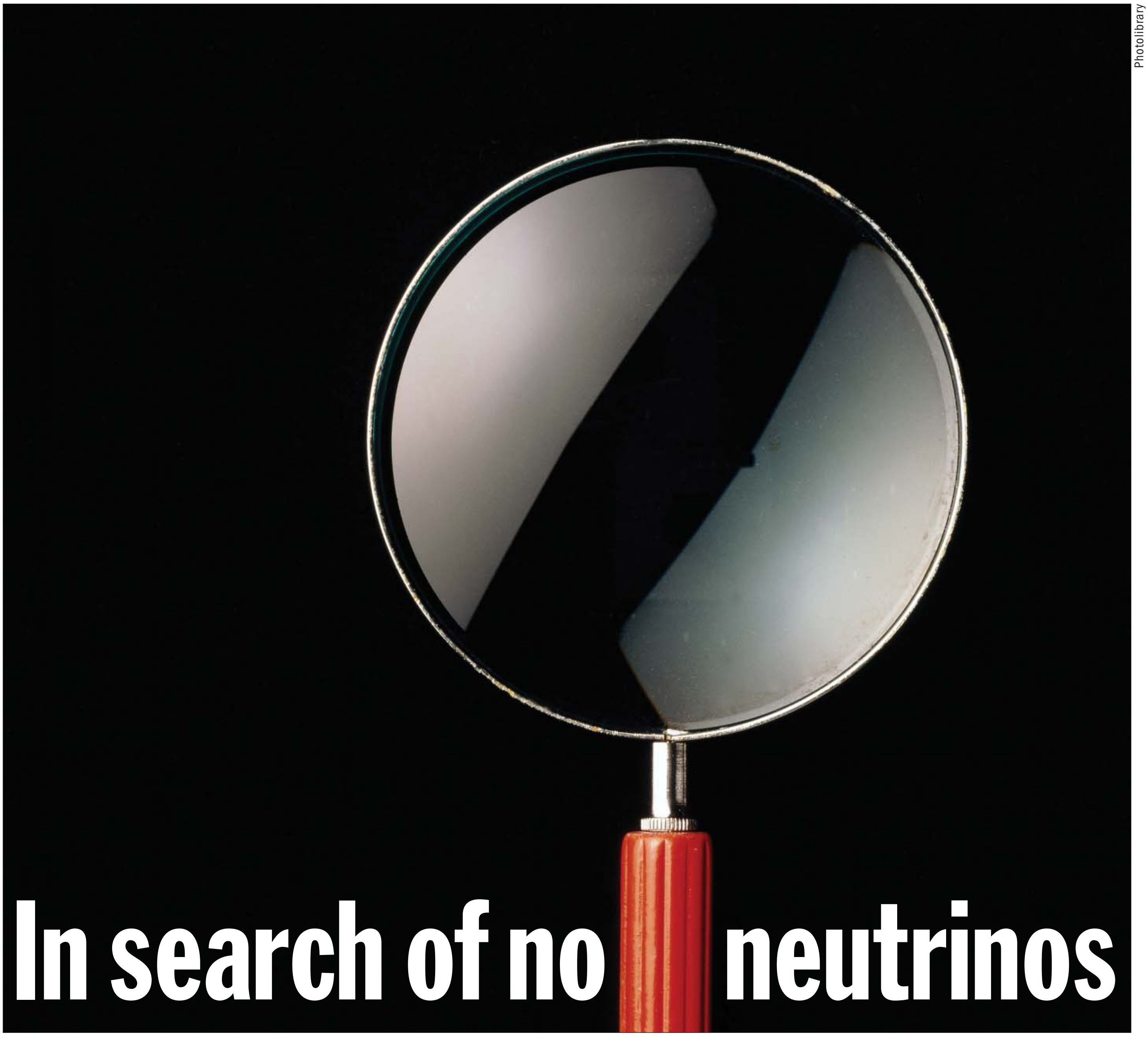


Photolibrary

In search of no neutrinos

Neutrinos were first observed almost 60 years ago by observing beta decay. **Giorgio Gratta** and **Naoko Kurahashi** explain why physicists are now on the lookout for an exceedingly rare variation of this process in which no neutrinos are created

