean Carroll of the California Institute of Technology in Pasadena. One way is to invent a new kind of particle called a sterile neutrino (*New Scientist*, 17 June 2006, p 46), a much heavier kind of neutrino that is right-handed. The sterile neutrino is even more ghostly than its counterpart, interacting with matter through gravity alone, which would explain why no one has ever observed one and probably never will.

VSR, on the other hand, makes several clear predictions that can be tested in the near future. One is to watch the radioactive decay of tritium, a heavy isotope of hydrogen with two extra neutrons. As it decays, tritium spits out an electron and an antineutrino. Because of the law of conservation of momentum, measuring the momentum of the outgoing electron (which is far easier to pin down than an elusive antineutrino) provides a detailed profile of the momentum of the antineutrino, which in turn depends on its mass.

If VSR is correct, it should limit tritium's momentum as it coughs up antineutrinos. This would show up in a graph plotting the

number of electrons versus energy. "You get a slightly different spectrum of the electrons coming out," says Cohen.

Predictive power

So far, tritium decay experiments have not seen any evidence of a neutrino's mass, let alone VSR. However, Cohen points out that they have not yet been done at the necessary sensitivity. A more sensitive experiment called KATRIN is being built at the Karlsruhe Research Centre in Germany. This might measure a neutrino's mass and possibly spot the first signs of Lorentz violation.

Another experiment involves looking at properties of electrons such as the magnetic dipole moment, a measure of the strength and direction of the electron's response to a magnetic field. "If space has a preferred direction, as VSR claims, it will influence the electron in a way that should show up as a very peculiar time-dependent effect," Cohen says.

Glashow and Cohen are trying to convince a Harvard colleague, Gerald Gabrielse, to look for the effect. Gabrielse's team recently measured the electron's magnetic moment in the most precise measure to date of the fine structure constant, a gauge of the strength of the electromagnetic interaction (*New Scientist*, 12 September 2006, p 40). Now Gabrielse has to determine whether it is possible to measure the electron's magnetic moment with enough sensitivity to look for the VSR effect. If it is, Glashow and Cohen's theory could be put to the test within a few years.

If VSR turns out to be right, it will mark a major turning point in physics not only for our understanding of how neutrinos get their mass, but also for our understanding of the very fabric of reality. "If they were to find experimental evidence of Lorentz violation, that certainly would be ground-breaking," says Carroll.

It would also be troublesome. "Most of the physics community would rather not believe that VSR is right, and with good reason," says Glashow. The reason is that even small deviations from special relativity translate into big problems for general relativity. "It's an unpleasant fact that anyone who thinks about violations of special relativity doesn't really know what to do to fix up general relativity," says Cohen. Solving one big mystery, it seems, may create an even bigger one. Those who challenge Einstein do so at their peril. ●

Further reading: "Very special relativity" by Andrew Cohen and Sheldon Glashow, *Physical Review Letters*, vol 97, p 021601

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