

Neutrinos: an introduction

What do continental drift, nuclear power stations and supernovae have in common? Neutrinos, as **Susana Cebrián** explains.

What are neutrinos?

Neutrinos, meaning 'little neutral ones', are everywhere, all around us. These tiny elementary particles travel through space at close to the speed of light and have no charge. They were once thought to have no mass either, but scientists now suggest that they *do* have a mass; it is estimated to be less than a billionth of the mass of a hydrogen atom, but the research continues^{w1}.

The existence of neutrinos, among the most abundant particles in the Universe, was first postulated by

Austrian physicist Wolfgang Pauli in 1930 to explain observations of radioactive beta decay. It was not until the first nuclear power stations were built, though, that a sufficiently high flux of neutrinos (actually their antiparticles, antineutrinos; see Landua & Rau, 2008, for more information on antiparticles) from decaying fission fragments was available to confirm their existence. In 1956, Clyde Cowan and Frederick Reines built two large water-filled tanks underground, mere metres away from the nuclear power plant at Savannah River near Aiken,

The Super-Kamiokande detector tank is filled with water



- ✓ Physics
- ✓ Earth science
- ✓ Particle physics
- ✓ Astrophysics
- ✓ Ages 14+

Neutrinos are strange particles – small but fascinating. This article describes their origin, properties and detection in an accessible way and with sound facts. It makes good background reading for physics teachers, but can also be a starting point for students doing a presentation project on the topic or to stimulate further discussions, e.g. about particle physics in general, the standard model, detector physics, CERN, astrophysics or radiation.

The article is mainly useful for physics lessons, but it contains links to earth science. To make the topic accessible to younger students (about the age of 14) as well, I would suggest the teacher selects parts of the article to discuss.

Gerd Vogt, Austria

REVIEW

South Carolina, USA, in which the antineutrinos interacted with the water's protons (see diagram below). Frederick Reines was awarded the Nobel Prize in Physics in 1995^{w2} for this experiment. Clyde Cowan could not share the prize, because he had passed away in 1974.

Neutrinos come in three types or *flavours*, according to the standard model of particle physics (see image, right): the *electron neutrino*, *muon neutrino*, and *tau neutrino*, which have all been confirmed experimentally. For the detection of the muon neutrino, Leon M Lederman, Melvin Schwartz and Jack Steinberger were awarded the Nobel Prize in Physics in 1988^{w2}.

A fourth, 'sterile' type has been proposed, which is immune to the weak force of the standard model, and recent data including a refined calculation of measurements performed at the Institut Laue-Langevin^{w3} in Grenoble, France, in the 1980s support this idea (Hand, 2010; Reich, 2011). Were sterile neutrinos to be found, a new realm of physics beyond the standard model would open up.

Even the three confirmed types of neutrinos are special: they oscillate from one flavour to another – electron, muon and tau neutrinos change from one to another. This phenomenon was first observed in 1998 by the Japanese

Image courtesy of PBS NOVA; image source: Wikimedia Commons

Three generations of matter			Bosons (forces)	
Mass	I	II	III	
Charge	2/3	2/3	2/3	0
Spin	1/2	1/2	1/2	0
Name	u up	c charm	t top	γ photon strong force
Quarks	4.8 MeV -1/3 d down	104 MeV -1/3 s strange	4.2 GeV -1/3 b bottom	0 1 g gluon electromagnetic force
Leptons	0.5 MeV -1/2 ν_e electron neutrino	105.7 MeV -1/2 ν_μ muon neutrino	1.777 GeV -1/2 ν_τ tau neutrino	91.2 GeV 0 Z weak force
	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau	91.2 GeV +2 W weak force

