AstroTalk: Behind the news headlines of November 2016

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Pure water in a Japanese mine offers clues to the nature of supernova explosions

Only three or four supernova explosions happen in our Milky Way galaxy every century. Supernovae are super-energetic events that release neutrinos at the speed of light. Neutrinos are neutral particles with near-zero mass produced abundantly in the Big Bang, by our Sun, and by cosmic rays striking the Earth's atmosphere. They are so tiny and interact so weakly that every second, trillions of them manage to pass through human bodies without anyone noticing. Studying them can reveal details about how stars in the Universe, including our Sun, work.

A kilometre underground, beneath Mount Ikenoyama, inside an old mining tunnel in Kamioka, central Japan, scientists have built a 50,000-tonne tank of ultra-pure water inside a gigantic cylinder full of so-called photomultiplier tubes. This is the Super-Kamiokande experiment, one of whose major objectives is the detection of neutrinos that come from nearby supernovae. Since supernova explosions occur so infrequently, the members of the international Super-Kamiokande scientific collaboration want to be prepared for one of these rare phenomena and have built a 'monitor' that is constantly on the lookout for a nearby supernova to inform the scientific community of the arrival of these mysterious particles, which can offer crucial information about the collapse of stars and the formation of black holes. The new computer system was installed and switched on this month.

> "*It is a computer system that analyses the events recorded in the depths of the observatory in real time and, if it detects abnormally large flows of neutrinos, it quickly alerts the physicists watching from the control room*," Luis Labarga, a physicist at the Autonomous University of Madrid (Spain) and a member of the collaboration, explained.

Thanks to this neutrino monitor, experts can assess the significance of the signal within minutes and see whether it actually originates from a nearby supernova, inside the Milky Way. If it is, they can issue an early warning to all interested research centres around the world, which they provide with information and the celestial coordinates of the source of neutrinos. They can then point all of their optical observation instruments towards it, since the electromagnetic signal arrives with a delay.

> "*Supernova explosions are one of the most energetic phenomena in the Universe and most of this energy is released in the form of neutrinos*," says Labarga. "*This is why detecting and analysing neutrinos emitted in these cases, other than those from the Sun or other sources, is very important for understanding the mechanisms in the formation of neutron stars—a type of*

> *stellar remnant—and black holes.*"
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> "*Furthermore*," he adds "*during supernova explosions an enormous number of neutrinos is generated in an extremely small space of time—a few seconds—and this why we need to be ready. This allows us to research the fundamental properties of these fascinating particles, such as their interactions, their hierarchy and the absolute value of their mass, their half-life, and surely other properties that we still cannot even imagine*."

Labarga says that the Super-Kamiokande is permanently ready to detect neutrinos, except for essential calibration or repair intervals. Any day could take us by surprise.

But the Super-Kamiokande detector is not just looking for supernovae in our own immediate vicinity. A second international team of researchers in Japan is getting ready to power up the neutrino detector by adding a single metal, which will turn it into the world's first detector capable of analysing exploding stars beyond the immediate neighbourhood of the Milky Way.

All supernova neutrinos that have been detected to date have come from the immediate vicinity of our Galaxy. No one knows whether neutrinos from older galaxies at great distances act the same way as neutrinos close to Earth, or whether there is a completely new class of tiny particles yet to be discovered.

Experimental physicist Mark Vagins of the Kavli Institute for the Physics and Mathematics of the Universe near Tokyo (Japan) and Ohio State University (USA) theorist John Beacom wanted to see if it were possible to improve Super-Kamiokande. One of their ideas was to add the rare-earth metal gadolinium to the detector's water tank, taking advantage of the gadolinium nuclei's ability to capture neutrons. If a neutron released from a neutrino interaction were located nearby, it would be absorbed by the gadolinium, which would release the extra energy by creating a flash of light: a signal that could be detected by the very sensitive measuring equipment. But before any tests could be run, the two researchers needed to find out if their idea made scientific sense and predict what complications they might need to overcome.

First, water inside the detector would need to be transparent. Neutrinos interact with water, creating tiny flashes of light that are picked up by the photomultiplier tubes lining the walls of the tank. If gadolinium made the water murky, it would prevent the phototubes from detecting any light. Second, the gadolinium needed to be uniformly spread within the tank so it could be close enough to a neutrino–water interaction to magnify its signal.

> "*These two criteria, uniformity and transparency, mean the gadolinium must be induced to dissolve*," says Dr Vagins. "*We've spent over ten years figuring out how to do it*."

Gadolinium is a by-product of the extraction of other rare-earth metals, some of which are used to produce the colours in flat-screen TVs. This makes gadolinium affordable so that Dr Vagins and his team will be able to purchase the 100 tonnes needed to help Super-Kamiokande detect neutrinos from distant supernovae. The pure water inside its giant tank acts as a target for a range of particles being studied today including neutrinos, resulting in a tiny light flash that is picked up by sensitive phototubes lining the walls. In 1987, Kamiokande, the original experiment in the same mine, recorded the first supernova neutrinos. The experiment was headed by the University of Tokyo's Masatoshi Koshiba, who was awarded a Nobel Prize in Physics in 2002. In 1998, Kamiokande and Super-Kamiokande proved neutrinos have mass, resulting in the 2015 Nobel Prize in Physics for Takaaki Kajita, who had been a graduate student of Dr Koshiba.

