Neutrino – a particle of the 21st century?

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At the turn of the 20th century, neutrino was certainly one of the most intensely investigated physical objects. On the list of Nobel prizes for physicists in the last twenty years, there are three prizes for work on neutrinos: in 1988 to Leon Lederman, Melvin Schwartz and Jack Steinberger for their experiment proving the existence of two kinds of neutrinos (performed a quarter of century earlier), in 1995 to Frederick Reines for the "experimental discovery of neutrino" (prize delayed by half a century!) and in 2002 to Raymond Davis and Masatoshi Koshiba for the investigations of neutrinos coming from the Sun and other "cosmic" sources. In the Science Citation Index of ISI one may check that ten years ago about 500 papers devoted to neutrino research were published yearly, and in 2005 there were more than 1400 such papers! Some of the papers published in the last decade in this field collected more than two thousand citations. How can one explain such an increase of interest in the particles which are not the components of the "ordinary" matter surrounding us and interact with matter so weakly, that they do not seem to influence it?

One should admit that the history of neutrino research is unusual. It is probably the only particle, for which we know "the birth date" with the accuracy of one day. On December 4, 1930 Wolfgang Pauli, the great German physicist (also a Nobel prize winner, but for work unrelated to neutrinos) sent to his colleagues gathered on the meeting of a local physical society the famous letter, addressing them jokingly as "honorable radioactive Ladies and Gentlemen". In this letter Pauli proposed the explanation of anomalies observed in the investigations of beta decay by the existence of a new "invisible" neutral particle, which originates in the decay beside the electron (the latter registered by the detectors). The name proposed by Pauli for the new particle was "neutron"; two years later another great physicist, Italian Enrico Fermi suggested to give this name to the neutral partner of proton, newly discovered by Chadwick, and to call the "Pauli particle" by Italian diminutive "neutrino", since the data suggested for this particle a value of mass much smaller than for proton (and electron).

Neutrino was supposed to be electrically neutral, therefore one expected that its detection should be much more difficult than the detection of electron; this explained the "invisibility" of neutrino. In fact, Pauli suggested that the probability of interaction of neutrino with matter would be not much smaller than the corresponding probability for photons with similar energies (e.g. ten times smaller). Soon, however, other eminent physicists, Bethe and Peierls estimated that this probability is smaller by many orders of magnitude. Not just Earth, but even the Sun is no obstacle for neutrinos – the probability of interaction during the passage through Sun for a single neutrino with energy typical for beta decay is much smaller than one. After this estimate was made, Pauli announced that he offers a box of champagne to the first physicist, who registers an interaction of neutrino.

The wager seemed perfectly safe, but the interactions of neutrinos with matter were in fact observed in Pauli's lifetime. It is easy to explain the rare mistake of the physicist known for his uncanny intuition: Pauli could not foresee the discovery of nuclear fission by neutrons, and the following discovery of the chain reaction of fissions, when each act of fission leads to the emergence of a few "new" neutrons, leading to the next fissions. Such a process occurs in a nuclear bomb, and (in controlled form) in a nuclear reactor. The enormous number of free neutrons and neutron-rich nuclei originating in this process and decaying via beta decay produces the flux of neutrinos millions times stronger than any sources known in 1930. Even if the probability of interaction in our detector is of the order of one trillionth for a single neutrino, we shall certainly register some interactions, if many trillions of neutrinos pass through our apparatus!

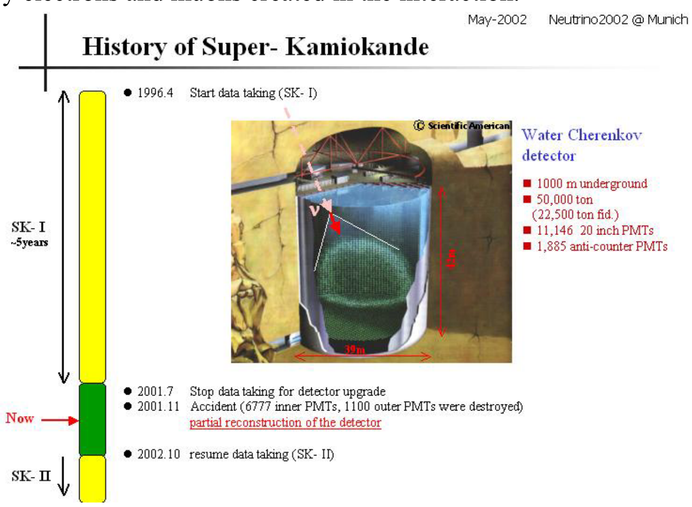
In fact, such an experiment is very difficult, since the reactor is of course the powerful source of many kinds of radiation, and it is difficult to discern the neutrino interaction from all other possible processes. It requires very sophisticated experimental methods, which we shall not discuss here; an interested reader may find the details in many textbooks and popular essays. Frederick Reines, mentioned above, conducted such investigations with his collaborator, Clyde Cowan Jr. (who, unfortunately, did not live long enough to get the Nobel Prize) for quite a few years in the 1950's. They had to transfer their equipment from Hanford to a new, more powerful reactor in Savannah River, before they succeeded. The discoverers notified Pauli, but never got even the congratulations, not to mention the champagne which was drunk by Pauli and his collaborators...