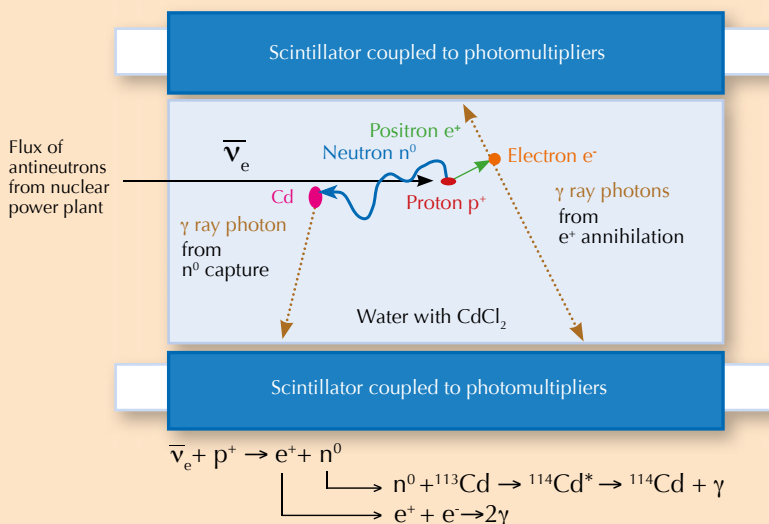
The standard model of particle physics. Matter particles come in two different types, leptons and quarks, forming a set of 12 particles, divided into three generations, each consisting of two leptons (one of which is a neutrino) and two quarks. Matter particles can 'communicate' with each other in different ways by exchanging different types of messenger particles named bosons (a different boson for each of the fundamental interactions), which can be imagined as little packets of energy with specific properties. The masses of certain particles are still being investigated by the scientific community; these are values from 2008

Super-Kamiokande experiment^{w4}, in which muon neutrinos generated in the atmosphere were found to 'disappear', presumably into tau neutrinos. A recent experiment has now successfully observed such an event from the other perspective – as an appearing tau neutrino rather than a disappearing muon neutrino: after three years in which a beam of muon neutrinos was released at CERN^{w5} in Geneva, Switzerland, a tau neutrino was detected in 2010 by the OPERA detector at the Gran Sasso National Laboratory^{w6} in Italy, 730 km away (see images on page 57). The detection of the oscillations also solved a 40-year-old mystery: scientists had

always found many fewer electron neutrinos arriving from the Sun than expected. In 2001, the Solar Neutrino Observatory^{w7} in Canada demonstrated that they changed into neutrinos of other flavours on their way to Earth (Bahcall, 2004). Further experiments to analyse neutrino oscillations are underway, for example in France and Japan, where accelerators and nuclear power stations provide large numbers of antineutrinos for observation^{w8}.

Where do neutrinos come from?

Neutrinos first originated some 14 billion years ago, 10^{-43} seconds after the Big Bang. A mere second later, they were already rapidly moving



The Reines and Cowan experiment: electron antineutrinos ($\bar{\nu}_e$) interact with the water's protons (p^+) in a big tank filled with water and cadmium chloride ($CdCl_2$); as a result, positrons (e^+ , the antiparticles of electrons) and neutrons (n^0) are produced. Positrons are annihilated when they encounter electrons from the medium (e^-) and neutrons are absorbed by the cadmium (Cd) nuclei. Both these reactions result in the release of gamma ray photons (γ) which are detected by means of scintillators. These transform the signal into flashes of visible light, which can then be detected and processed by photomultiplier tubes

