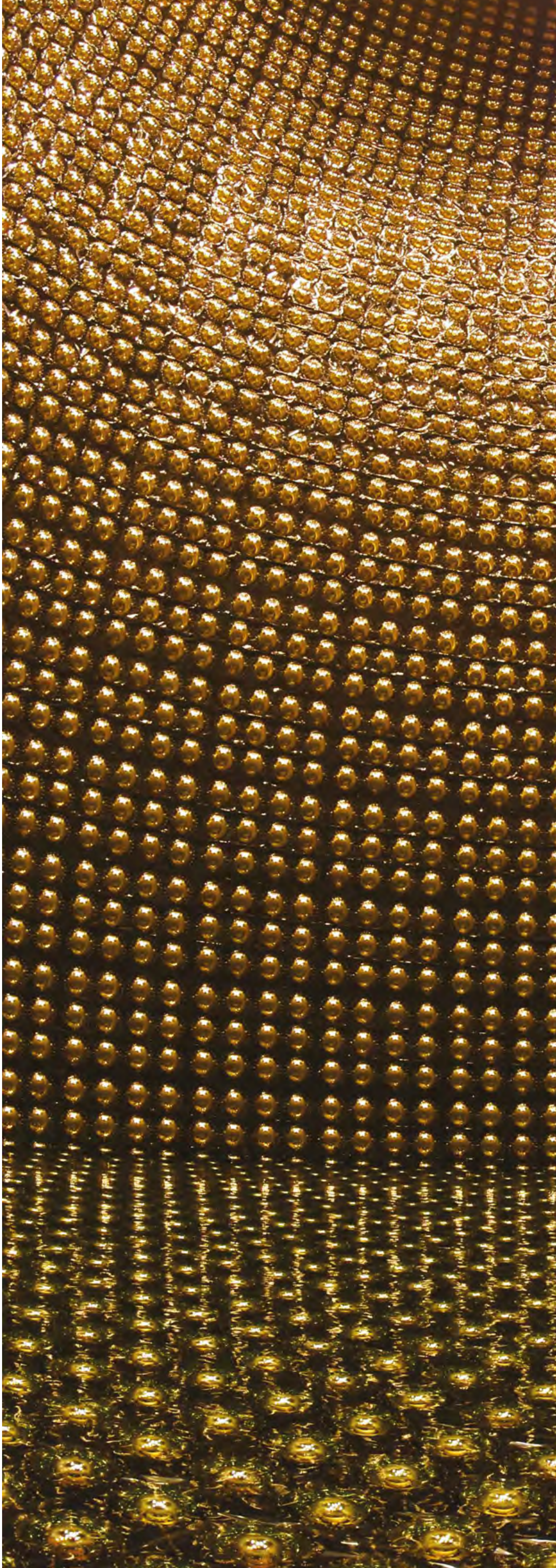
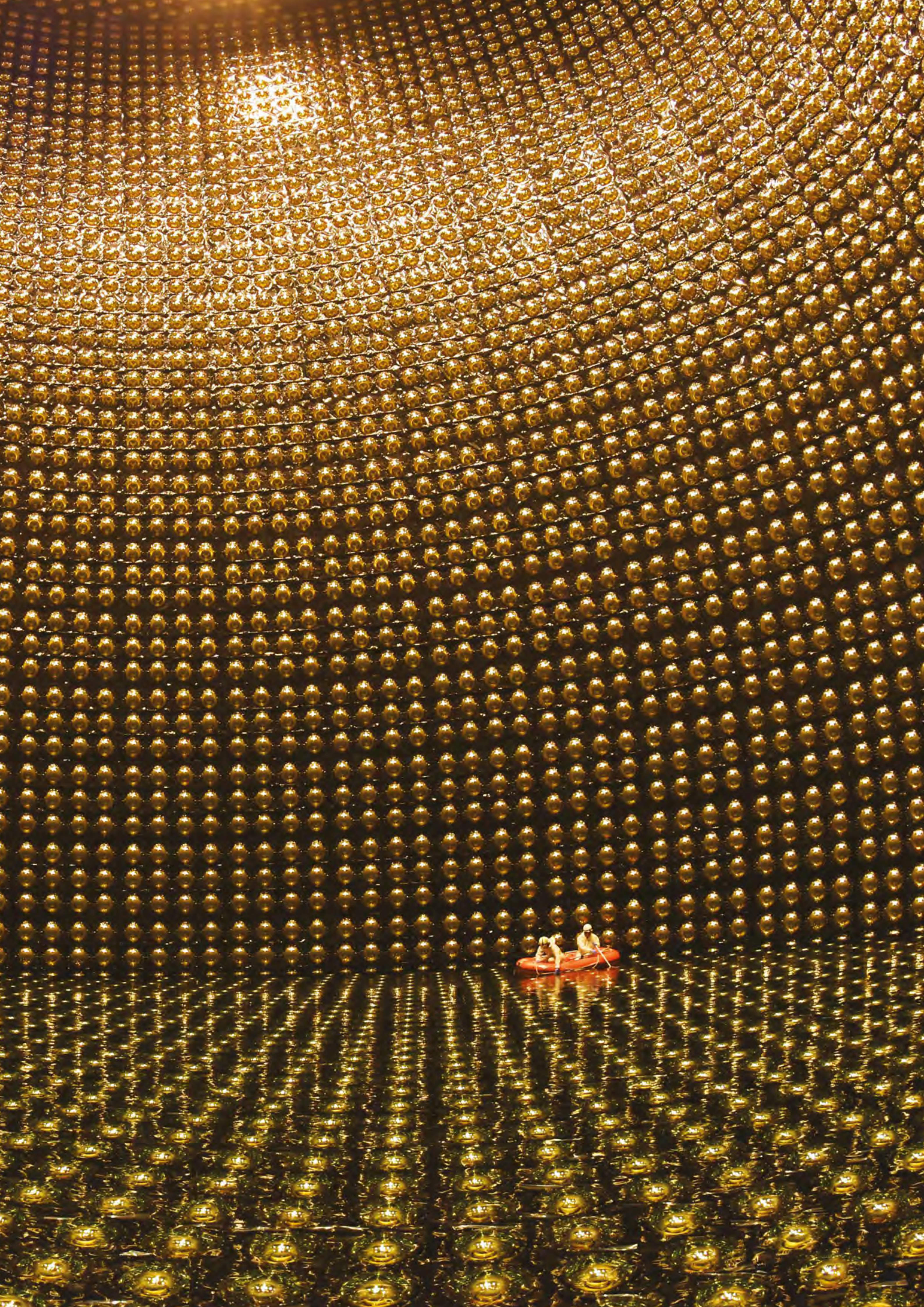
