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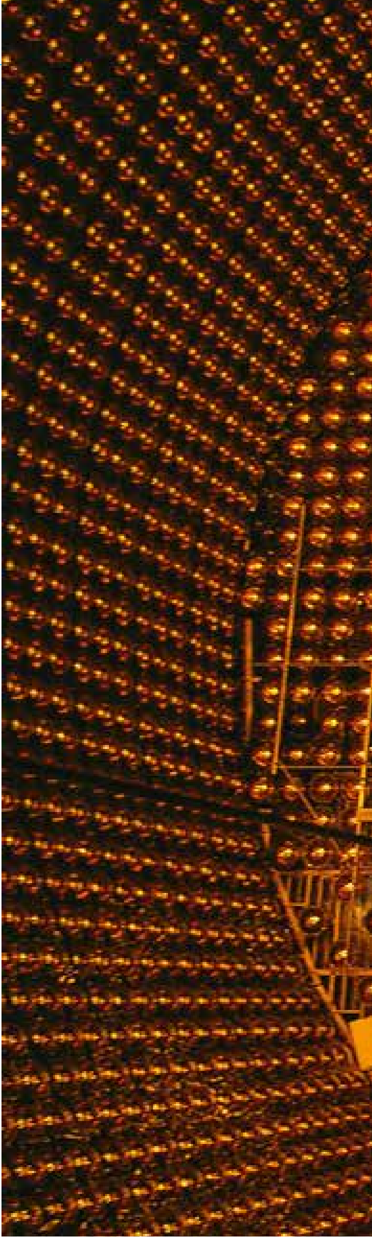
Flavor-Switching Neutrinos


PIOTR MIJAKOWSKI

Prof. Ewa Rondio from the National Center for Nuclear Research (NCBJ) explains the nature of neutrinos, the measurements taken by the Super-Kamiokande detector, and the involvement of Polish scientists in the project.

ACADEMIA: **What are neutrinos?**

PROF. EWA RONDIO: Literally translated, the word "neutrino" means "little neutral one." The name was first suggested when the existence of neutrinos was proposed to patch up the law of conservation of energy. It had turned out that without postulating their existence we could not explain why the spectrum of energy in beta decay is continuous, whereas two-body decay should give a single constant value. Back then, that postulate was considered very risky, because it was believed that such particles would be impossible to observe. Experimental physicists have nowadays managed that, although it took them quite a long time. Neutrinos come in three types, called flavors. They appear in interactions together with different charged leptons, from which they derive their names. The electron neutrino, associated with the electron, and the muon neutrino, associated with the muon, have been known for a long time. The tau neutrino, associated with the heavy lepton tau, was discovered this century. These days, we use neutrinos as regular particles. We study the neutrinos coming from space, but we also make our own beams of neutrinos: controlled, artificial, created here on Earth.