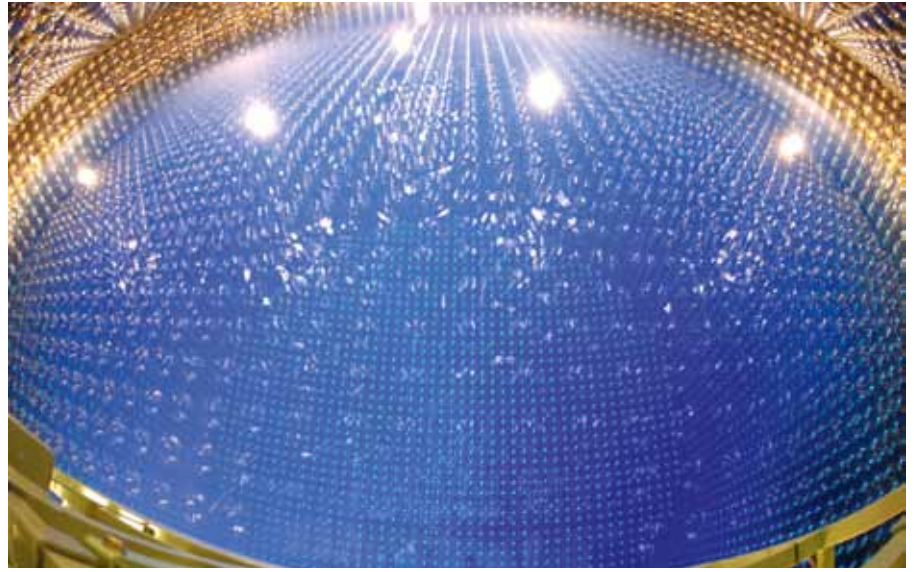
Image courtesy of Susana Cebrián

Image courtesy of CERN



The OPERA detector at the Gran Sasso National Laboratory in Italy

Image courtesy of Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo



The Super-Kamiokande tank, nearly full of water, seen from above

away from the rest of the hot and dense primary particle soup; scientists are still seeking to detect neutrinos that survive from the Big Bang.

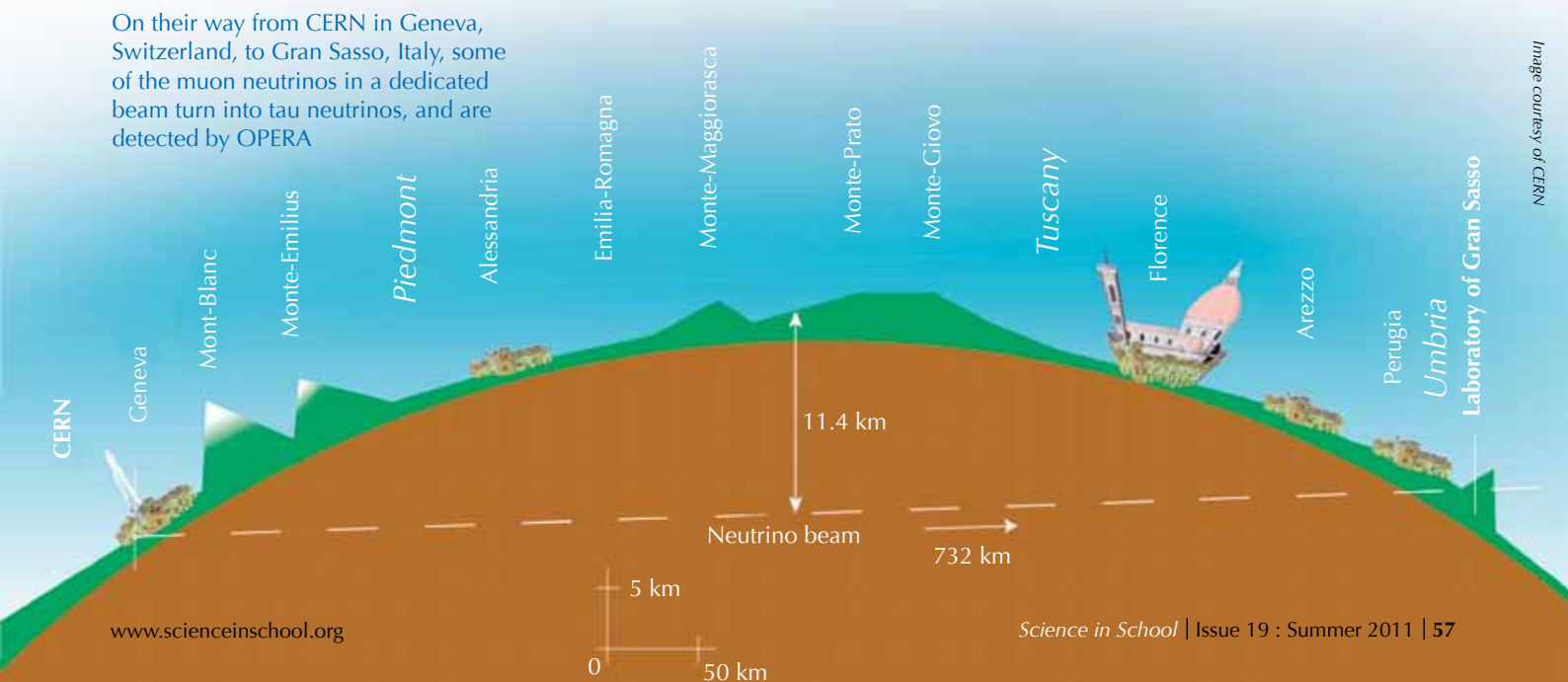
It is neutrinos' weak interaction with matter that makes them almost impossible to detect, but it is also what makes them of interest to scientists. Unlike most other particles, neutrinos are able to escape from dense regions such as the core of the Sun or the Milky Way, and they can travel long distances from far-away galaxies without being absorbed, carrying

