Tracking neutrino oscillations

Physicists are firing neutrinos hundreds of kilometres through the Earth's crust and then measuring their properties using enormous underground detectors. Edwin Cartlidge explains why

Fermilab

For Konrad Elsener and colleagues working at the Gran Sasso National Laboratory in central Italy, the idea of looking for a needle in a haystack must seem trivial by comparison. Their aim is to detect subatomic particles known as neutrinos that are fired in a beam from the CERN particle-physics laboratory in Geneva, travel 730 km through the Earth's crust in central Europe and arrive at their detector under the Gran Sasso mountain. Making such detections will be extremely difficult because neutrinos react so weakly with other matter – the researchers expect that of the roughly 10^{14} neutrinos to arrive at their huge lead detector each year only one or two will interact with the nuclei in it.

The scientists working on the CERN to Gran Sasso (CNGS) project, which started up last month, are not alone in their quest. In the US, researchers working on a similar “long-baseline” neutrino experiment called the Main Injector Neutrino Oscillation Search (MINOS), some 735 km in length, have recently announced their first results. Both experiments are designed to study the mysterious phenomenon of neutrino oscillation, in which neutrinos change from one

of three “flavours” – electron, muon or tau – into another as they travel through space. This phenomenon requires that neutrinos have mass, in contradiction with the Standard Model of particle physics.

Previous experiments have demonstrated the principle of neutrino oscillation. But scientists have still to prove which of the different types of oscillation are possible – i.e. which flavours can oscillate into which other flavours. They also have a very limited understanding of some of the basic properties of neutrino oscillation. In particular they would like to know whether neutrinos and antineutrinos oscillate differently. Such a difference could point to a fundamental contrast in the behaviour of matter and antimatter, which might explain why today the universe appears to consist solely of matter – even though equal quantities of matter and antimatter were believed to have been created in the Big Bang. “We have proved that neutrinos oscillate,” says Dave Wark, a physicist at Imperial College London and a member of the Sudbury Neutrino Oscillation (SNO) collaboration in Canada. “But we do not understand the details of the process or what the implications are.”

Mining neutrinos
The MINOS neutrino experiment in the US.

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Penetrating physics In the CNGS project, a beam of muon neutrinos created at CERN in Geneva is fired through the Earth (no tunnel needed) towards a detector at the Gran Sasso laboratory in central Italy. The aim is to observe muon neutrinos oscillate into tau neutrinos.

From theory to practice

Neutrino oscillation is a fundamentally quantum-mechanical phenomenon. When neutrinos arrive at the detectors they do so in one of the three specific flavours. But because neutrinos have mass, we can represent the wavefunction of a particular flavour as a superposition, or “mixing”, of three mass states. It is these mass states, rather than the flavour states, that propagate through space and allow neutrinos to oscillate.

An electron neutrino generated by the fusion reactions in the Sun, for example, will contain a specific mixing of the three mass states, each of which has a well-defined de Broglie wavelength. Because each mass, and therefore wavelength, is different, the phase difference between the mass states will change as the waves propagate. In time the phase difference associated with an electron neutrino will instead equal that of a muon or tau neutrino, in other words the electron neutrino will have oscillated into a different flavour.

The theory of neutrino oscillation involves a number of parameters: three “mixing angles” (θ_{12} , θ_{13} , θ_{23}), which define the extent to which each of the mass states is mixed into each flavour state; two squared “mass differences” (Δm_{32}^2 , Δm_{21}^2), which provide a value for the difference in mass between the mass states; and a phase, δ , that is related to possible differences between matter and antimatter (*Physics World* June 2005 pp29–36).

Early experiments by Ray Davis in the US and by Masatoshi Koshiba in Japan demonstrated that electron neutrinos do seem to disappear *en route* from the Sun. Then in 1998 the SuperKamiokande experiment demonstrated that muon neutrinos made by cosmic rays in the Earth’s atmosphere also seem to disappear in a way that depends on how far they have travelled. SNO subsequently proved that solar neutrinos were actually changing flavour. Meanwhile, the KamLAND experiment, built in the same underground cavern in Japan as SuperKamiokande, showed that electron antineutrinos produced by nuclear reactors were disappearing on the way to the detector. Finally, the K2K long-baseline experiment in Japan observed the disappearance of artificially created muon neutrinos. Physicists believe that when considered together, these results can only be explained if neutrinos oscillate.