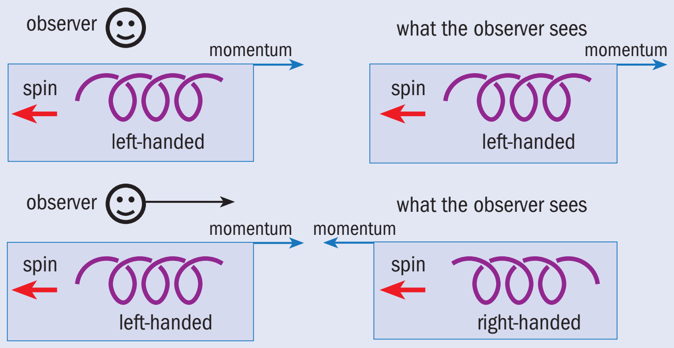
As you sit down to relax and read this article, take a moment to consider that more than 10 million neutrinos created in the Big Bang are traversing your body at any one time. These tiny subatomic particles have been travelling across the universe for the last 13 billion years, carrying the fingerprints of the primordial cosmic explosion. As they course through your body they will ignore it, because – challengingly for anyone wishing to study these particles experimentally – the probability of neutrinos interacting with matter is so minute that they can cross entire planets or stars without being disturbed.

First postulated in 1930 by Wolfgang Pauli and eventually observed by Frederick Reines and Clyde Cowan in 1953, neutrinos were originally thought to have no mass. But in the last 20 years, researchers at several underground neutrino detectors around the world showed that in fact these particles, which come in three different types or "flavours", do have masses – albeit very small ones. However, their technique, which relies on a sophisticated type of interferometry, is only able to determine the mass *differences* between the three types of neutrino, leaving their *absolute* masses unmeasured.

For many years it has been known that there might be a way to probe the absolute mass of neutrinos: by measuring the half-life of a very rare nuclear process known as neutrinoless double beta decay. This decay can only occur if the quantum nature of neutrinos is of a novel type, in which the distinction between particles

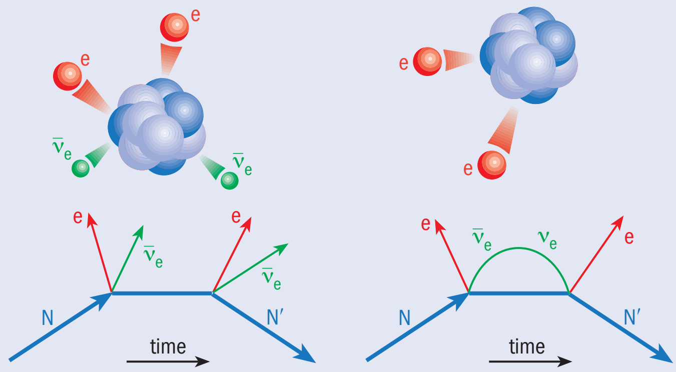
Giorgio Gratta is a professor of physics in the department of physics and **Naoko Kurahashi** is a postgraduate student in the department of applied physics, both at Stanford University, US, e-mail gratta@stanford.edu

1 A handy explanation



In the upper part of the figure, the handedness of a particle of finite mass is shown as seen by an observer in a reference frame that is at rest with respect to the page. In the lower part of the figure, the same particle is analysed from the point of view of an observer travelling at a faster speed, in such a way as to overtake the particle. In this reference frame the momentum of the particle appears to be flipped backwards with respect to the previous case, while the direction of the spin does not change. This shows that for a non-relativistic particle, the handedness depends on the choice of reference frame.

2 Double beta decay



Illustrations (top) and Feynman diagrams (bottom) showing (left) two-neutrino double beta decay and (right) zero-neutrino double beta decay. In the Feynman diagrams, the blue arrows represent the nucleus that is decaying, while the other arrows represent particles that are emitted. Lines without an arrowhead that connect two vertices represent "virtual" particles that cannot be seen or detected. N, nucleus before decay; N′, nucleus after decay; e, electron; ν_e, electron neutrino; $\bar{\nu}_e$, electron antineutrino.

and antiparticles is somewhat blurred.

