High-energy physics

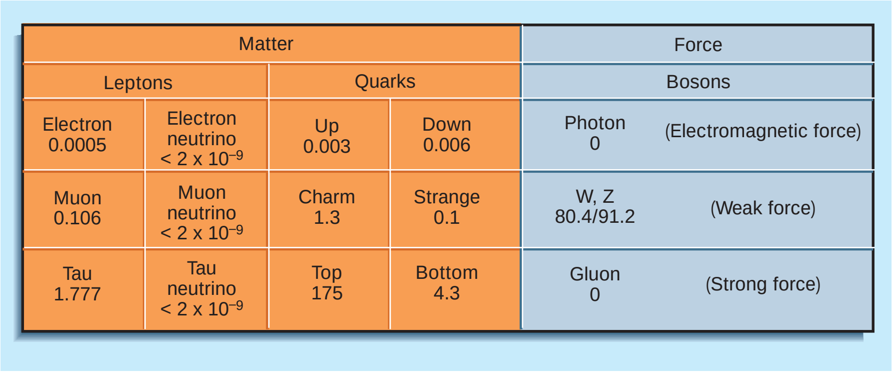
The mass question

Edward Witten

Do the elementary particles known as neutrinos have mass? Yes, according to recent experiments. But how much? A surprising — and controversial — result suggests that the answer is not what we thought.

Neutrinos were long believed to be, like photons, massless particles that always travel at the speed of light. In the past few years, by studying neutrinos emitted by the Sun or created by cosmic rays in the Earth's atmosphere, physicists have learned that neutrinos actually have tiny but non-zero masses, roughly ten million times smaller than the mass of an electron. These masses are believed to result from physical processes occurring at energies well beyond those of known particle interactions. In *Modern Physics Letters A*, Klapdor-Kleingrothaus and colleagues[1] now claim to have observed a new type of nuclear decay process. If this somewhat controversial finding holds up, it implies that the three types of neutrino have almost the same mass, and gives us a window on physics that goes far beyond our present knowledge.

To put the mass of the neutrino in context, consider the mass of other elementary particles. The electron, for example, is about 1,800 times lighter than the proton or neutron, and about 200,000 times lighter than the heaviest known elementary particles, which are the W and Z bosons and the top quark (Fig. 1). Why these masses vary



Matter				Force	
Leptons		Quarks		Bosons	
Electron 0.0005	Electron neutrino < 2 x 10^{-9}	Up 0.003	Down 0.006	Photon 0	(Electromagnetic force)
Muon 0.106	Muon neutrino < 2 x 10^{-9}	Charm 1.3	Strange 0.1	W, Z 80.4/91.2	(Weak force)
Tau 1.777	Tau neutrino < 2 x 10^{-9}	Top 175	Bottom 4.3	Gluon 0	(Strong force)

Figure 1 **The standard model of high-energy physics: fundamental particles and their masses (in GeV $c^{1 2}$, where *c* is the speed of light). Leptons and quarks interact through exchange of the particles associated with three forces (weak, strong and electromagnetic) to form the matter we see around us. The fourth fundamental force, gravity, cannot yet be described within the framework of the standard model. Although we do not yet understand why, the matter particles form three 'families' in order of increasing mass. The observation of a rare nuclear decay by Klapdor-Kleingrothaus *et al.*[1] suggests that neutrino masses may not follow this trend, but are in fact similar in value.**

so much is a mystery, even in the modern standard model of elementary particles. By contrast, until recently, neutrinos seemed to be massless, and in the 1950s physicists thought they had worked out why.

The key is chirality. In biochemistry, chirality describes the 'handedness' of a molecule, which may look different from its mirror image. A simple molecule such as H_2O looks the same as its mirror image, but a more complex molecule such as dextrose may not. That certain chiral molecules are important in biology, and their mirror-image molecules are not, is believed to reflect accidents in the evolution of life, rather than any inherent difference between the molecules.