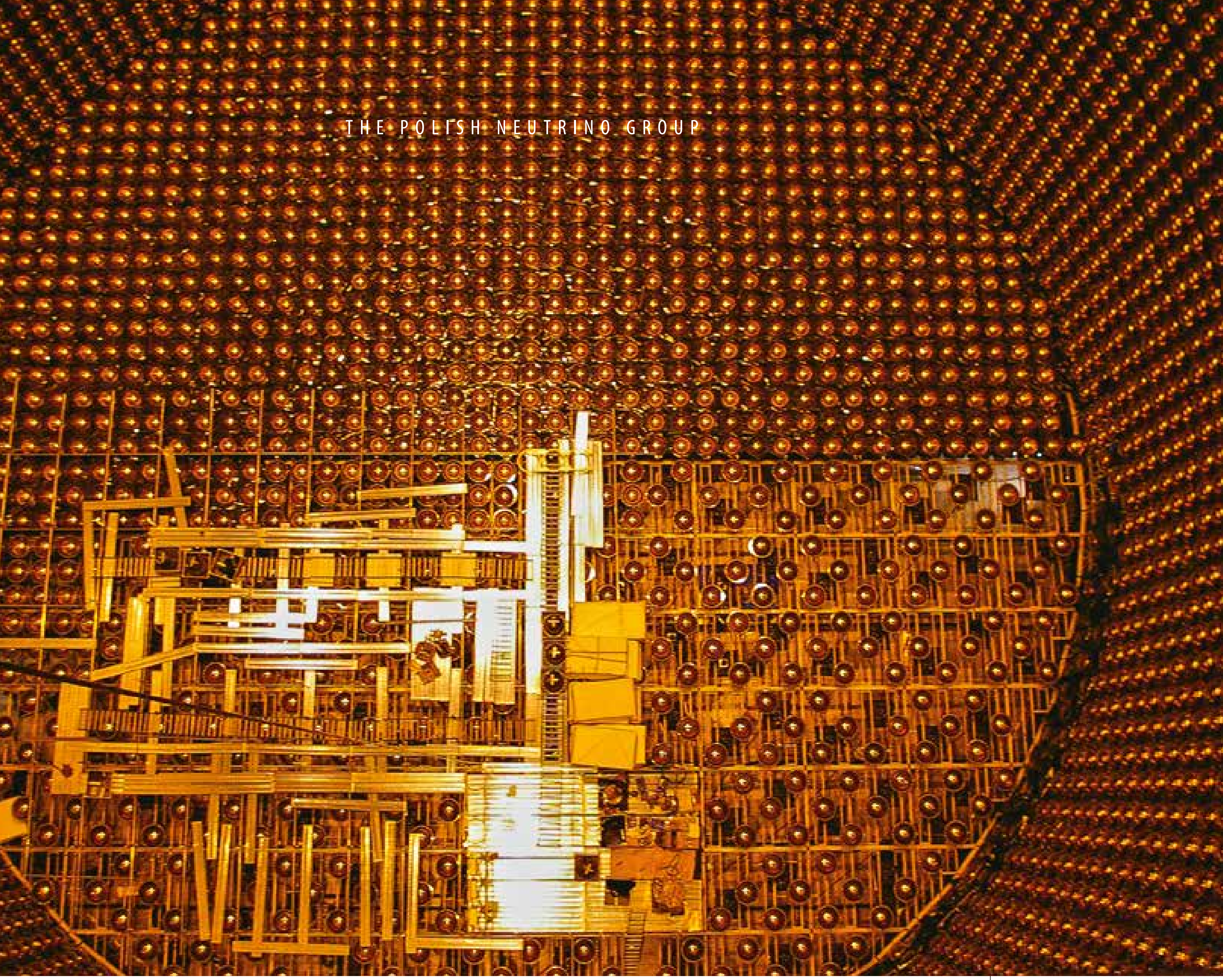
What is the difference between the neutrinos that come from space and the neutrinos created on Earth?

Neutrinos arriving from space are almost as abundant as photons in the cosmic background radiation, but their energies are so small that we're unable to detect them. We can't see them, even though there are so many of them. We can only observe higher-energy neutrinos, for example those arriving from the Sun.

At first glance, they do not differ in any way from those made on Earth. However, they have somewhat different energies. Also, those arriving from space are predominantly neutrinos, whereas those we produce on Earth produce are chiefly antineutrinos. This is because solar neutrinos are produced when light elements are fused into heavier ones, whereas most of the neutrinos produced on Earth are produced in nuclear reactors, in nuclear fission reactions triggered by neutrons. They release energy and produce unstable nuclei, the decays of which produce antineutrinos.

Does this mean that the National Center for Nuclear Research in Świerk produces antineutrinos?

Yes, but we conduct no research using antineutrinos. The trouble with all experiments involving neutrinos



is that they are extremely unwilling to interact. They pass through the whole Earth and most of them don't even notice it. If we wanted to perform measurements involving reactor neutrinos in Świerk, we would have to wait for a very long time to get enough interactions.

Why did neutrino physics prove worthy of the Nobel Prize in 2015?

In various experiments observing both neutrinos arriving from the Sun and those that are produced in the Earth's atmosphere, the numbers of neutrinos of particular types were not consistent with expectations. Models were used to predict how many electron neutrinos the Sun should emit, but the measurements showed a deficit. In turn, experiments involving neutrinos that were created in the atmosphere and reached the detector from various directions showed that the largest deficit was observed for neutrinos coming from below, ones that had traveled all the way through the Earth.

