New experimental data, which show that neutrinos have mass, are forcing theorists to revise the Standard Model of particle physics

The origin of neutrino mass

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IF WE look deep into the universe, we see stars and galaxies of all shapes and sizes. What we do not see, however, is that the universe is filled with particles called neutrinos. These particles – which have no charge and have little or no mass – were created less than one second after the Big Bang, and large numbers of these primordial low-energy neutrinos remain in the universe today because they interact very weakly with matter. Indeed, every cubic centimetre of space contains about 300 of these uncharged relics.

Trillions of neutrinos pass through our bodies every second – almost all of these are produced in fusion reactions in the Sun's core. However, neutrino production is not just confined to our galaxy. When massive stars die, most of their energy is released as neutrinos in violent supernova explosions. Even though supernovas can appear as bright as galaxies when viewed with optical telescopes, this light represents only a small fraction of the energy released (see figure).


AAO/David Malin

Ground-based telescopes, like the Anglo-Australian Observatory, saw the light from supernova 1987A several hours after the Kamiokande and IMB experiments had already detected the neutrinos that were emitted.

Physicists detected the first neutrinos from a supernova in 1987 when a star collapsed some 150 000 light-years away in the Large Magellanic Cloud, the galaxy nearest to the Milky Way. Two huge underground experiments – the Kamiokande detector in Japan and the IMB experiment near Cleveland in Ohio, USA – detected neutrinos from supernova 1987A a full three hours before light from the explosion reached Earth.

The event marked the birth of neutrino astronomy. New neutrino telescopes were built soon after, including the AMANDA experiment in Antarctica, and plans are under way to build an even larger experiment called ICECUBE to detect neutrinos from gamma-ray bursters billions of light-years away.

However, neutrinos are still the least understood of the fundamental particles. For half a century physicists thought that neutrinos, like photons, had no mass. But recent data from the SuperKamiokande experiment in Japan overturned this view and confirmed that the Standard Model of particle physics is incomplete. To extend the Standard Model so that it incorporates massive neutrinos in a natural way will require far-reaching changes. For example, some theorists argue that extra spatial dimensions are needed to explain neutrino mass, while others argue that the hitherto sacred distinction between matter and antimatter will have to be abandoned. The mass of the neutrino may even explain our existence.

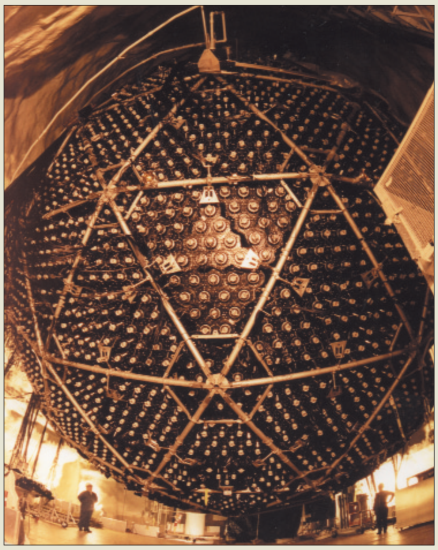
Birth of neutrinos

Neutrinos have been shrouded in mystery ever since they were first suggested by Wolfgang Pauli in 1930. At the time physicists were puzzled because nuclear beta decay appeared to break the law of energy conservation. In beta decay, a neutron in an unstable nucleus transforms into a proton and emits an electron at the same time. After much confusion and debate, the energy of the radiated electron was found to follow a continuous spectrum. This came as a great surprise to many physicists because other types of radioactivity involved gamma rays and α-particles with discrete energies. The finding even led Niels Bohr to speculate that energy may not be conserved in the mysterious world of nuclei.

Pauli also struggled with this mystery. Unable to attend a physics meeting in December 1930, he instead sent a letter to the other "radioactive ladies and gentlemen" in which he proposed a "desperate remedy" to save the law of energy conservation. Pauli's remedy was to introduce a new neutral particle with intrinsic angular momentum or "spin" of $\hbar/2$, where $\hbar$ is Planck's constant divided by 2π. Dubbed the "neutron" by Pauli, the new particle would be emitted together with the electron in beta decay so that the total energy would be conserved.