information about these areas. In this sense, neutrinos are cosmic messengers, and neutrino astronomy is becoming increasingly important.

So far, only two sources of extraterrestrial neutrinos have been observed: the Sun and supernovae. Raymond Davis Jr and Masatoshi Koshiba won the third neutrino Nobel Prize in Physics in 2002^{w2} for their detection of solar and supernova neutrinos. Like other stars, the Sun emits electron neutrinos at several steps of the process by which light nuclei fuse into

heavier ones (see image on page 58, and to learn more, see Westra, 2006, and Boffin & Pierce-Price, 2007); more than 10^{10} solar neutrinos hit a square centimetre of Earth every second. Unlike photons, which take about 100 000 years to travel from the core of the Sun to its outer photosphere before speedily travelling to Earth, neutrinos released in the same fusion process do the entire trip in a mere 8 minutes. This is why solar neutrinos are useful messengers carrying information about the current fusion

On their way from CERN in Geneva, Switzerland, to Gran Sasso, Italy, some of the muon neutrinos in a dedicated beam turn into tau neutrinos, and are detected by OPERA



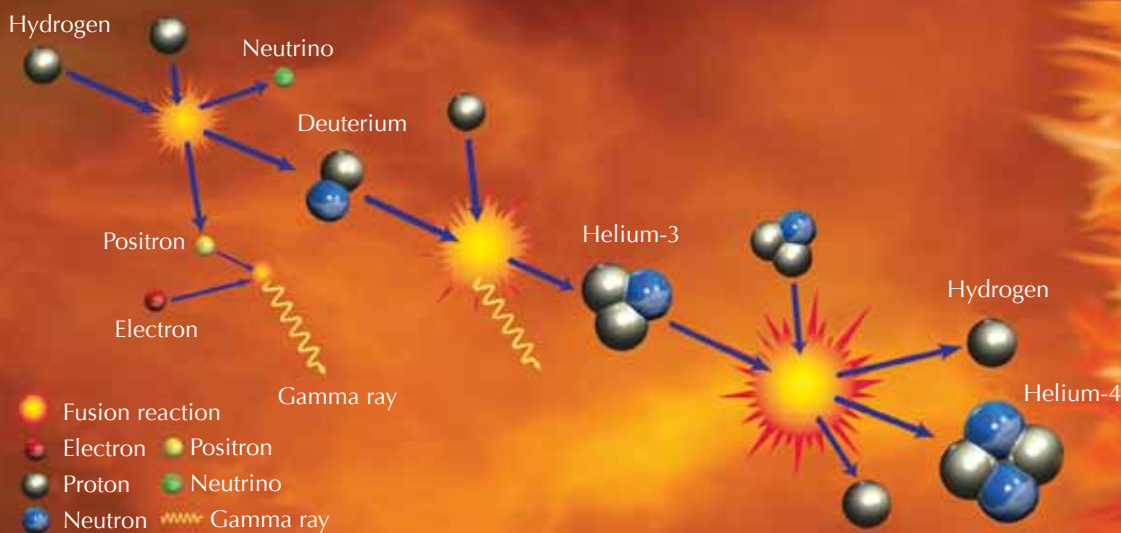


Image courtesy of Mark Tiele Westra

processes inside the Sun, such as the chemical composition of its core^{w9}.