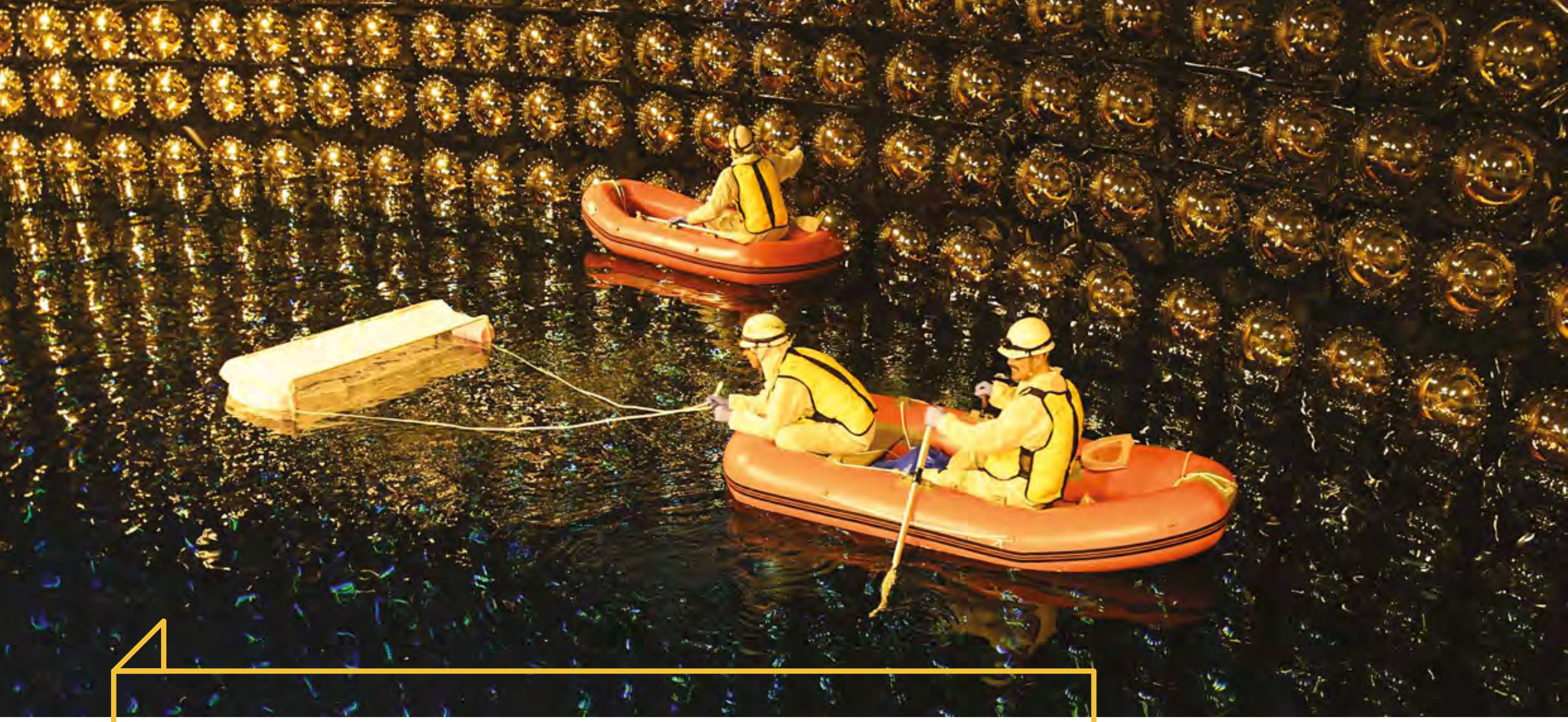
text: Dr. Małgorzata Kłoskowicz