Two years later, James Chadwick discovered what we now call the neutron, but it was clear that this particle was too heavy to be the "neutron" that Pauli had predicted. However, Pauli's particle played a crucial role in the first theory of nuclear beta decay formulated by Enrico Fermi in 1933 and which later became known as the weak force. Since Chadwick had taken the name "neutron" for something else, Fermi had to invent a new name. Being Italian, "neutrino" was the obvious choice: a little neutral one.

1 Rounding up neutrinos



A view of the SNO detector located 2000 metres underground in the Creighton mine near Sudbury, Canada. The vessel is 12 metres across and is filled with 1000 tonnes of heavy water. A few of the neutrinos that pass through the detector interact to produce electrons that travel faster than the speed of light in the heavy water. These electrons create flashes of Cerenkov light that are detected by the 9600 photomultiplier tubes surrounding the vessel.

Because neutrinos interact so weakly with matter, Pauli bet a case of champagne that nobody would ever detect one. Indeed this was the case until 1956, when Clyde Cowan and Fred Reines detected antineutrinos emitted from a nuclear reactor at Savannah River in South Carolina, USA. When their result was announced, Pauli kept his promise.

Two years later, Maurice Goldhaber, Lee Grodzins and Andrew Sunyar measured the "handedness" of neutrinos in an ingenious experiment at the Brookhaven National Laboratory in the US. The handedness of a particle describes the direction of its spin along the direction of motion – the spin of a left-handed particle, for example, always points in the opposite direction to its momentum.

Goldhaber and co-workers studied what happened when a europium-152 nucleus captured an atomic electron. The europium-152 underwent inverse beta decay to produce an unstable samarium-152 nucleus and a neutrino. The samarium-152 nucleus then decayed by emitting a gamma ray. When the neutrino and the gamma ray were emitted back-to-back, the handedness of the two particles had to be the same in order to conserve angular momentum. By measuring the handedness of the gamma ray using a polarized filter made of iron, the Brookhaven team showed that neutrinos are always left-handed.

This important result implies that neutrinos have to be exactly massless. To see why this is, suppose that neutrinos do have mass and that they are always left-handed. According to special relativity, a massive particle can never travel at the speed of light. In principle, an observer moving at the speed of light could therefore overtake the spinning massive neutrino and would see it moving in the opposite direction. To the observer, the massive neutrino would therefore appear right-handed. Since right-handed neutrinos have never been detected, particle physicists concluded that neutrinos had to be massless.

The Standard Model

We now know that all the elementary particles – six quarks and six leptons – are grouped into three families or generations. Indeed, precision experiments at the Large Electron Positron (LEP) collider at CERN in Switzerland have demonstrated that there are exactly three generations. Everyday matter is built from members of the lightest generation: the up and down quarks that make up protons and neutrons; the electron; and the electron neutrino involved in beta decay. The second and third generations comprise heavier versions of these particles with the same quantum numbers. The analogues of the electron are called the muon and the tau, while the muon neutrino and tau neutrino are equivalent to the electron neutrino. Each particle also has a corresponding antiparticle with opposite electric charge. In the case of neutrinos, the antineutrino is neutral but right-handed.

The Standard Model also includes a set of particles that carry the forces between these elementary particles. Photons mediate the electromagnetic force; the massive W^+ and W^- particles carry the weak force, which only acts on left-handed particles and right-handed antiparticles; and eight gluons carry the strong force.

All the particles that make up matter have mass – from the lightest, the electron, to the heaviest, the top quark – and can be left- or right-handed. Although the Standard Model cannot predict their masses, it does provide a mechanism whereby elementary particles acquire mass. This mechanism requires us to accept that the universe is filled with particles that we have not seen yet.