Supernova neutrinos are the result of the violent end of some stars, which explode and produce even more neutrinos than photons (see Székely & Benedekfi, 2007): in 1987, several detectors registered an unusually strong signal (several events within a few seconds, as opposed to the usual frequency of about one per day), attributed to neutrinos from supernova SN1987A in the Large Magellanic Cloud. To allow astronomers to prepare to observe these events, several neutrino detectors are now linked together as the Supernova Early Warning System^{w10}, because during these stellar explosions, the neutrinos are released before the photons that the astronomers seek to detect.

Astronomers, however, are not the

only scientists interested in neutrino detectors. On Earth, both natural and artificial neutrino sources exist: radioactive materials from inside Earth can undergo beta decay, producing geo-neutrinos. In addition, nuclear fission reactors produce neutrinos, and dedicated particle accelerators are being used as neutrino sources for research. These are interesting to particle physicists, of course, to further characterise neutrinos, but also to earth scientists and maybe even politicians (see 'Neutrinos as nuclear police' and 'Powering Earth').

Finally, when cosmic rays hit Earth's atmosphere, atmospheric neutrinos are emitted as decay products of pions and muons. This most abundant source of naturally occurring neutrinos on Earth is a nuisance to neutrino astronomers (see 'How to detect

neutrinos'), who are interested in neutrinos that originate in outer space, but it provides neutrino physicists with another means of studying their favourite particles.

How to detect neutrinos

Neutrinos are very useful for studying astronomical and cosmological phenomena, and neutrino detectors are being built worldwide, deep underground to filter out the 'noise' of other particles. The recently finished IceCube^{w11} is the largest detector yet: a cubic kilometre of ice at the South Pole, acting as a telescope to search for neutrinos from astrophysical sources (see images below). When a neutrino hits a proton of Antarctic ice, a muon is released. Like any charged particle travelling at more than the speed of light in a specific medium

The IceCube neutrino telescope array is located at the South Pole (A; South Pole Station to the left of the runway, IceCube to the right). It consists of thousands of autonomous digital optical modules (B), which record the arrival time of each neutrino. They are deployed in deep holes in the ice, drilled with hot water (C). When a neutrino hits a proton of Antarctic ice, a Cherenkov cone of blue light is generated (D), and the path of light is reconstructed from the times of neutrino detection



Images courtesy of NSF



Fusion in the Sun: two hydrogen nuclei fuse to form a deuterium nucleus, a positron and a neutrino. The positron quickly encounters an electron, they annihilate each other, and only energy remains. The deuterium nucleus goes on to fuse with another hydrogen nucleus to form helium-3. In the final step, two helium-3 nuclei fuse to form helium-4 and two hydrogen nuclei

(though less than the speed of light in vacuum), the muon will generate a conical trail of blue light – Cherenkov radiation, the photonic equivalent of a supersonic boom, which can also be seen in some nuclear reactors.

Thousands of optical sensors, in a three-dimensional grid 1.5-2.5 km deep in the ice, detect this light; combined, the data can be used to determine the energy of the neutrino and the direction it came from. To distinguish muons that are generated from cosmic neutrinos from the millions more muons that are produced by cosmic rays in the atmosphere above the detector, IceCube uses Earth as a filter, only looking at muons that

come from underground. Neutrinos are the only particles able to penetrate the Earth unhindered, so any muon coming from that direction must have been newly generated in the detector from a cosmic neutrino.

Other detectors use different materials and strategies – but all put as much material in the neutrinos’ way as possible, trying to make them interact and reveal themselves.