In order to explain those deficits, researchers hypothesized the existence of neutrino oscillations, postulating that neutrinos switched identities in mid-flight. A neutrino of a certain type sometimes stays the same, but sometimes changes its flavor. Such transformations depend on the neutrino's energy and the distance it has travelled. Since this process is cyclical, which means that neutrinos of a specific type disappear and then appear again, the changes were called oscillations. In recognition of that discovery, the 2015 Nobel Prize in Physics went to Takaaki Kajita from the Super-Kamiokande experiment, who studied atmospheric neutrinos, and Arthur B. McDonald from the Sudbury Neutrino Observatory (SNO) experiment, who studied solar neutrinos and demonstrated that neutrinos of a certain type disappeared while those of a different type appeared. All those experiments showed that the overall count of all types of neutrinos detected was as expected, even if some of a given flavor were missing. As for solar neutrinos, that was a breakthrough; as long as the count was wrong only for solar neutrinos, it was said that our model of the Sun might be inaccurate. Meanwhile, showing that the overall count of neutrinos remained unchanged offered tangible proof of the existence of oscillations.

Those studies were conducted at the turn of the century: the Super-Kamiokande experiment in 1998, in which Takaaki Kajita led the group that examined atmospheric neutrinos, was the first to present results

The Super-Kamiokande detector – a water-filled cylinder with photomultipliers covering all the walls, located 1,000 meters underground in the Kamioka mine, Japan at a conference, showing deficits of neutrinos that were coming in from below. The SNO experiment, for which Arthur B. McDonald was one of the initiators and project leaders, demonstrated in the early 2000s that the total count of neutrinos from the Sun is consistent with expectations.

Where are these detectors located?
Such detectors are located underground in order to isolate them from the background of charged particles coming in from space, interacting and creating noise. The Super-Kamiokande detector – located in Kamioka, Japan – is a cylinder filled with ultra-pure water and located in a mine over 1,000 meters underground. The detector's walls are covered with huge and extremely photogenic photomultipliers.

We find neutrinos by observing the products of their interactions. These products are charged particles, which leave traces in the detector. We can measure these traces and use these measurements to determine the energy of neutrinos, say something about their properties. The Super-Kamiokande detector shows us the tracks of charged particles that travel through the detector, provided that these particles move sufficiently fast.

Such detectors use the Cherenkov effect, or the fact that a particle that passes through a medium at a speed greater than the speed of light in that medium emits radiation. This is possible in a medium, because the speed of the particle still doesn't exceed the speed of light in a vacuum, which is the greatest possible speed. The detector used in the SNO experiment was also a Cherenkov detector, but it used heavy water to make it easier to record interactions in which a neutrino remained a neutrino and dissociated deuterium as a result of transferring energy. Observing the products of such dissociation made it possible to count muon neutrinos arriving from the Sun for the first time.

This is why we talk about two types of interactions: charged-current interactions, in which neutrinos convert into charged particles, and neutral-current interactions, in which neutrinos remain neutrinos.

How are Polish researchers involved in these experiments?
Prof. Danuta Kiełczewska was involved in the Super-Kamiokande experiment from the outset. Also, she had been involved in earlier Cherenkov experiments, including the projects involving the Irvine-Michigan-Brookhaven (IMB) detector. Together with the Super-Kamiokande detector, the IMB detector observed the signal of neutrinos from the explosion of a supernova in 1987. Initially, Prof. Kiełczewska was the only Pole there.

After returning to Poland, she was one of the creators of the Polish neutrino group. I think that is something we can be proud of. We currently have team of nearly 30 individuals who work closely with one another in experimental neutrino physics.

The group was formed in 2000 to take part in experiments in which a neutrino beam was directed from the European Organization for Nuclear Research (CERN) to the Gran Sasso laboratory in Italy, where a huge detector called ICARUS was being built. Instead of water, it used liquid argon to observe the traces left by charged particles.

The areas of study later expanded, because the experiment at the Gran Sasso laboratory was delayed by several years. We had a team ready to work, so we decided to join the experiment called T2K, or Tokai to Kamioka. It started in 2009 and the first neutrinos in a beam were observed in 2010. The accelerator that prepares the beam of neutrinos for us is located in Tokai, Japan. We direct the beam through the whole of the island of Honshu to Kamioka, where the underground Super-Kamiokande detector is located. It's the same detector that earlier worked on atmospheric neutrinos.

As for the T2K experiment, Polish groups participated in the construction of the part of the detector that recorded the interactions near the source of the beam. They are actively involved in data analysis and they are working to improve the models that describe neutrino interactions.