Both MINOS and CNGS are designed to study the

oscillation of muon neutrinos into tau neutrinos, mimicking the process that is believed to be taking place in the atmosphere and which was also studied at K2K. But the two experiments take different approaches. In the \$170m MINOS experiment, a beam of muon neutrinos created at Fermilab travels through the Earth to the Soudan mine in Minnesota. The composition of the beam is measured as it leaves Fermilab and then again when it arrives at Soudan, so that researchers can work out how many muon neutrinos disappear *en route*. The detector at Soudan is a 6000 tonne iron calorimeter immersed in a magnetic field, which measures the momentum of the charged muon particles generated by neutrinos in the iron.

Having taken data for just under a year, the Soudan detector has recorded 215 events that are believed to correspond to muon neutrinos. This compares with the 336 ± 21 events that would be expected if the muon neutrinos did not change flavour, therefore providing strong evidence of neutrino oscillation. The experiment also provides a value for Δm_{32}^2 of 0.0027 eV^2 . According to MINOS spokesperson Stan Wojcicki of Stanford University, over its five-year lifetime the experiment should collect about 15 times more data than K2K.

On the other hand, CNGS, which cost €110m, will not measure how many muon neutrinos disappear but how many tau neutrinos appear. A tau neutrino interacting with a lead nucleus in the 1800 tonne OPERA detector at the Gran Sasso lab will produce a charged particle known as a tau lepton, which then decays, usually into an electron. Physicists will observe the tracks of the electrons left in a series of layers of photographic emulsion and may even be able to image the tracks left by the tau leptons themselves, although these will be less than a millimetre long. The beam at CERN was turned on in July, having been delayed for a couple of months, and is expected to reach full intensity this month. But with only about two tau neutrinos expected to be detected per year, it is likely that the first sighting will not happen until 2007.

The CNGS collaboration is also hoping to use a second detector, called ICARUS, to observe tau neutrinos. This would use an entirely different, and complementary, technique to OPERA – observing electrons, muons and a wide range of secondary particles given off by the interaction of the incoming neutrinos with nuclei in a large tank of liquid argon, allowing the researchers to work back to the interaction without actually observing the motion of the tau lepton. Unfortunately ICARUS will probably not come online for several years, if at all, because of increased scrutiny of experiments at Gran Sasso following the accidental leakage of a volatile liquid from the lab into a nearby mountain river three years ago.

A new angle

So how will these two experiments contribute to our understanding of neutrinos? CNGS project leader Konrad Elsener admits that some physicists believed it was unnecessary to build CNGS when other experiments had already proved the existence of neutrino oscillations. But he points out that nobody has yet directly measured the flavours that neutrinos oscillate

Weighty issues The 1800 tonne OPERA detector at the Gran Sasso laboratory in Italy.

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into. It is still possible that the disappearing muon neutrinos in the atmospheric and long-baseline experiments are not oscillating but decaying or disappearing off into higher dimensions. "One experiment to look for the appearance of tau neutrinos has its place," he says. "Positive results from this experiment would completely remove the speculation."

CNGS and MINOS may also be able to resolve one of the major outstanding uncertainties in neutrino physics – the value of the mixing angle θ_{13} (θ_{12} and θ_{23} having already been measured precisely). This parameter can be calculated by measuring the oscillation of muon neutrinos into electron neutrinos, since θ_{13} is one of a number of variables that makes up the complicated mathematical description of this particular oscillation. But this oscillation is much weaker than the main muon to tau transformation, and it remains to be seen whether the beams for the CNGS and MINOS experiments are intense enough to make this measurement. The θ_{13} mixing angle is currently only known to be less than 10° : if it is just below this value, then the current experiments may be able to study it, since the larger the mixing angle, the larger the oscillation effect; but if it is significantly lower, then physicists will have to wait for the results from the next generation of neutrino-oscillation experiments.

Among these will be T2K, a more powerful version of K2K that is scheduled to start taking data in 2009, and an upgrade of MINOS known as NOvA (should it receive funding). As well as measuring θ_{13} , T2K and NOvA may also be able to determine the ordering of the different mass states. Results from experiments thus far have left physicists with two possible orderings for the three masses.

The other unknown that may be accessible to T2K and NOvA is the neutrino-oscillation phase, δ , a non-zero value of which implies a difference in the oscillation of neutrinos and antineutrinos, and, via a process known as charge-parity violation, could help explain the existence of matter in the universe. Whether or not these experiments can obtain this measurement depends on the value of δ . If they cannot, physicists will have to hope that they can raise the billions of dollars needed to build a "neutrino factory", a source of very pure and intense neutrino beams that could be fired thousands of miles through the Earth to distant detectors.

Wark, for one, believes the scientific case is strong enough to merit the construction of a neutrino factory and a number of other less-expensive intermediate oscillation projects. He believes that only then will we truly understand the nature of the neutrino. "There is still much to do," he says. "To stop now would have been like stopping all nuclear-physics experiments after Rutherford's discovery of the nucleus."

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