No matter how empty the vacuum looks, it is packed with particles called Higgs bosons that have zero spin (and are therefore neither left- or right-handed). Quantum field theory and Lorentz invariance show that when a particle is injected into the "vacuum", its handedness changes when it interacts with a Higgs boson (figure 2*a*). For example, a left-handed electron will become right-handed after the first collision, then left-handed following a second collision, and so on. Put simply, the electron cannot travel through the vacuum at the speed of light; it has to become massive. Similarly, muons collide with Higgs bosons more frequently than electrons, making them 200 times heavier than the electron, while the top quark interacts with the Higgs boson almost all the time.

This picture also explains why neutrinos are massless. If a left-handed neutrino tried to collide with the Higgs boson, it would have to become right-handed. Since no such state exists, the left-handed neutrino is unable to interact with the Higgs boson and therefore does not acquire any mass. In this way, massless neutrinos go hand in hand with the absence of right-handed neutrinos in the Standard Model.

Evidence for neutrino mass

I was at the conference in Takayama, near Kamioka, in 1998 when the SuperKamiokande collaboration announced the first evidence for neutrino mass. It was a moving moment. Uncharacteristically for a physics conference, people gave the speaker a standing ovation. I stood up too. Having survived every experimental challenge since the late 1970s, the Standard Model had finally fallen. The results showed that at the very least the theory is incomplete.

The SuperKamiokande collaboration looked for neutrinos that were produced when cosmic rays bombarded oxygen or nitrogen nuclei in the atmosphere. These "atmospheric neutrinos" are mostly muon neutrinos and interact very weakly with matter. Filled with 50 000 tonnes of water, however, the SuperKamiokande detector located deep in the Kamioka mine in Japan is so large that it can detect atmospheric neutrinos. These neutrinos interact with atomic nuclei in the water to produce electrons, muons or tau leptons that travel faster than the speed of light in water to produce a shock wave of light called Cerenkov radiation. This radiation can be detected by sensitive photomultiplier tubes surrounding the water tank.

From these signals, the SuperKamiokande team could also determine the directions from which the neutrinos came. Since the Earth is essentially transparent to neutrinos, those produced high in the atmosphere on the opposite side of the planet can reach the detector without any problems. The team discovered that about half of the atmospheric neutrinos from the other side of the Earth were lost, while those from above were not. The most likely interpretation of this result is that the muon neutrinos converted or "oscillated" to tau neutrinos as they passed through the Earth. SuperKamiokande is unable to identify tau neutrinos. The particles coming from the other side of the Earth have more opportunity to oscillate than those coming from above. Moreover, if neutrinos convert to something else by their own accord, we conclude that they must be travelling slower than the speed of light and therefore must have a mass.

SuperKamiokande was also used to monitor solar neutrinos. The fusion reactions that take place in the Sun only produce electron neutrinos, but these can subsequently oscillate into both muon and tau neutrinos. Though the experiment was able to detect the solar neutrinos, it was unable to distinguish between the different neutrino types. In contrast, the Sudbury Neutrino Observatory (SNO) in Canada can identify the electron neutrinos because it is filled with "heavy water", which contains hydrogen nuclei with an extra neutron. Small numbers of electron neutrinos react with the heavy-hydrogen nuclei to produce fast electrons that create Cerenkov radiation (figure 1).

