

The chameleons of space

They solved the neutrino puzzle and opened a new realm in particle physics. **Takaaki Kajita** and **Arthur B. McDonald** were key scientists of two large research groups, Super-Kamiokande and Sudbury Neutrino Observatory, which discovered the neutrinos mid-flight metamorphosis.

The hunt was on – deep inside the Earth in gigantic facilities where thousands of artificial eyes waited for the right moment to uncover the secrets of neutrinos. In 1998, Takaaki Kajita presented the discovery that neutrinos seem to undergo metamorphosis; they switch identities on their way to the Super-Kamiokande detector in Japan. The neutrinos captured there are created in reactions between cosmic rays and the Earth's atmosphere.



Torn between identities – tau-, electron- or muon-neutrino?

Meanwhile, on the other side of the globe, scientists at the Sudbury Neutrino Observatory in Canada, SNO, were studying neutrinos coming from the Sun. In 2001, the research group led by Arthur B. McDonald proved that these neutrinos, too, switch identities.

Together, the two experiments have discovered a new phenomenon – neutrino oscillations. A far-reaching conclusion of the experiments is that the neutrino, for a long time considered to be massless, must have a mass. This is of ground-breaking importance for particle physics and for our understanding of the universe.

Reluctant heroes

We live in a world of neutrinos. Thousands of billions of neutrinos are flowing through your body every second. You cannot see them and you do not feel them. Neutrinos rush through space almost at the speed of light and hardly ever interact with matter. Where do they come from?

Some were created already in the Big Bang, others are constantly being created in various processes in space and on Earth – from exploding supernovas, the death of massive stars, to reactions in nuclear power plants and naturally occurring radioactive decays. Even inside our bodies an average of 5,000 neutrinos per second is released when an isotope of potassium decays. The majority of those that reach the Earth originate in nuclear reactions inside the Sun. Second only to particles of light, photons, the neutrinos are the most numerous particles in the entire universe.

For a long time, however, their existence was not even certain. Quite the opposite; when the particle's existence was proposed by the Austrian Wolfgang Pauli (Nobel Prize Laureate in 1945) it was mainly in a desperate attempt to explain conservation of energy in beta decay, a type of radioactive decay in atomic nuclei. In December 1930, Pauli wrote a letter to his physicist colleagues whom he addressed as *Dear Radioactive Ladies and Gentlemen*. In this letter he suggested that some of the energy is carried away by an electrically neutral, weakly interacting and very light particle. Pauli, himself, hardly believed in the existence of this particle. He supposedly stated: *“I have done a terrible thing, I have postulated a particle that cannot be detected”*.

Soon the Italian Enrico Fermi (Nobel Prize Laureate in 1938) was able to demonstrate an elegant theory that included Pauli's lightweight, neutral particle. It was called the neutrino. No one could predict that this tiny particle would revolutionise both particle physics and cosmology.

It would take a quarter of a century before the neutrino was actually discovered. The opportunity came about in the 1950s, when neutrinos began to stream in great numbers from nuclear power plants then being built. In June 1956, two American physicists, Frederick Reines (Nobel Prize Laureate in 1995) and Clyde Cowan sent a telegram to Wolfgang Pauli – the neutrinos had left traces in their detector. The discovery showed that the ghostly neutrino, or *Poltergeist* as it had been called, was a real particle.

A peculiar trio

This year's Nobel Prize in Physics awards a discovery that solved a long-standing neutrino puzzle. Since the 1960s, scientists had theoretically calculated the number of neutrinos that were created in the nuclear reactions that make the Sun shine, but when carrying out measurements on Earth, up to two thirds of the calculated amount was missing. Where did the neutrinos go?

There was no lack of suggestions. Maybe there was something wrong with the theoretical calculations of how the neutrinos are produced in the Sun? One of the other suggestions to solve the solar neutrino puzzle was that the neutrinos change identities. According to the Standard Model of particle physics there are three types of neutrinos – electron-neutrinos, muon-neutrinos and tau-neutrinos. Each has its respective charged partner, the electron, and its two much heavier and short-lived relatives, the muon and the tau. The Sun only produces electron-neutrinos. But if they would be transformed to muon-neutrinos or tau-neutrinos on their way to Earth, that would make the deficit of the captured electron-neutrinos understandable.