In fact, the 2015 Nobel Prize in Physics was shared by Arthur B. McDonald, the leader of the Sudbury Neutrino Observatory (SNO), and Takaaki Kajita "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

The discovery of neutrino oscillations and mass has profoundly affected our understanding of these elusive particles, their role in the theoretical underpinning of physics, and the evolution of the Universe. The success of nuclear-physics calculations of solar energy generation has been dramatically confirmed. The discovery, moreover, opens new doors to an understanding of such basic questions as why the Universe contains more matter than antimatter, and what properties a new and successful standard model must have.

Neutrinos have long been thought to be massless, a prediction of the standard model of particles and fields. Beginning in the 1960s, Raymond Davis Jr. began to measure the flux of neutrinos from the Sun. His experiment—and subsequent ones at Kamiokande in Japan, Baksan in Russia, and Gran Sasso in Italy—found that the flux was much smaller than expected. In 1985, Herbert Chen observed that if neutrinos oscillated, they would still arrive at Earth but in 'flavours' undetectable in the Davis experiment, which was designed for electron neutrinos. There are three flavours—electron, mu, and tau—but the Sun can only produce electron neutrinos. He proposed a detector based on heavy water (where the hydrogen atom is replaced by deuterium) that could detect all flavours equally.

The result was the SNO detector, and in 2001 SNO showed that two-thirds of the electron neutrinos had converted to non-electron flavours. Meanwhile, in 1998 Super-Kamiokande had found a similar effect in which mu neutrinos produced in the atmosphere converted to a non-electron flavour. These conversions can only occur via a quantum-mechanical effect that requires neutrino mass to be non-zero.

The confirmation of the solar-neutrino flux predictions resolved a problem that had continued to baffle physicists for more than 30 years and shows that nuclear processes in the Sun's core are understood very accurately. The discovery of neutrino mass forces a revision in our basic model of particles and fields. New theories are being developed, but a decisive choice cannot be made without more information. Experimental work to determine the actual mass (which is not given by oscillations), to answer the question of whether neutrinos and antineutrinos are the same particle, and to see if neutrinos respect a natural symmetry, the reversal of time, need to be carried out. The discovery also means that neutrinos are a part of the dark matter in the Universe, but only a small part. Nevertheless, their abundance and small mass mean that they affect the form and evolution of the largest structures and clusters of galaxies in the Universe.

We have come a long way from the humble beginnings of neutrino research. Indeed, it has taken over eight decades for physicists to reach their current-best understanding of the physical nature of the neutrino. Here is a timeline of ongoing efforts to understand the neutrino:

- 1930: Austrian-born quantum-physics pioneer Wolfgang Pauli hypothesises the existence of an as-yet-undetected, electrically neutral particle, which Italian physicist Enrico Fermi later dubs the 'neutrino.' However, the particle is hard to track down since it does not interact strongly with any other matter in the Universe, shooting undeterred through our bodies and the Earth itself.

- 1956: Two American scientists, Frederick Reines and Clyde Cowan, report the first hard evidence of the existence of neutrinos.

- 1988: Again, two American researchers, Leon Lederman and Melvin Schwartz, as well as German-born scientist Jack Steinberger receive the Nobel Prize in Physics for uncovering—in the 1960s—the existence of at least two kinds of neutrino. Their work was a key contribution to the Standard Model of particle physics, which seeks to explain how the Universe is put together.

- 1995: More than 20 years after Cowan's death, Reines is awarded the Nobel Prize in Physics for their discovery, which used a fission reactor (which splits atomic nuclei into smaller particles) to pump out neutrinos and a sensitive detector to spot them. He shared the award with American Martin Perl who unearthed another type of particle, which suggested the existence of a third neutrino flavour.

- 1998: Kajita and a team observe that neutrinos can switch from one type to another, in a process called 'oscillation,' as they travel between the atmosphere and the Super-Kamiokande underground particle detector. The change was drastic—like having "*an orange in your hand which suddenly turns into an apple*," Oxford University neutrino researcher Alfons Weber once said in a media interview.

- 1999: McDonald announces that neutrinos from the Sun were not 'disappearing,' as long suspected, but changing form before they arrive at the SNO observatory in Ontario, Canada.

- 2002: Raymond Davis Jr. Masatoshi Koshiba receive the Nobel Prize in Physics for the first detection of neutrinos from beyond Earth—originating in the Sun and an exploding star.

- 2011: European scientists cause a storm by publishing experimental results showing that neutrinos can travel faster than the speed of light—challenging Albert Einstein's 1905 Theory of Special Relativity.

- 2012: The scientists admit their experiment was flawed and reaffirm that neutrinos—like everything else—are bound by the universal speed limit.

What next? Scientists believe there may be a fourth type of neutrino, and the hunt is on. Measurements have yielded slightly fewer neutrinos than calculations say there should be, which might mean they are transforming into a fourth, as-yet-undetected flavour.