WHY DOES THE UNIVERSE CONSIST PRIMARILY OF MATTER?



The universe we know consists mainly of matter. All objects around us are made up of particles. Therefore, matter can be reached with our hands. What is more, it is the building block of these hands. It turns out that there are also traces of antimatter in the same universe. It is the rarest and thus the most expensive substance in the world. Why is the Universe much, much more material than "antimaterial?" The results of research on the nature of neutrinos and antineutrinos in the T2K experiment bring us closer to solving this puzzle | Photo: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo





Cleaning the surface of water. The water level is about 31 meters / photo: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

Their nature is still being discovered. Observations from recent years suggest that the analysis of these particles may bring us closer to understanding why the universe is primarily composed of matter. The inconspicuous neutrinos discussed in this article have already paved the way to several Nobel Prizes. Will history repeat itself?

In December 1930, Austrian physicist Wolfgang Pauli proposed an ingenious solution to all the problems related to beta decay by adding a missing element to the model. It suggested the existence of a neutral particle of negligible mass, moving at a speed below the speed of light. The hypothesis of the existence of an electron-neutrino was confirmed only in 1956 in an experiment by Clyde Cowan and Frederick Reines. In the 1960s the existence of the muon neutrino was experimentally confirmed, and in 2000 the third and last type was discovered – the tau neutrino.

What do we know about these elementary particles? Assoc. Prof. Arkadiusz Bubak, from the Institute of Physics at the University of Silesia answers this question without hesitating.

– Five light years of concrete – a wall would have to be of this thickness to stop all the solar neutrinos (the stream on Earth: $10^{11}/cm^2/s$). These are unusual particles that have very little interaction with matter. To understand this, it is enough to imagine that billions of them pass each centimeter of our body every second. Has anyone of us felt how easily they constantly penetrate matter? – asks the scientist, who together with Prof. Jan Kisiel participates in the Tokai-to-Kamioka neutrino experiment (T2K).

In order to capture their presence and investigate the properties of neutrinos, it was necessary to design powerful detectors mounted in places which will be reached by a small amount of cosmic radiation. Only under such conditions it is possible to observe neutrino effects.

A huge technological challenge was met by the designers of two powerful detectors built for the T2K experiment. The near ND280 detector is located in Tokai, Japan. The Japan Proton Accelerator Research Complex (J-PARC) facility, which manufactures a proton beam directed towards a specially designed graphite shield, is also based there. As a result of the interaction between protons and the shield, other particles are produced, including pions, which decay and produce neutrinos. The newly created neutrinos can be registered by detectors e.g. by the already mentioned ND280 (located 280 m from the target) and by the far detector Super-Kamiokande, located 295 km from the J-PARC center, in a mine inside a mountain in Kamioka, Japan.

– Hence the name of the T2K experiment – Tokai-to-Kamioka, explains Prof. Jan Kisiel, who heads a group of scientists from the Institute of Physics at the University of Silesia in Katowice participating in the experiment.

– We look at the nature of neutrinos, we want to know them better. Physicists refer to the three discovered types of these elementary particle as flavors. These particles have an interesting "skill" and can change their flavor during weak interactions. In practice, this means that, for example, muon neutrinos "traveling" from the accelerator in Tokai to the detector in Kamioka, become… electron neutrinos. The process of flavor change is called oscillation, adds the scientist from the University of Silesia. It is worth mentioning that the two physicists who had discovered the phenomenon of neutrino oscillations, Takaaki Kajita and Arthur McDonald, were awarded the Nobel Prize in 2015.

Why is neutrino oscillation so important? To answer this question, we need to introduce one more protagonist, the antineutrino, the trace of antimatter in the universe.

As Professor Jan Kisiel explains, when we talk about matter and antimatter, we use the concepts of *particles* and *antiparticles*. Particles and antiparticles have identical properties, for example the same mass or spin, but they differ with regard to quantum numbers, such as electric charge or the so-called lepton number. Physicists know many such pairs. They include electrons and positrons, protons and antiprotons, or neutrons and antineutrons. The latter are electrically inert particles that differ from the quarks or antiquarks which form them.