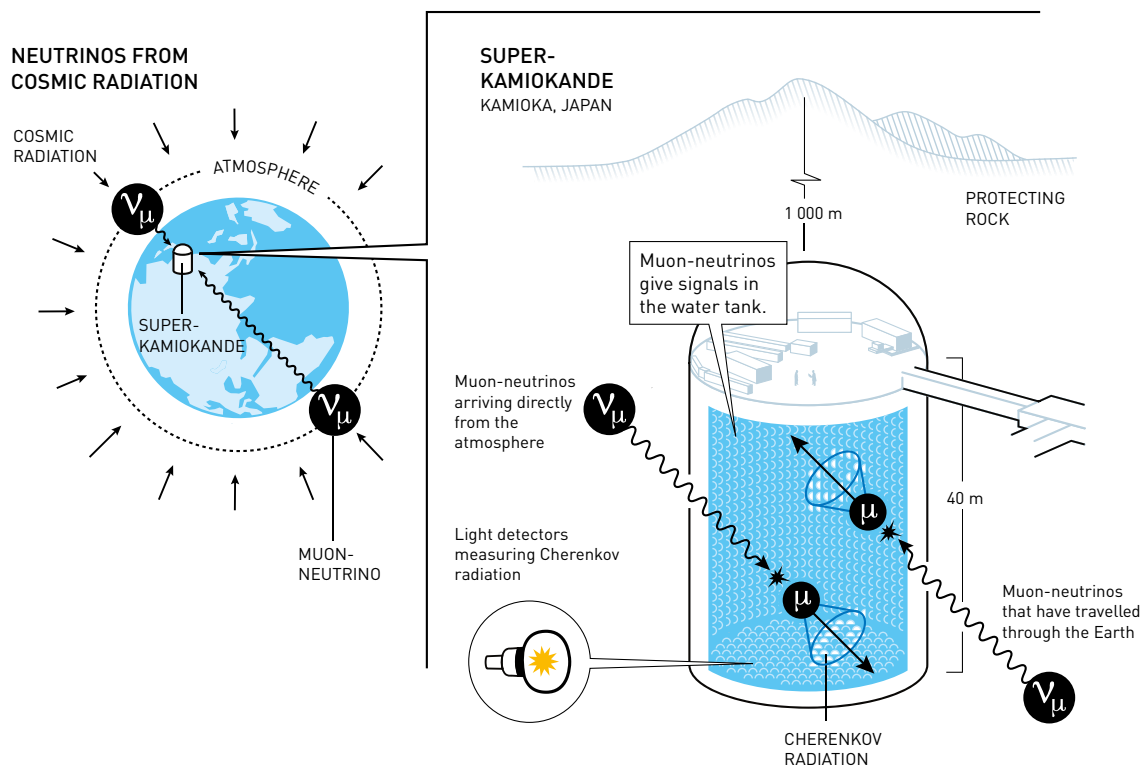
Hunting for neutrinos underground

Speculations about the neutrino's identity change remained just speculations until larger and more sophisticated facilities were taken into operation. Day and night, neutrinos were hunted in colossal detectors built deep underground, in order to shield out noise from cosmic radiation from space and from spontaneous radioactive decays in the surroundings. Yet, it is a difficult art to separate a few true neutrino signals from billions of false ones. Even the air in the mines and the detector material contain naturally occurring trace elements that decay and interfere with the measurements.

Super-Kamiokande became operational in 1996 in a zinc mine 250 kilometres North-West of Tokyo, while Sudbury Neutrino Observatory, built in a nickel mine in Ontario, began the observations in 1999. Together they would unveil the chameleon-like nature of the neutrino, the discovery that is rewarded with this year's Nobel Prize in Physics.

Super-Kamiokande is a gigantic detector built 1,000 metres below the Earth's surface. It consists of a tank, 40 metres high and as wide, filled with 50,000 tonnes of water. The water is so pure that light beams can travel 70 metres before their intensity is halved, compared to just a few metres in an ordinary swimming pool. More than 11,000 light detectors are located in the tank's top, sides and bottom, with the task to discover, amplify and measure very weak light flashes in the ultra-pure water.

The vast majority of neutrinos pass right through the tank, but every now and then, a neutrino collides with an atomic nucleus or an electron in the water. In these collisions charged particles are created – muons from muon-neutrinos and electrons from electron-neutrinos. Around the charged particles, faint flashes of blue light are generated. This is Cherenkov light, which arises when a particle travels faster than the speed of light. This is not in contradiction to Einstein's theory of relativity, which states that nothing can move



Super-Kamiokande detects atmospheric neutrinos. When a neutrino collides with a water molecule in the tank, a rapid, electrically charged particle is created. This generates Cherenkov radiation that is measured by the light sensors. The shape and intensity of the Cherenkov radiation reveals the type of neutrino that caused it and from where it came. The muon-neutrinos that arrived at Super-Kamiokande from above were more numerous than those that travelled through the entire globe. This indicated that the muon-neutrinos that travelled longer had time to change into another identity on their way.

faster than light in vacuum. In the water, the light is slowed down to 75 per cent of its maximum speed, and can be “overtaken” by the charged particles. The shape and intensity of the Cherenkov light reveals what type of neutrino it is caused by, and from where it comes.