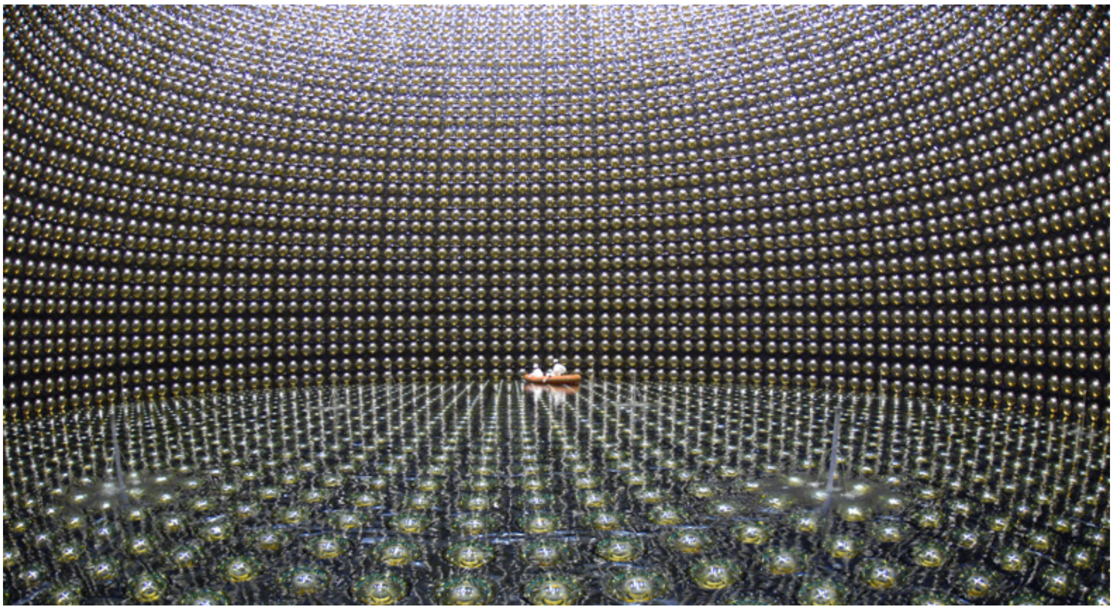

Figure 1: The Super-Kamiokande experiment is located at the Kamioka Observatory, 1,000 metres below ground in a mine near the Japanese city of Kamioka. (*Credit: Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo, Japan*)

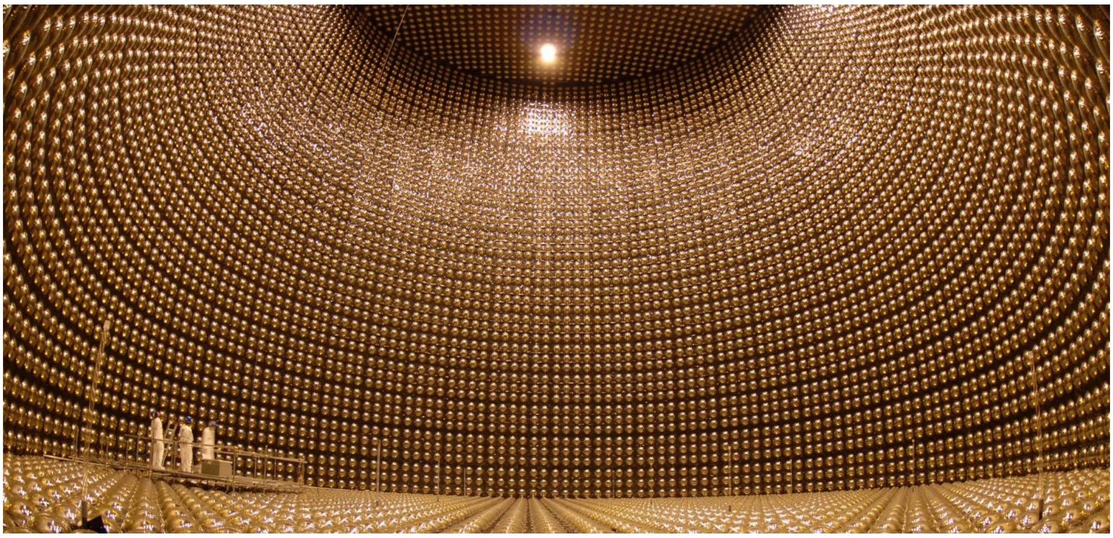

Figure 2: Scientists stand on a platform at the world's largest underground neutrino detector Super-Kamiokande. (*Credit: Kavli Institute for the Physics and Mathematics of the Universe, Japan*)

Figure 3: Completion of the SNO detector: A technician crouches inside the 12-metre-diameter acrylic vessel, so clear it can hardly be seen. Surrounding him are almost 10,000 photomultipliers, sensitive detectors of the light flashes produced by neutrino interactions in the heavy water with which the vessel will be filled. (*Credit: Lawrence Berkeley National Laboratory, USA*)

Figure 4: Scientist entering the SNO detector for upgrade work to transform this experiment into SNO+. (*Credit: The SNO+ collaboration; James Sinclair, University of Sussex*)