But this is no pipe dream – hidden deep in underground sites around the world are a number of large detectors that seek to observe this extremely uncommon decay. These experiments, which are now starting up, could soon not only provide values for the neutrino masses, but also reveal that neutrinos are their own antiparticles.

What we know and what we do not know

Neutrinos make up three of the 12 known fundamental matter particles, which cannot be divided into more parts. The neutrinos ("little neutral ones" in Italian) have no charge and fall into the category of "leptons", along with the much more massive charged electron, muon and tau leptons. When a neutrino is produced, it exists in one of its three flavours as an electron-, muon- or tau-neutrino – depending on the charged lepton with which it was simultaneously created.

The remaining six elementary matter particles are quarks. Both quarks and charged leptons experience the electromagnetic force, and quarks also feel the strong force. These forces cause the particles to interact frequently with other matter particles. But having no charge, neutrinos can only feel the weak and gravitational forces, and hence interact very little with matter. Around this simple fact revolve many of the difficulties of experimental neutrino physics. As an example, the mean free path in lead for neutrinos with energies similar to those produced in nuclear reactors is about a third of a light-year.

Neutrino detectors need to be huge and run for a long time for researchers to stand a chance of observing their prey

Neutrino detectors therefore need to be huge and run for a long time for researchers to stand a chance of observing their prey. Combined with the tricky task of building a detector that is not swamped by an overwhelming background from other types of nuclear radiation, this makes neutrino detection extremely challenging, and the data we have collected preciously scarce.

A groundbreaking experiment carried out by Maurice Goldhaber and collaborators in 1957 – only four years after the first experimental observation of neutrinos – found that these particles are always emitted with left-handedness, which means that a particle's spin is oriented in the opposite direction to its momentum. Given that the only way to probe a neutrino is to make it interact with something, handedness, like any other property, can only be defined in the context of an interaction. In fact, weak-force interactions are the only method by which we can "measure" the handedness of the neutrino, and so neutrino handedness was incorporated into the Standard Model of particle physics – the ultimate rule book for how fundamental particles interact with one another – by requiring that only left-handed neutrinos and right-handed antineutrinos participate in interactions involving the weak force.

The implications of the fact that neutrinos are left-handed and antineutrinos are right-handed are far more profound than they may at first appear. As figure 1 shows, the handedness of a particle can change sign by moving from one reference frame to another. In this scenario there is no way to assign an "absolute" handedness to the particle – unless the particle is massless. If the mass of the particle is zero, then, according to special relativity, the particle will move at the speed of light and no reference frame will be able to overtake it and see it. In this case, the handedness is an absolute property of the particle. Neutrinos were therefore "coded" in the Standard Model as particles with zero mass and fixed handedness, and for a long time no better measurement was able to challenge this assertion.

But such a challenge did come, and showed us that we were wrong. Neutrinos do in fact have mass. This was discovered by observing the strange phenomenon of "neutrino oscillation", which involves neutrinos changing between their three different flavours as they propagate through space (see box opposite). But the problem with neutrino oscillation, big breakthrough though it was, is that it tells us nothing about the absolute masses of the neutrinos, only the mass differences between the different flavours.

Enter the massive Majorana particle

In nuclear physics the simplest phenomenon involving neutrinos is "beta decay", a process within a nucleus in which a neutron decays into a proton, an electron and an electron antineutrino. This type of nuclear decay is very common and it is responsible for much natural and artificial radioactivity.

Figure 2 shows a more exotic process in which the beta decay repeats itself twice, in such a way that the state in between the two decays cannot be seen or measured. This "double beta decay" process can occur in two distinct ways. Two-neutrino double beta decay is a conventional process in that the Standard Model predicts its existence and it does not violate any of the known laws of physics. This is not the case, however, for zero-neutrino (or neutrinoless) double beta decay, which violates a number of physical laws enshrined in the Standard Model. If this decay were discovered experimentally, it would reveal some unknown physics that the Standard Model is currently unable to describe.