In the meantime it was discovered that the nature provided us with a commonly available source of neutrinos, offering the flux comparable to those produced in the nuclear reactors. This source is our Sun, which draws the energy from the nuclear reactions running in its interior. The number of neutrinos born during these processes is so enormous, that even on Earth, at the distance of 150 million kilometers, their detection is possible. Every second more than 60 billion neutrinos from the Sun pass through each square centimeter of Earth surface (or the surface of our bodies). Fortunately, few of them interact during our lifetime.

The registration of neutrinos from the Sun is, however, not easy. Raymond Davis, mentioned above, constructed in 1950's a detector, whose main element was a big tank filled with carbon tetrachloride (a cheap cleaning fluid) and placed it in an old mine Homestake in the US. Neutrinos penetrated through the surface of Earth and several kilometers of rock (which absorbs most of other kinds of cosmic radiation) and interacted with chlorine nuclei inside the tank, converting them into radioactive argon nuclei. Every few weeks the tank was flushed with gas, which “collected” argon, and then the decays of argon nuclei were registered, measuring the number of neutrino interactions. The result was surprising: for almost fifty years one systematically registered only a half of the number of interactions predicted by the theory! It seemed that there are only two possible explanations: either the detector was “losing” events, or the Sun was emitting less neutrinos than it should.

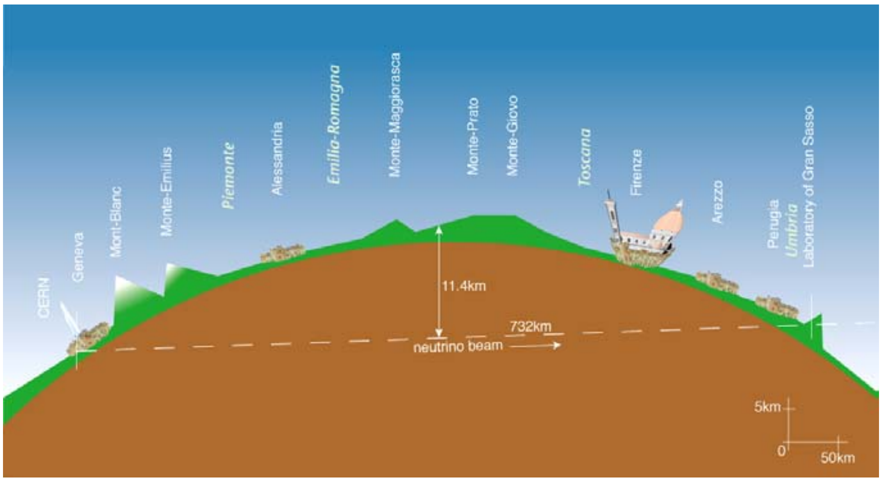
Finally, however, both the analysis of experiment and the theory describing the Sun were verified to be correct. The effect responsible for the observed “deficit” was different: the neutrinos born in Sun were transformed on their way to Earth into different kind of neutrinos, for which the detector was “blind”.

The existence of two different kinds of neutrinos was proven in 1962 by the experiment of Schwartz and collaborators mentioned already above, and the third kind of neutrinos was discovered in the next decade (and directly registered only in the XXI century). The neutrinos of two new kinds could not interact in the way employed in the Davis experiment, which explained the observed deficit. The consecutive experiments confirmed that neutrinos transform on their way from the Sun, and the similar effect appears also for the neutrinos born in the Earth atmosphere from the decay of particles created by cosmic rays. The key experiments for the “atmospheric” neutrinos were “Kamiokande” and “Superkamiokande”, initiated by Masatoshi Koshiba, another Nobel Prize winner, in the old Kamioka mine in Japan. The interactions of neutrinos in the underground tank (containing 50 thousand tons of ultra pure water) were registered by the Cherenkov radiation emitted by electrons and muons created in the interaction.