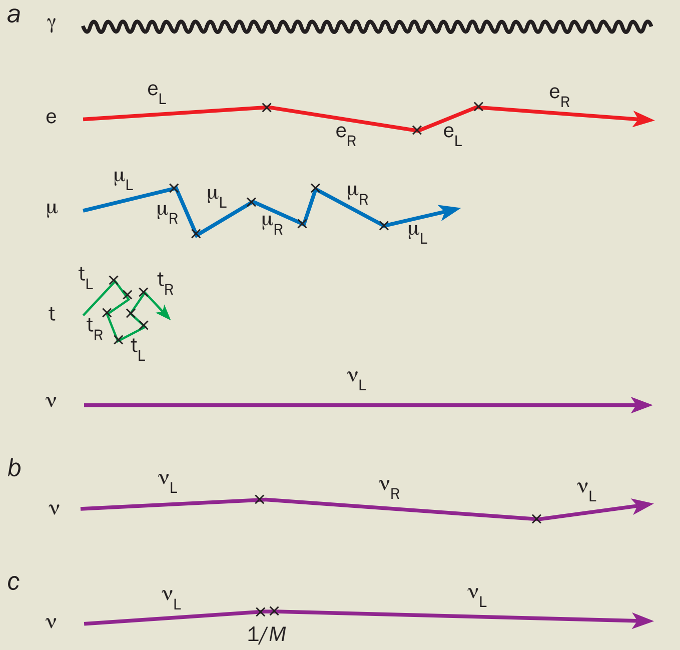
By combining the data from SuperKamiokande and its own experiment, the SNO collaboration determined how many muon neutrinos or tau neutrinos were incident at the Japanese detector. The SNO results also provided further evidence for neutrino mass and confirmed that the total number of neutrinos from the Sun agreed with theoretical calculations.

The implications of neutrino mass are so great that it is not surprising that particle physicists had been searching for direct evidence of its existence for over four decades. In retrospect, it is easy to understand why these searches were unsuccessful (figure 3). Since neutrinos travel at relativistic speeds, the effect of their mass is so tiny that it cannot be determined kinematically. Rather than search for neutrino mass directly, experiments such as SuperKamiokande and SNO have searched for effects that depend on the *difference* in mass between one type of neutrino and another.

In some respects these experiments are analogous to interferometers, which are sensitive to tiny differences in frequency between two interfering waves. Since a quantum particle can be thought of as a wave with a frequency given by its energy divided by Planck's constant, interferometry can detect tiny mass differences because the energy and frequency of the particles depend on their mass.

Interferometry works in the case of neutrinos thanks to the fact that the neutrinos created in nuclear reactions are actually mixtures of two different "mass eigenstates". This means, for example, that electron neutrinos slowly transform into tau neutrinos and back again. The amount of this "mixing" is quantified by a mixing angle, θ. We can only detect interference between two eigenstates with small mass differences if the mixing angle is large enough. Although current experiments have been unable to pin down the mass difference and mixing angle, they have narrowed down the range of possibilities (figure 4).

2 Neutrinos meet the Higgs boson



(*a*) According to the Higgs mechanism in the Standard Model, particles in the vacuum acquire mass as they collide with the Higgs boson. Photons (γ) are massless because they do not interact with the Higgs boson. All particles, including electrons (e), muons (μ) and top quarks (t), change handedness when they collide with the Higgs boson; left-handed particles become right-handed and vice versa. Experiments have shown that neutrinos (ν) are always left-handed. Since right-handed neutrinos do not exist in the Standard Model, the theory predicts that neutrinos can never acquire mass. (*b*) In one extension to the Standard Model, left- and right-handed neutrinos exist. These Dirac neutrinos acquire mass via the Higgs mechanism but right-handed neutrinos interact much more weakly than any other particles. (*c*) According to another extension of the Standard Model, extremely heavy right-handed neutrinos are created for a brief moment before they collide with the Higgs boson to produce light left-handed Majorana neutrinos.

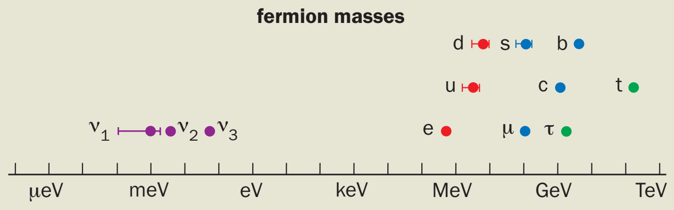
Implications of neutrino mass

Now that neutrinos do appear to have mass, we have to solve two problems. The first is to overcome the contradiction between left-handedness and mass. The second is to understand why the neutrino mass is so small compared with other particle masses – indeed, direct measurements indicate that electrons are at least 500 000 times more massive than neutrinos. When we thought that neutrinos did not have mass, these problems were not an issue. But the tiny mass is a puzzle, and there must be some deep reason why this is the case.