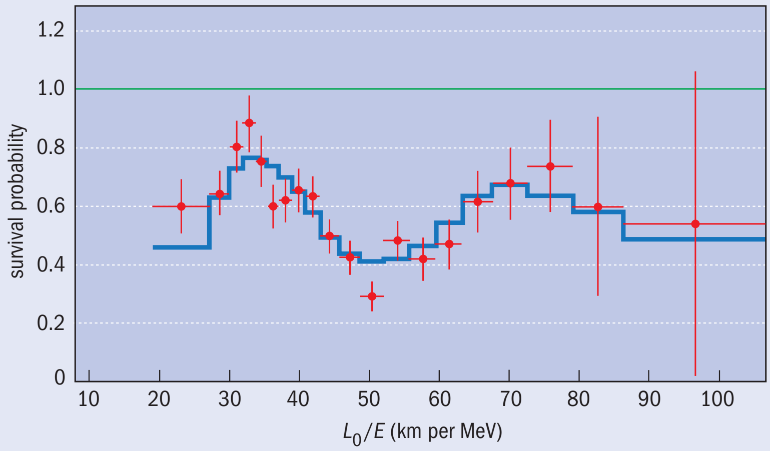
For example, over the years particle physicists have noticed that no process seems to change the "lepton number" – this is the total number of leptons minus the total number of antileptons. Therefore, it was postulated that the lepton number would always be conserved. We do not have a deep reason to justify this rule, we have just never seen it violated. Two-neutrino double beta decay conserves lepton number, as in the initial state there are no leptons, just a nucleus, and in the final state the total lepton number cancels to zero. But the neutrinoless decay on the right-hand side of figure 2 has a lepton number of two in the final state, thus violating conservation of lepton number.

Another peculiar feature of neutrinoless double beta decay is that it blurs the definition of particles and antiparticles. The Standard Model describes the neutrino, like all the matter particles, as having a complementary antiparticle with equal mass but opposite electrical charge. These are known as "Dirac particles", named after Paul Dirac who proposed them in 1928. In the 1930s the enigmatic physicist Ettore Majorana developed a theory of another type of particle that does not require distinct particle/antiparticle states. These are now known as "Majorana particles". This could suit neutrinos, which have no electrical charge and so could conceivably act as their own antiparticle.

Double beta decay could show us this. It requires two antineutrinos to be emitted, which according to quantum physics is equivalent to two neutrinos being absorbed. More interestingly, it is also equivalent to one antineutrino being emitted and one neutrino being absorbed. If neutrinos are their own antiparticles, then an emitted antineutrino could be re-absorbed as a neutrino, as shown on the right-hand side of figure 2, resulting in a neutrinoless double beta decay in which no neutrinos are observed.

So we have seen that merely discovering that neutrinoless double beta decay happens would unveil two new pieces of physics: that lepton number is not always conserved; and that Majorana particles do exist in nature. But what about the actual neutrino masses? For this we need to go back to the concept of handedness: a requirement for the neutrinoless double beta decay is that handedness is not fixed for neutrinos, thereby allowing, for instance, a neutrino emitted as left-handed to be re-absorbed as right-handed. If this neutrinoless decay exists, neutrinos would therefore have to be ambidextrous. This means that they could flip between being left-handed and right-handed, implying that they must travel slower than the speed of light and therefore have mass.

Neutrino oscillations and why they imply mass



Adapted from the KamLAND Collaboration

Often in physics, the most sensitive measurements are obtained by interferometry – that is, by measuring the small difference in frequency between two waves. The simplest example of this concept is the "beat" one hears when listening to two musical notes that have nearly the same pitch – i.e. nearly the same frequency. Together, the two sounds interfere, so that their overall superposition has peaks and troughs. This is perceived by the listener as the note cyclically rising and falling in volume, the rate of which is equal to the difference between the two frequencies. This is the time-honoured way to tune musical instruments and its extreme sensitivity derives from the fact that the frequency difference is the quantity directly detected.