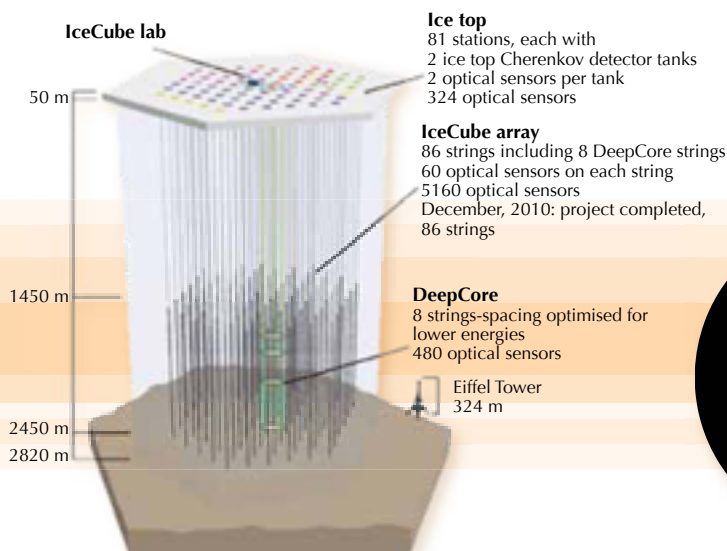
Neutrinos as nuclear police

Detection of nuclear weapons and material is important for many reasons, including the prevention of nuclear proliferation and terrorism. Scientists now propose that cubic-

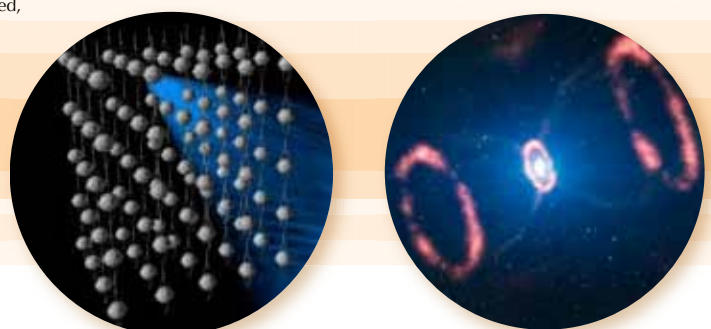
metre antineutrino detectors could be used to non-intrusively monitor and safeguard nuclear reactors^{w12}.

At present, reactors are monitored indirectly (for example using satellites, gas and dust emissions, and seismic and infrasound signatures for weapons testing), which can result in misleading data. Neutrino detectors would provide real-time information about the reactor core power and possibly even its isotopic composition. An array of about 500 such detectors worldwide would be able to calculate the power output of individual reactors, allowing the detection of clandestine nuclear weapons testing.

C



D



An artist's impression of the material around supernova SN1987A: two outer rings, one inner ring and the deformed, innermost expelled material

Image courtesy of ISON / L. Calçada



The KATRIN spectrometer in Karlsruhe, Germany, is one of the experiments aims to 'weigh' neutrinos

Powering Earth

Neutrinos are also detected in geophysics. Natural radioactive decay of uranium, thorium and potassium in Earth's crust and mantle sustains the flow of molten material in convective currents, which drive continental drift, seafloor spreading, volcano eruptions and earthquakes.

There are several models for this decay, depending on the composition of Earth's crust. Geo-neutrinos produced during decay may help answer the question of crust composition. Geo-neutrinos were first detected in 2005 by the KamLAND^{w13} experiment in Japan, although an abundance of nuclear power stations limited the studies, because the antineutrinos they release have similar energetic signatures to those of geo-neutrinos. In 2009, an international team from the Borexino project^{w6, w14} was more successful because there are fewer nuclear power stations nearby, so eventually, statistically significant numbers of geo-neutrinos should be collected to determine the relative amounts of uranium, thorium and potassium.

In the time that you have been reading this article, about

10 000 000 000 000 000 neutrinos have passed through you without your noticing. Tiny, yet with the power to confirm or overthrow a number of scientific theories.

Acknowledgement

The editors would like to thank Dr Christian Buck, neutrino physicist from the *Max-Planck-Institut für Kernphysik* (Max Planck Institute for Nuclear Physics), Heidelberg, Germany, for advice in developing the article.

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- Download the article free of charge from the *Science in School* website (www.scienceinschool.org/2011/issue19/neutrinos#resources), or

subscribe to *Nature* today:
www.nature.com/subscribe

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Westra MT (2006) Fusion in the Universe: the power of the Sun. *Science in School* 3: 60-62. www.scienceinschool.org/2006/issue3/fusion

Web references

w1 – Scientists from the University College of London have estimated the mass of the neutrino: www.ucl.ac.uk/news/news-articles/1006/10062204

Hopes for the most accurate measurements yet lie with the KATRIN experiment, which is in Karlsruhe, Germany: www-ik.fzk.de/~katrin