Neutrinos have a similar kind of chirality. Elementary particles have an intrinsic quantum-mechanical 'spin'. Most particles can spin in a right-handed or left-handed sense around their direction of motion, but neutrinos always spin in a left-handed sense (Fig. 2). Like chirality in biology, this property may conceivably have its origins in a chance event, in this case an accident of the Big Bang. Such an intrinsic chirality is impossible for particles with mass (because the direction of spin of a massive particle can be changed by rotating the particle in its rest frame), so physicists concluded that neutrinos must have zero mass.

But there is a problem with this argument, and it has to do with antimatter. Every particle of elementary matter has a corresponding antiparticle, with the same mass but opposite electric charge. For example, the antiparticle of the electron, e^{1}, is the positron, denoted e$^{\&}$. Similarly, the neutrino has an antiparticle: the antineutrino. The antineutrino has the opposite chirality to the neutrino — it always spins in a right-handed sense around its direction of motion (Fig. 2).

Apart from their chirality, how can you tell a neutrino from an antineutrino? They are both electrically neutral, so we cannot distinguish them by their electric charge. But there is another apparently conserved charge in interactions between elementary particles: the lepton number. The electron and the neutrino are leptons, and the positron and the antineutrino are antileptons. The number of leptons minus the number of antileptons in an interaction is called the lepton number. Leptons and antileptons can be created by many processes, such as the decay of a neutron to a proton, an electron and an antineutrino. In this example, there are no leptons at the outset (the neutron is a 'baryon'), then one lepton (the electron) and one antilepton (the antineutrino) are created, so the lepton number does not change. Indeed, it is conserved in all the usual elementary particle processes.

The concept of lepton-number conservation was derived from experiment, and originally had no theoretical explanation behind it. In the 1970s, the newly developed standard model of high-energy physics offered some insight: given the particles assumed to exist in the standard model and the rules by which it is constructed, it is actually impossible to violate lepton-number conservation.

The standard model was barely in place before physicists started trying to go beyond it. They wanted to build a unified theory that would motivate the existence of elementary particles and forces, rather than just describing them, as the standard model does[2,3]. In this more ambitious framework — optimistically dubbed 'grand unification' — lepton-number conservation is not automatic. Thus, a new perspective emerged[4–6]: lepton number should be very nearly conserved in nature because it is exactly conserved in the well-tested standard model; but it should be very slightly violated by the effects of grand unification.

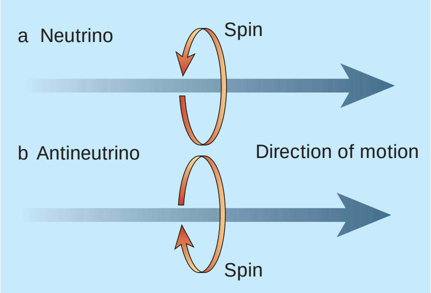


Figure 2 **Chirality is the spice of life.** a, **The neutrino spins in a left-handed sense around its direction of motion;** b, **the antineutrino spins in a right-handed sense.**

If lepton number is not conserved, it no longer provides a way of distinguishing a neutrino from an antineutrino. They could, in fact, be two forms of the same particle. This particle has one state that spins one way and another state that spins the other way (Fig. 2), just like a particle with mass, such as the electron. So if lepton number is not conserved, neutrinos could have mass. But this mass can only be very small, because it arises from effects that are absent in the standard model. Direct measurement of such a small mass is difficult, but studies of the decay of the tritium nucleus have demonstrated[7] that one type of neutrino is lighter than about 2 electron volts.

A more subtle way of looking for neutrino mass depends on the fact that there are three kinds of neutrino: the electron neutrino, the muon neutrino and the tau neutrino (which are typically produced alongside electrons, muons and tau leptons, respectively). This leads to the possibility of an interesting quantum-mechanical effect: while travelling through a vacuum, one type of neutrino can convert spontaneously into another. This is known as neutrino oscillation, and can only happen if neutrinos have mass.