Basically, there are two ways to extend the Standard Model in order to make neutrinos massive. One approach involves new particles called Dirac neutrinos, while the other approach involves a completely different type of particle called the Majorana neutrino.

The Dirac neutrino is a simple idea with a serious flaw. According to this approach, the reason that right-handed neutrinos have escaped detection so far is that their interactions are at least 26 orders of magnitude weaker than ordinary neut-

3 Fermions weigh in



A comparison of the masses of all the fundamental fermions, particles with spin $\hbar/2$. Other than the neutrino, the lightest fermion is the electron, with a mass of 0.5 MeV c^{-2}. Neutrino-oscillation experiments do not measure the mass of neutrinos directly, rather the mass difference between the different types of neutrino. But by assuming that neutrino masses are similar to this mass difference, we can place upper limits on the mass of a few hundred millielectron-volts.

rinos. The idea of the Dirac neutrino works in the sense that we can generate neutrino masses via the Higgs mechanism (figure 2*b*). However, it also suggests that neutrinos should have similar masses to the other particles in the Standard Model. To avoid this problem, we have to make the strength of neutrino interactions with the Higgs boson at least 10^{12} times weaker than that of the top quark. Few physicists accept such a tiny number as a fundamental constant of nature.

An alternative way to make right-handed neutrinos extremely weakly interacting was proposed in 1998 by Nima Arkani-Hamed at the Stanford Linear Accelerator Center, Savas Dimopoulous of Stanford University, Gia Dvali of the International Centre for Theoretical Physics in Trieste and John March-Russell of CERN. They exploited an idea from superstring theory in which the three dimensions of space with which we are familiar are embedded in 10- or 11-dimensional space–time. Like us, all the particles of the Standard Model – electrons, quarks, left-handed neutrinos, the Higgs boson and so on – are stuck on a three-dimensional “sheet” called a three-brane.

One special property of right-handed neutrinos is that they do not feel the electromagnetic force, or the strong and weak forces. Arkani-Hamed and collaborators argued that right-handed neutrinos are not trapped on the three-brane in the same way that we are, rather they can move in the extra dimensions. This mechanism explains why we have never observed a right-handed neutrino and why their interactions with other particles in the Standard Model are extremely weak. The upshot of this approach is that neutrino masses can be very small.

The second way to extend the Standard Model involves particles that are called Majorana neutrinos. One advantage of this approach is that we no longer have to invoke right-handed neutrinos with extremely weak interactions. However, we do have to give up the fundamental distinction between matter and antimatter. Although this sounds bizarre, neutrinos and antineutrinos can be identical because they have no electric charge.

Massive neutrinos sit naturally within this framework. Recall the observer travelling at the speed of light who overtakes a left-handed neutrino and sees a right-handed neutrino. Earlier we argued that the absence of right-handed neutrinos means that neutrinos are massless. But if neutrinos and antineutrinos are the same particle, then we can argue that the observer really sees a right-handed antineutrino and that the massive-neutrino hypothesis is therefore sound.

So how is neutrino mass generated? In this scheme, it is possible for right-handed neutrinos to have a mass of their own without relying on the Higgs boson. Unlike other quarks and leptons, the mass of the right-handed neutrino, M, is not tied to the mass scale of the Higgs boson. Rather, it can be much heavier than other particles.

When a left-handed neutrino collides with the Higgs boson, it acquires a mass, m, which is comparable to the mass of other quarks and leptons. At the same time it transforms into a right-handed neutrino, which is much heavier than energy conservation would normally allow (figure 2*c*). However, the Heisenberg uncertainty principle allows this state to exist for a short time interval, Δt, given by $\Delta t \sim \hbar/Mc^2$, after which the particle transforms back into a left-handed neutrino with mass m by colliding with the Higgs boson again. Put simply, we can think of the neutrino as having an average mass of m^2/M over time.