- w2 – Read about the Cowan and Reines experiments here: <http://library.lanl.gov/cgi-bin/getfile?00326606.pdf>
To find out more about the Nobel Prizes in Physics 1988, 1995 and 2002, see: http://nobelprize.org/nobel_prizes/physics/laureates
- w3 – The Institut Laue-Langevin operates one of the most intense neutron sources in the world. It is a member of EIROforum, the publisher of *Science in School*. See: www.ill.eu
- w4 – For more information on the Japanese Super-Kamiokande experiment, see: www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html
- w5 – To find out more about CERN, the world's largest particle physics laboratory and one of the eight members of EIROforum, see: www.cern.ch
To read more about the successful detection of a muon neutrino turned into a tau neutrino in CERN's press release, see <http://public.web.cern.ch/press> or use the direct link: <http://tinyurl.com/64crhr5>
Or watch a video on the topic: www.youtube.com/watch?v=M3aB_zUZ1c8
- w6 – The Gran Sasso National Laboratory in Abruzzo near L'Aquila, Italy, is the largest underground laboratory in the world for experiments in particle physics, particle astrophysics and nuclear astrophysics, including the OPERA and Borexino experiments. To learn more, see: www.lngs.infn.it
- w7 – For more information about the Canadian Solar Neutrino Observatory experiment, see: www.sno.phy.queensu.ca
- w8 – In France and Japan, detectors have been installed to further analyse neutrino oscillations. See: <http://doublechooz.in2p3.fr> and <http://jnusrv01.kek.jp>
- w9 – To find out more about current solar neutrino research, see:

<http://arxiv.org/pdf/0811.2424>
For more information about fusion in the Sun and elsewhere in the Universe, see the *Science in School* article series: www.scienceinschool.org/fusion

- w10 – The Supernova Early Warning System website can be found here: <http://snews.bnl.gov>
- w11 – For more information about ongoing research projects at IceCube, see: <http://icecube.wisc.edu>

Olivier Hainaut from the European Southern Observatory (ESO), the world's most productive astronomical observatory, which is a member of EIROforum, talked to the IceCube scientists during the 24-h live webcast 'Around the world in 80 telescopes' during the International Year of Astronomy 2009. Start watching the online video from minute 1:27: www.eso.org/public/videos/10msouthpole

For the ESO website, see: www.eso.org

For further astronomy resources, see:

Starr C, Harwood R (2009) Education resources for the International Year of Astronomy. *Science in School* 13. www.scienceinschool.org/2009/issue13/iya

- w12 – To learn more about the idea of detecting secret fission reactors using neutrinos, see: <http://physicsworld.com/cws/article/news/44411>

- w13 – If you would like to find out more about the KamLAND experiment in Japan, see: <http://kamland.lbl.gov>

- w14 – Find out the latest about the Borexino experiment: <http://borex.lngs.infn.it>

Resources

The Booster Neutrino Experiment and Interactions.org have pro-

duced good overview brochures on neutrinos, freely available online. See: www-boone.fnal.gov/about/nusmatter (Neutrinos Matter) and www.interactions.org/pdf/neutrino_pamphlet.pdf (Neutrino Odyssey)

The IceCube project website hosts a wonderful teaching activity on 'popcorn neutrinos', in which students can investigate the concepts behind beta decay. See: www.icecube.wisc.edu or use the direct link: <http://tinyurl.com/45ytuq7>

For slides of three talks on neutrino research for school students, available in German, see: www.mpi-hd.mpg.de/hfm/wh/pams/PamS0708.htm

Particle Adventure is a fun interactive online tour of particle physics: <http://particleadventure.org>

The Contemporary Physics Education Project offers student and teacher worksheets in English and Spanish for classroom activities on particle physics, including one on conservation laws, following Pauli's footsteps in postulating the neutrino (Activity 5). See: www.cpepweb.org/Class_act.html

The UK Science and Technology Council has compiled a resource guide for teaching particle physics. See: www.stfc.ac.uk/Public_and_Schools/2563.aspx

Susana Cebrián is a professor at the University of Zaragoza, Spain, working on several experiments in the field of astroparticle physics at the Spanish Canfranc Underground Laboratory.



To learn how to use this code, see page 1.