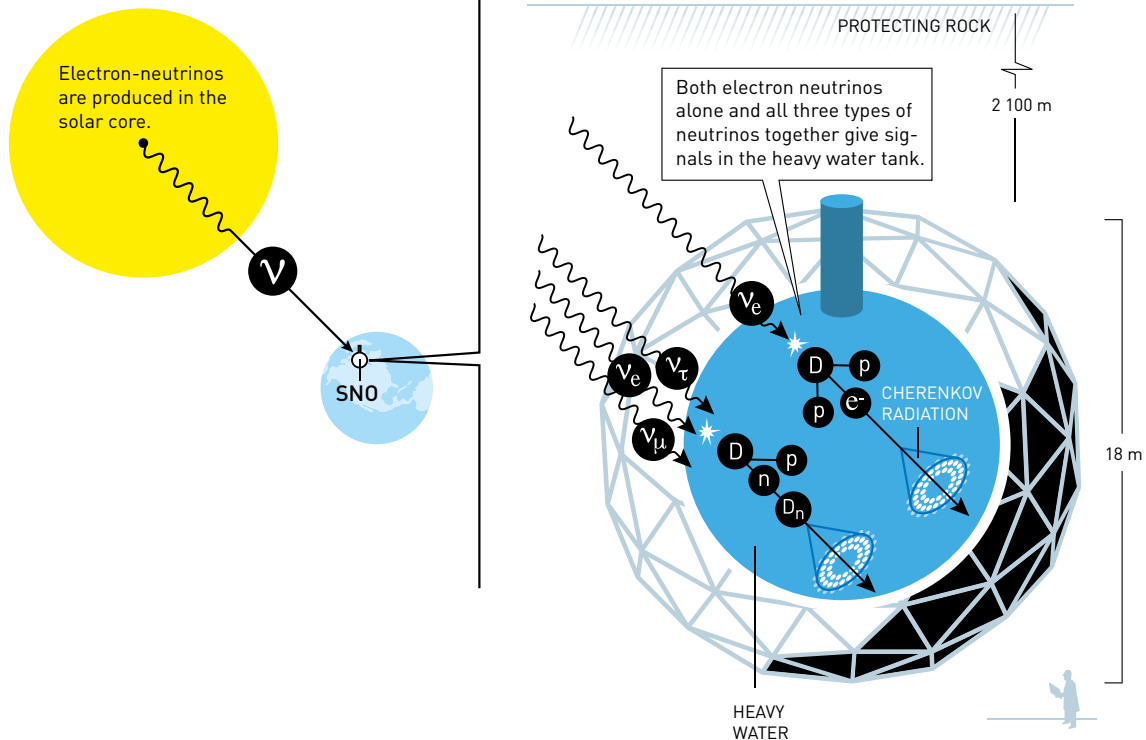
A solution to the enigma

During its first two years of operation, Super-Kamiokande sifted out about 5,000 neutrino signals. This was a lot more than in previous experiments, but still fewer than what was expected when scientists estimated the amount of neutrinos created by the cosmic radiation. Cosmic radiation particles come from all directions in space and when they collide at full speed with molecules in the Earth’s atmosphere, neutrino showers are produced.

Super-Kamiokande caught muon-neutrinos coming straight from the atmosphere above, as well as those hitting the detector from below after having traversed the entire globe. There ought to be equal numbers of neutrinos coming from the two directions; the Earth does not constitute any considerable obstacle to them. But the muon-neutrinos that came straight down to Super-Kamiokande were more numerous than those first passing through the globe.

This indicated that muon-neutrinos that travelled longer had time to undergo an identity change, which was not the case for the muon-neutrinos that came straight from above and only had travelled a few dozen kilometres. As the number of electron-neutrinos arriving from different directions were in agreement with expectations, the muon-neutrinos must have switched into the third type – tau-neutrinos. However, their passage could not be observed in the detector.

NEUTRINOS FROM THE SUN



Sudbury Neutrino Observatory detects neutrinos from the Sun, where only electron-neutrinos are produced. The reactions between neutrinos and the heavy water in the tank yielded the possibility to measure both electron-neutrinos and all three types of neutrinos combined. It was discovered that the electron-neutrinos were fewer than expected, while the total number of all three types of neutrinos combined still corresponded to expectations. The conclusion was that some of the electron-neutrinos had changed into another identity.