This so-called seesaw mechanism can naturally give rise to light neutrinos with normal-strength interactions. Normally we would worry that neutrinos with a mass, m, that is similar to the masses of quarks and leptons would be too heavy. However, we can still obtain light neutrinos if M is much larger than the typical masses of quarks and leptons. Right-handed neutrinos must therefore be very heavy, as predicted by grand-unified theories that aim to combine electromagnetism with the strong and weak interactions.

Current experiments suggest that these forces were unified when the universe was about 10^{-32} m across. Due to the uncertainty principle, the particles that were produced in such small confines had a high momentum and thus a large mass. It turns out that the distance scale of unification gives right-handed neutrinos sufficient mass to produce light neutrinos via the seesaw mechanism. In this way, the light neutrinos that we observe in experiments can therefore probe new physics at extremely short distances. Among the physics that neutrinos could put on a firm footing is the theory of supersymmetry, which theorists believe is needed to make unification happen and to make the Higgs mechanism consistent down to such short distance scales.

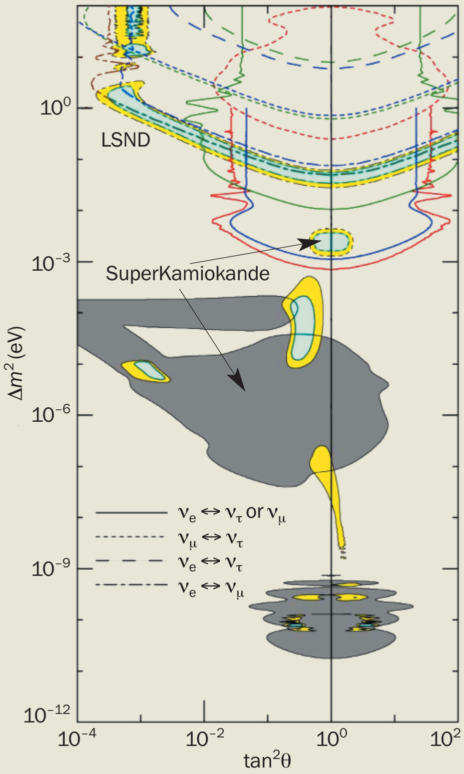
Why do we exist?

Abandoning the fundamental distinction between matter and antimatter means that the two states can convert to each other. It may also solve one of the biggest mysteries of our universe: where has all the antimatter gone? After the Big Bang, the universe was filled with equal amounts of matter and antimatter, which annihilated as the universe cooled. However, roughly one in every 10 billion particles of matter survived and went on to create stars, galaxies and life on Earth. What created this tiny excess of matter over antimatter so that we can exist?

With Majorana neutrinos it is possible to explain what caused the excess matter. The hot Big Bang produced heavy right-handed neutrinos that eventually decayed into their lighter left-handed counterparts. As the universe cooled, there was insufficient energy to produce further massive neutrinos. Being an antiparticle in its own right, these Majorana neutrinos decayed into left-handed neutrinos or right-handed antineutrinos together with Higgs bosons, which underwent further decays into heavy quarks. Even slight differences in the probabilities of the decays into matter and antimatter would have left the universe with an excess of matter.

It is encouraging that we have seen such a phenomenon recently. In the past three years, the KTeV experiment at Fermilab near Chicago and the NA48 experiment at CERN have established that the neutral kaon – a bound state of a down quark and anti-strange quark – and its antiparticle decay in a slightly different manner. At only one part in a million, this difference is very small. However, we only need one part in 10 billion for us to exist. If a similar difference in the decay probabilities exist in right-handed neutrinos, which is quite likely, it could have produced a small excess of primordial matter from which all the other particles have been formed.