– We treat antimatter as something unusual. However, antiparticles are found e.g. in our organisms. The human body consists mainly of matter. It is formed by such elements as oxygen, carbon, hydrogen, nitrogen, calcium, or phosphorus but also – in much smaller quantities – potassium, sodium, sulfur, magnesium, or chlorine. What is important is that some of them are unstable (radioactive) and undergo radioactive decay. This group includes a radioactive isotope of potassium ^{40}K, which as a result of $\beta+$ decay emits positrons, i.e. positive electrons which are... antiparticles, says Prof. Arkadiusz Bubak.

When a particle meets an antiparticle on its path, both are immediately annihilated and turn into pure energy. This is what happens in our body and in the universe, although we do not feel any effects of the processes that are permanently taking place. The same was probably the case shortly after the Big Bang when the universe was created.

– If the annihilation of all particles and antiparticles had taken place at that point, only pure energy would have been created. But this did not happen. Of course, the vast majority of matter and antimatter turned into quanta of gamma electromagnetic radiation, but there is a certain residue left, which is everything we know today and all that surrounds us. It has also formed us. It is estimated that 1 in 1 billion particles survived. This delicate difference was enough to create a whole universe, says Prof. Arkadiusz Bubak.

Scientists have long suspected that immediately after the Big Bang there might have been some differences in the way matter and antimatter interacted. Therefore, they started to look for traces of the source of this asymmetry in the universe. One of the theories assumes that just after the Big Bang there was a process called baryogenesis. At that time, particles such as protons and neutrons, the main components of matter, could have been formed. Soviet nuclear physicist Andrei Sakharov formulated three conditions which must be met in order to explain such a great quantitative excess of matter.

– One of the conditions is the violation of the charge conjugation parity symmetry. We already mentioned the fact that matter and antimatter have the same properties. We had also assumed that they interact in the same way. But it turns out that this might not be the case. There are some indications pointing to small differences in the interactions of particles and antiparticles, more specifically neutrinos and antineutrinos. Therefore, the key question is what these differences are and whether they were enough to cause the universe as we know it to come into existence, says Prof. Bubak.

So the right question is the following: Why is the oscillation of neutrinos and antineutrinos so important? Neutrinos and antineutrinos, like all particles and antiparticles, have the same properties and are able to oscillate, i.e. to change their flavor. So far, the results of the T2K experiment suggest that the process of oscillation itself may be slightly different for neutrinos and antineutrinos.

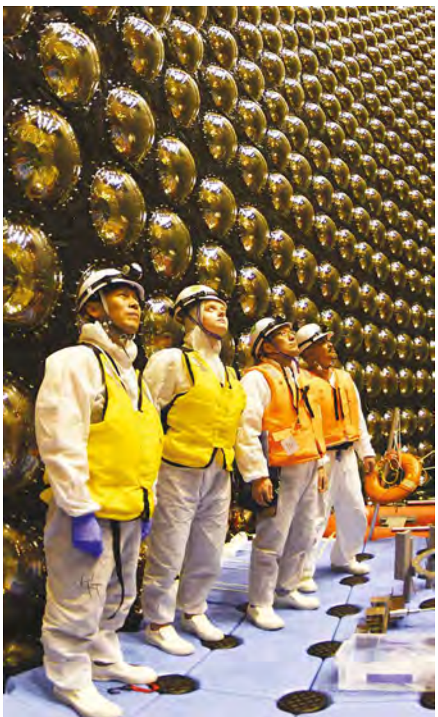


photo: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

– A beam of muon neutrinos is released from the J-PARC Center, and their oscillation into electron neutrinos is observed. Subsequently, a beam of muon antineutrinos appears, and we observe the process of their oscillation into electron antineutrinos. If the process was symmetrical, we would not notice any differences, explains Prof. Jan Kisiel. – However, it turns out that, with a certain degree of probability, we can assume that this symmetry becomes broken. This seems to be the missing element which may bring us closer to explaining the difference between the observed amounts of matter and antimatter in the universe.

However, this is still an indication, not a discovery. Therefore, physicists will continue to study the phenomenon of neutrino and antineutrino oscillations. In order to enable them to obtain even more accurate results, the infrastructure of the T2K experiment is being extended. Prototypes of two parts of the near detector are being prepared. Several segments will be modernized, which requires significant financial support and time. At the same time, work is underway to increase the intensity of the neutrino and antineutrino beams at the J-PARC Accelerator Center in Tokai. This will positvely affect the accuracy of the measurements and, ultimately, enable us to finally determine whether the assumptions of a group of several hundred physicists from around the world are correct.

The results of the research to date have been published in the article "Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations" written by scientists cooperating in the T2K experiment. The material was published in the April issue of the journal *Nature*.

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