The recipe for producing neutrino beams reflects the way neutrinos are produced in nature, in the atmosphere. An accelerated proton or nucleus hits the nucleus of the shield. In the atmosphere, the fast particles of cosmic rays hit the nuclei of nitrogen and oxygen. The collision creates mesons, which decay to produce neutrinos. In artificial beams, we accelerate a proton or a nucleus and smash it into a shield to produce mesons. We use magnetic field to focus them into a beam, redirect them to fly in the same direction. After that, we wait until they decay and the neutrino beam continues to fly. Since neutrinos have no charge,

Polish researchers studying the "little neutral ones"

The history of Poland's participation in neutrino oscillation experiments started from Prof. Danuta Kiełczewska's involvement in the IMB experiment, which was searching for proton decay in which neutrino interactions were the most important background, The IMB experiment observed neutrinos from Supernova 1987A. In that experiment, Prof. Kiełczewska worked in Prof. Frederick Reines's group at the University of California in Irvine. The University of Warsaw has been an official partner of the Super-Kamiokande project from the outset. The Polish neutrino group was formed in 2000 based on Prof. Kiełczewska's experience in the field. Teams from six institutions from the whole of Poland have been involved in the group's work from the beginning. These are mostly experimental groups in Warsaw (the NCBJ, the University of Warsaw, and the Warsaw University of Technology), in Kraków (a team from the PAS Institute of Nuclear Physics headed by Prof. Agnieszka Zalewska) in Katowice (a team from the University of Silesia led by Prof. Jan Kisiel). There is only one group of theoretical physicists at the University of Wrocław led by Prof. Jan Sobczyk – they are involved in modeling neutrino interactions. They are highly valued in the T2K collaboration, where they are working on improving the way to describe interactions.

we cannot steer them after they are produced. We can only steer the particles that will produce neutrinos.

How important is the participation of Polish researchers in these experiments?
The group's development and commitment is reflected in the fact that last year neutrino physicists received not only the Nobel Prize but also the Breakthrough Prize, shared by experimental teams. It went to teams working on several neutrino experiments. Twenty-four people from Poland were awarded a share of that prize! This shows that the group is active. The Breakthrough Prize is awarded to coauthors of publications that are considered groundbreaking.

What was the content of those publications?
We were awarded the Prize for measuring the missing mixing angle, a parameter that described how neutrinos switched between flavors. Two angles were known. As for the third angle, we only knew that it was smaller than the remaining two. It was measured in the T2K experiment in 2011.

What are the Polish group's plans for the future?
There are two directions for the near future. One involves continuing the T2K experiment. The planned modifications of the detectors will make it possible to improve the accuracy of measurements and attempt to measure the phase breaking the CP symmetry. That's a very difficult experiment, because it involves comparing the interactions of neutrinos and antineutrinos and drawing conclusions from potential differences, which are tiny. Another direction involves short-baseline experiments at Fermilab that seek a possible fourth type of neutrinos, called sterile neutrinos. There are signs, though not entirely unambiguous ones, indicating that such neutrinos may exist in nature. If they exist, they are even less willing to interact than other neutrinos. Discovering them would mark a major turning point, because that would mean going beyond the standard model, a revolution in our understanding of physics. In the experiment that is being prepared, liquid argon detectors will be located at different yet relatively small distances, up to 2 km away from the neutrino source.

On the horizon for the longer term – in neutrino physics, this means after 2025 – are two projects involving long-baseline experiments. One in Japan, which is similar to T2K but has a much larger Cherenkov detector, and the other in America, with a large liquid argon detector. They will examine classic oscillations between three types of neutrinos, but with great accuracy.

From the everyday standpoint, why does it pay to take part in such experiments?
Those directly involved in the studies are surely driven by their scientific curiosity. But participation in these experiments also gives us a chance to get to know the world's top-notch technologies and bring them to Poland. For example, these are technologies used to record light, not just these huge photomultipliers but also tiny silicon detectors, which have a growing number of applications. We get to know these technologies and we can bring them to Poland in the form of industrial orders. If there is a strong group from one country involved in a certain experiment, it has a chance to convince other participants that they should order production from its country of origin. The industry not only earns money but also gains access to such technologies, which gives it preference in future tenders.

There is yet another aspect people don't consider very often. Such international collaboration teaches us to work together in large teams, to fall in line with others and simultaneously to promote our own ideas and concepts. That is something we need very much, but it cannot be measured, calculated or expressed in a report. Our teams consist of several hundred or sometimes several thousand individuals who do something together with no tools of administrative pressure. The leader of the collaboration cannot explicitly order anyone to do anything. He or she can only ask the group to do something. And that works! I think it contributes greatly to the general culture of international contacts and is absolutely impossible to overestimate.

INTERVIEW BY **ANNA ZAWADZKA** AND **AGNIESZKA POLLO**

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