4 Limits on neutrino properties



Previous experiments have failed to detect neutrino oscillations due to a lack of sensitivity. The lack of a signal, however, can be interpreted as a limit on the mass difference Δm^2 between types of neutrinos and the mixing angle, θ. This plot of Δm^2 as a function of $\tan^2\theta$ shows the regions inside the lines that are excluded. The grey region is excluded by SuperKamiokande. The solid lines are from searches for electron neutrinos (ν_e) transforming into any other type of neutrino. The limits on oscillations specifically between muon neutrinos (ν_μ) and tau neutrinos (ν_τ) are indicated by the dotted line, while the dashed line shows the results for ν_e to ν_τ oscillations. The dot-dashed line highlights the limits on ν_e to ν_μ oscillations. For experiments that are able to detect neutrino oscillations, the blue and yellow areas highlight the preferred values of Δm^2 and $\tan^2\theta$ with 90% and 99% confidence. The LSND experiment at the Los Alamos National Lab also reported evidence for neutrino oscillations, but this is unconfirmed.

Outlook

It is an exciting time for neutrino physics. Many experiments are currently under way – or are being constructed or planned – to put the evidence for neutrino mass on a more solid footing. Physicists prefer to use "man-made" neutrinos produced by accelerators or in nuclear reactors because these neutrinos can be controlled, unlike atmospheric or solar neutrinos.

The difficulty is that neutrinos only appear to oscillate over long distances, thereby motivating a series of so-called long-baseline experiments. The K2K experiment in Japan has already been running for a few years. It involves firing a beam of muon neutrinos produced in an accelerator at the KEK laboratory towards the SuperKamiokande detector, some 250 km away. So far the experiment has detected the disappearance of muon neutrinos due to neutrino oscillations, which is completely consistent with what we have learned from atmospheric neutrinos. An even better experiment called MINOS will extend the search for neutrino oscillations. Currently under construction, the neutrinos produced at Fermilab will be sent a distance of 750 km to the Soudan mine in Minnesota, and there are similar plans to fire muon neutrinos produced at CERN towards detectors at the Gran Sasso Laboratory in Italy. Particle physicists there are also hoping to detect tau leptons produced by the oscillation of muon neutrinos into tau neutrinos.

Last year the SNO collaboration upgraded its detector in an effort to detect muon neutrinos or tau neutrinos directly. On the rare occasions when these neutrinos interact in the detector, they break up the deuterium nuclei in the heavy water to release neutrons. In order to count the muon neutrinos and tau neutrinos, the SNO team added purified sodium chloride, which captures the neutrons. And another experiment called KamLAND in Japan is studying antineutrinos from commercial nuclear-power plants some 175 km away. Researchers there are hoping to establish that electron neutrinos do indeed convert to other types of neutrinos.

In the longer term, there are serious discussions about sending neutrinos thousands of kilometres. Beams produced at Fermilab or Brookhaven, for example, could be fired towards experiments in Japan or Europe. Also, a serious effort is being made to observe the conversion of matter and antimatter using a rare process in nuclei called neutrinoless double beta decay. In this reaction, which is forbidden by the Standard Model, two neutrons decay into two protons and two electrons without emitting any antineutrinos. Recently Hans Klapdor-Kleingrothaus and co-workers at the Max Planck Institute for Nuclear Physics in Heidelberg claimed to have observed such a process, but the evidence is far from conclusive (see *Physics World* March p5).

Conclusion

We are at an amazing moment in the history of particle physics. The Higgs boson, the mysterious object that fills our universe and disturbs particles, will be found sometime this decade, and evidence for neutrino mass appears very strong. The Standard Model, which was established in late 1970s and has withstood all experimental tests, has finally been found to be incomplete. To incorporate neutrino mass into the theory – and to explain why it is so small – requires major changes to the Standard Model. We may need to invoke extra dimensions or we may need to abandon the sacred distinction between matter and antimatter. If the latter is the case, neutrino mass may reveal the very origins of our existence. One thing is certain, we are sure to learn a lot more about neutrinos in the coming years.

Further reading

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