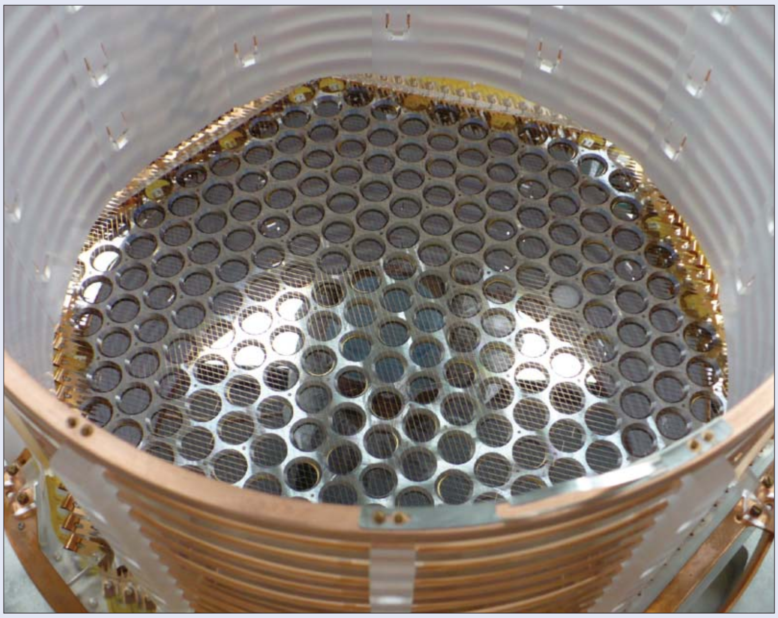
Quantum mechanics provides a way to use this technique for neutrinos (as well as for many other systems). In fact, neutrinos, like all particles, can be described by Schrödinger waves, the square of which provides the probability of finding the particle in a particular place. A small difference in the three neutrino masses will result in a "beat" that manifests itself in a rate of detections that depends on the flight pathlength of the neutrinos. (The beat cannot be detected as a modulation in time for a number of technical reasons.) Exactly massless neutrinos would produce no beats. Observing this subtle phenomenon is a most exquisite way to measure the mass difference between neutrinos.

Researchers have so far determined two mass differences between the three neutrino flavours – 0.009 eV and 0.05 eV – although they do not yet know which flavours they are between. These are remarkably small differences in comparison with the next lightest particle – the electron, which has a mass of 500 000 eV.

The simplest evidence of oscillation is data collected by the KamLAND collaboration in Japan, showing the quantum "beat" produced by (anti)neutrinos emitted by nuclear reactors and detected about 100 km away. In this case the variable "scanning" the beats is the ratio L_0/E – the neutrino flight distance, L_0, divided by its energy, E. In the figure above, the vertical axis shows the probability that the antineutrino flavour stays the same as when it was produced at its source. The blue line shows the theoretical model for neutrino oscillation, and the KamLAND measurements are plotted in red. The horizontal green line represents the expectation in the case of no neutrino oscillation. The close agreement between model and experiment provides one of the most persuasive illustrations of neutrino oscillation.

While the interferometric method allows us to detect mass differences and to assert that neutrinos are not massless particles as was coded in the Standard Model, it says nothing about the absolute masses of the neutrinos. If we knew the mass of – say – the lightest neutrino, then we could use the data from oscillations to compute the masses of the other two neutrino states.

3 EXO-200 awaits its summer switch on



EXO Collaboration

The EXO-200 double-beta-decay detector is a cylinder 40 cm in diameter that will be filled with about 200 kg of xenon enriched to 80% with the isotope ^{136}Xe. Double beta decay reveals itself by producing two electrons, which in turn cause xenon atoms to emit light. The large, silver-coloured avalanche photodiodes detect the "scintillation" photons emitted in this process. Barely visible above the photodiodes is an array of wires that collects the emitted electrons using an electric field, allowing their energy to be accurately measured. The energy spectrum of the two electrons is very different in the case of two-neutrino decay and the much rarer neutrinoless decay that we are after. All materials in the detector are exceptionally pure and free from radioactive contaminations.