A decisive piece of the puzzle fell in place when Sudbury Neutrino Observatory, SNO, performed their measurements of neutrinos arriving from the Sun, where the nuclear processes only give rise to electron-neutrinos. Two kilometres below the Earth's surface the rushing electron-neutrinos were monitored by 9,500 light detectors in a tank filled with 1,000 tonnes of heavy water. It is different from ordinary water in that each hydrogen atom in the water molecules has an extra neutron in its nucleus, creating the hydrogen isotope deuterium.

The deuterium nucleus offers additional possibilities for the neutrinos to collide in the detector. For some reactions only the amount of electron-neutrinos could be determined, while others allowed scientists to measure the amount of all three types of neutrinos together, without distinguishing them from each other.

Since only electron-neutrinos were supposed to arrive from the Sun, both ways of measuring the number of neutrinos should yield the same result. Hence, if the detected electron-neutrinos were fewer in number than all three neutrino types together, this would indicate that something had happened to the electron-neutrinos during their 150 million kilometre long journey from the Sun.

Out of the over 60 billion neutrinos per square centimetre that every second reach the Earth on their way from the Sun, the Sudbury Neutrino Observatory captured only three per day during its first two years of operation. This corresponded to a third of the expected number of electron-neutrinos that should have been caught in the detector. Two thirds had disappeared. The sum however, if counting all three types together, corresponded to the expected number of neutrinos. The conclusion was that the electron-neutrinos must have changed identities on the way.

Metamorphosis in the quantum world

The two experiments confirmed the suspicion that neutrinos can change from one identity to another. The discovery have spurred many new experiments and have forced particle physicists to think in new ways.

Together these two experiments have given rise to a ground-breaking conclusion: the neutrino's metamorphosis requires that the neutrinos have mass. Otherwise they cannot change. How, then, does this metamorphosis come about?

Quantum physics is required to explain this magic. In the quantum world, particle and wave are different aspects of the same physical state. A particle with a certain energy is described by a corresponding wave of a certain frequency. In quantum physics the electron-, muon- and tau-neutrinos are represented by superposed waves that correspond to neutrino states with different masses.

When the waves are in phase it is not possible to distinguish the different neutrino states from each other. But when neutrinos travel through space the waves go out of phase. Along the way the waves are superposed in varying ways. The superposition in any given location yields the probability for what type of neutrino is most likely to be found there. The probabilities vary from one location to another, they oscillate, and the neutrinos appear in their various identities.

This peculiar behaviour is thus due to the differences in neutrino masses. Experiments indicate that these differences are extremely small. The mass of the neutrino is also estimated to be very small, although it has never been measured directly. Nevertheless, since neutrinos exist in enormously large quantities in the universe, the sum of their very tiny masses becomes significant. The combined weight of the neutrinos is estimated to be roughly equal to the weight of all visible stars in the universe taken together.

Gate to new physics

The discovery of the neutrino's mass has been ground-breaking for particle physics. Its Standard Model of the innermost parts of matter had been immensely successful and for over twenty years it had resisted all experimental challenges. But the model requires that neutrinos are massless. The experiments have thus revealed the first apparent crack in the Standard Model. It has become obvious that the Standard Model cannot be the complete theory of how the fundamental constituents of the universe function.

Several key questions about the nature of the neutrino need to be answered before new theories beyond the Standard Model can be fully developed. What are the neutrinos' masses? Why are they so light-weight? Are there more types than the three currently known? Are neutrinos their own antiparticles? Why are they so different from other elementary particles?

The discovery that is awarded with this year's Nobel Prize in Physics have yielded crucial insights into the almost entirely hidden world of the neutrino. The experiments are continuing and intense activity is under way around the world to capture the neutrinos and examine their properties. New discoveries of the neutrino's closely guarded secrets are expected to change our understanding of the history, structure and future fate of the universe.

LINKS AND FURTHER READING

Additional information on this year's prizes, including a scientific background in English, is available on the website of the Royal Swedish Academy of Sciences, <http://kva.se>, and at <http://nobelprize.org>. There, and at <http://kvatv.se>, you can watch video footage of the press conferences, the Nobel Lectures and more. Information on exhibitions and activities related to the Nobel Prizes and the Prize in Economic Sciences is available at www.nobelmuseum.se.

Books

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Close, F. (2010) *Neutrino*, Oxford University Press

Popular science articles

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Links

Super-Kamiokande Official Homepage: www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

Sudbury Neutrino Observatory Homepage: sno.phy.queensu.ca

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