There is now extensive evidence for neutrino oscillations, both from neutrinos produced by cosmic rays in the Earth's atmosphere[8,9] and from neutrinos produced by the Sun[10]. (The interpretation in terms of neutrino oscillations has resolved a long-standing discrepancy[11] between the number of neutrinos expected from the Sun and the number we actually detect.) In this fast-moving area, experiment is well ahead of theory, and many important measurements are expected in the next few years. The results so far support the rough range of possible neutrino masses that arises from grand-unification theory. The experiments have also turned up a surprise: the measured 'mixing angles' (which determine the probability that neutrinos oscillate from one type to another) are much larger than theorists generally expected.

It seems logical to suspect that neutrino mass results from the non-conservation of lepton number. But the neutrino-oscillation measurements alone do not show that lepton number is not conserved. So can we do this in some other way? This is what Klapdor-Kleingrothaus *et al.*[1] claim to have done, by observing the nuclear decay ^{76}Ge→^{76}Se& 2e^{1}. This reaction is called neutrinoless double-b-decay, as the final state contains two electrons (historically known as b-particles) and no antineutrinos — so the reaction violates the conservation of lepton number by two units. Taken together with the oscillation measurements, and assuming that the only relevant particles are the three known types of neutrino, the new result implies that the three neutrinos have approximately equal masses, probably a few tenths of an electron volt. This is a surprising result because other particle families, such as quarks and the charged leptons, do not have approximately equal masses (Fig. 1), and it will put a severe constraint on theories of the origin of neutrino masses.

Some caution is called for, however, because of the exceptionally difficult nature of the experiment. Criticisms of the assumptions made by the authors in analysing the background and extracting an extremely small signal have already been offered[12,13]. At any rate, planned future experiments using much larger quantities of ^{76}Ge (or similar nuclei) will achieve much greater sensitivity. By extrapolating from the oscillation measurements, many physicists have guessed, prior to this claim, that a sensitivity 10^3 or 10^4 times greater than that of this experiment may be needed to conclusively observe the violation of lepton-number conservation. Such sensitivity suggests how difficult, as well as how potentially rewarding, future experiments are likely to be. ■

Edward Witten is at the School of Natural Sciences,
Institute for Advanced Study, Olden Lane,
Princeton, New Jersey 08540, USA.
e-mail: witten@ias.edu

---

1. Klapdor-Kleingrothaus, H. V., Dietz, A., Harney, H. L. & Krivosheina, I. V. *Mod. Phys. Lett. A* **16,** 2409–2420 (2001).
2. Pati, J. & Salam, A. *Phys. Rev. D* **10,** 275–289 (1974).
3. Georgi, H. & Glashow, S. *Phys. Rev. Lett.* **32,** 438–441 (1974).
4. Yanagida, T. in *Proc. Workshop on Unified Theory and Baryon Number in the Universe* (eds Sawada, O. & Sugamoto, A.) 95–98 (KEK, Tsukuba, 1979).
5. Gell-Mann, M. *et al.* in *Supergravity* (eds van Nieuwenhuysen, P. & Freedman, D. Z.) 315–321 (North-Holland, Amsterdam, 1979).
6. Weinberg, S. in *First Workshop on Grand Unification* (eds Frampton, P., Glashow, S. L. & Yildiz, A.) 347–362 (Math. Sci. Press, Brookline, MA, 1980).
7. Bonn, J. *et al.* (MAINZ collaboration) *Nucl. Phys. Proc. Suppl.* **91,** 273–279 (2001).
8. Fukuda, S. *et al.* (SuperKamiokande collaboration) *Phys. Rev. Lett.* **85,** 3999–4003 (2000).
9. Giacomelli, G. & Giorgini, M. (MACRO collaboration) Preprint hep-ex/0110021 (2001); http://xxx.lanl.gov
10. http://www.sns.ias.edu/~jnb/SNexperiments/experiments.html
11. Bahcall, J. N. & Davis, R. Jr in *Essays in Nuclear Astrophysics* (eds Barnes, C. A., Clayton, D. D. & Schramm, D. N.) 243–285 (Cambridge Univ. Press, 1982).
12. Ferruglio, F., Strumia, A. & Vissani, F. Preprint hep-ph/0201291 (2002); http://xxx.lanl.gov
13. Aalseth, C. E. *et al.* Preprint hep-ex/0202018 (2002); http://xxx.lanl.gov