Going back to figure 1, it is easy to imagine that the heavier the neutrino is, the slower it propagates and the more likely it is to be overtaken, thus "flipping" the perceived handedness. Measuring the rate of neutrinoless double beta decay tells us how likely it is for the handedness flip to occur. This rate, in turn, tells us how massive the neutrino is. Now we have a way to probe the absolute masses of the neutrinos.

A rare detection

From many years of observation, we know that neutrinoless double beta decay, if it exists, is exceedingly rare – we have not yet seen it. This allows us to pin down the current limit for the mass of the neutrino at about 1 eV (tiny masses are often quoted in electron-volts). In general this corresponds to neutrinoless-decay half-lives longer than 10^{24} years, which means that it would take 10^{24} years – an incredible 10^{14} times the age of the universe – for half of a sample of nuclei that can undergo neutrinoless double beta decay to do so. The strategy to deal with such a slow decay is to observe an extremely large sample of nuclei for a reasonably long time – say a few years – and measure the half-life from the very few decays that we hope to observe. In practice we are talking about being able to discern a few neutrinoless double beta decays per year in tonnes of nuclei, on top of thousands of two-neutrino double beta decays.

Experimentally, we face two main challenges: shielding detectors to give minimal background radiation; and obtaining large amounts of the appropriate nuclear isotopes. These are no mean feats, as many natural nuclear processes occur every second in tonnes of standard matter. Materials used for the construction of double-beta-decay detectors must therefore be billions of times less radioactive than the ground we stand on. Researchers must also try to block out the cosmic rays that continuously bombards matter, producing radioactive elements and spraying the detectors with spurious nuclear fragments. This flux of cosmic particles is substantially attenuated by placing the detectors underground. Since some of the particles coming from outer space are extremely energetic, hundreds of metres or kilometres of rock are required for this purpose. The only practical solution is to use a mine or tunnel so that the huge amount of shielding material necessary is provided by nature.

Not all nuclei can undergo double beta decay and, as it turns out, the isotopes that are suitable for studying the decay are not particularly common in nature. Most experiments are resorting to isotopic enrichment, the same process used to produce fuel for nuclear reactors and weapons, to increase the concentration of the right isotopes. Future experiments are seeking to produce tonnes of enriched material – another technical challenge.

As an example, figure 3 shows part of the Enriched Xenon Observatory's EXO-200 detector (which one of us, GG, is working on). EXO-200 is so called because it uses 200 kg of ^{136}Xe – one of xenon's nine stable isotopes. This source of double beta decay is kept in its liquid form by cooling it to –100 °C. Located deep underground in a salt mine in New Mexico, EXO-200 is currently the world's largest double-beta-decay detector and is set to start taking data this summer. The ultimate goal is to search for neutrinoless double beta decay in several tonnes of xenon in a larger-scale experiment planned to follow later this decade. Other major experiments installed in Europe, Japan and North America are using the isotopes ^{130}Te, ^{76}Ge, and ^{150}Nd.

Particle physicists around the world will now cross their fingers and toes in the hope of discovering neutrinoless double beta decay, which would settle some issues and yet raise so many further questions. Although a group in Heidelberg, Germany, led by Hans Klapdor-Kleingrothaus controversially claimed to have detected the decay back in 2002, many particle physicists consider the evidence provided to be far from conclusive. This time, physicists are making sure that if a detection is made, it is beyond contestation. This is a challenging undertaking, but if neutrinoless double beta decay is found, it will be worth it.

Unravelling the mysterious characteristics of neutrinos and, in particular, measuring their masses is one of the great challenges of modern particle physics. And given that neutrinos have played a central role in the formation of the universe as swift energy carriers, and in the dynamics of very energetic astrophysical phenomena such as supernova explosions where they carry away 99% of the energy, understanding their properties will feed essential information into these fields of science as well as many others. The search for neutrinoless double beta decay has a central role to play in this quest. Around the world, the race is now on for a confirmed detection of no neutrinos.