The effect of transformation, the so-called neutrino oscillations, is a quantum effect, and its analysis requires the use of advanced mathematical methods. It is very important that oscillations can occur only for particles with non-zero mass. Till now, no experiments allowed to measure the neutrino masses; only the upper bounds were found. These bound were set so low at the end of 20^{th} century that neutrinos were found to be more than hundred thousand times "lighter" than electrons, the particles with smallest measured mass. It seemed natural to assume that neutrinos have zero mass. Now we learned it is not true! This requires significant modifications of the standing model of elementary interactions, so-called standard model.

The neutrino oscillations are so fascinating that physicists decided to investigate them in the neutrino beam which is better controlled than that of neutrinos from the Sun or from Earth atmosphere. The neutrinos were sent to the Super-kamiokande detector from KEK accelerator centre, few hundred kilometers away. Let us note that such a beam does not require any beam pipe – the Earth, as already mentioned, is practically transparent for neutrinos. The first results from this experiment called "K2K" confirm the earlier data for oscillations. We hope that the next experiment, where the neutrino beam from the CERN laboratory near Geneva will be sent under Alps to the underground Gran Sasso laboratory, 700 km away, will yield more accurate data on oscillations, which would help to determine the neutrino masses and to explain theoretically their values.



The facts presented above do not exhaust the rich list of reasons, why the neutrino physics is so attractive. The neutrino oscillations were investigated in

Japan by another experiment, in which the neutrinos from all the reactors within the thousand kilometer range were registered. It is easy to imagine that a similar experiment may serve as a "reactor remote control" once the oscillation theory is well established. The in situ missions of inspectors will no longer be necessary to check if some rogue country obeys IAEA rules. Recently, a project on the verge of science fiction ideas was presented: a powerful neutrino beam may destroy illegal stores of nuclear weapons from arbitrary distance.

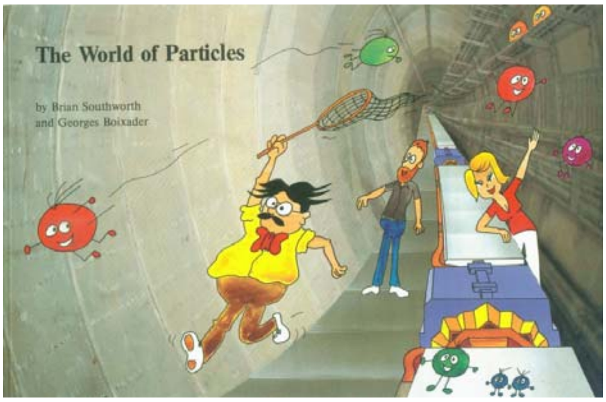
Another application of the same detector was a recent experiment in which the net radioactivity of the Earth interior was measured. The results suggest that the standing models of our planet should be modified: it seems that the radioactive decays were more relevant for the Earth history than generally believed. Great hopes are set on the future investigations of cosmic neutrinos, which may provide a "tomography picture" of the Earth interior, which they penetrate as easily as X-rays penetrate our bodies.

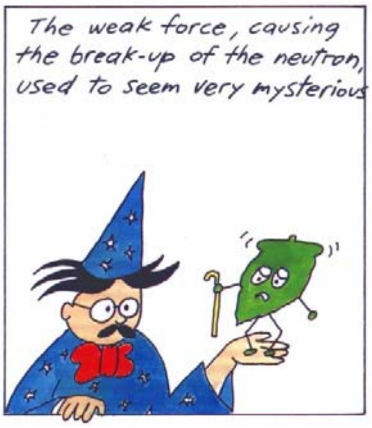
We expect also that the role neutrino research has played in the understanding of processes occurring in the Sun (and the registration of neutrinos from a Supernova explosion, which occured in 1987) were just the first steps of a new branch of science: neutrino astrophysics. The investigation of neutrinos from the Sun was so valuable because neutrinos created in the centre of Sun emerge "intact" on the Sun surface after only a few seconds, whereas photons interact so often, that they need thousands of years to pass this way. Our knowledge of the processes occurring in more "exotic" astrophysical objects (e.g. in the galactic nuclei) is based solely on the electromagnetic radiation, and thus very indirect and distorted. If we learn how to register neutrinos from such sources, we shall certainly learn many new facts and phenomena.

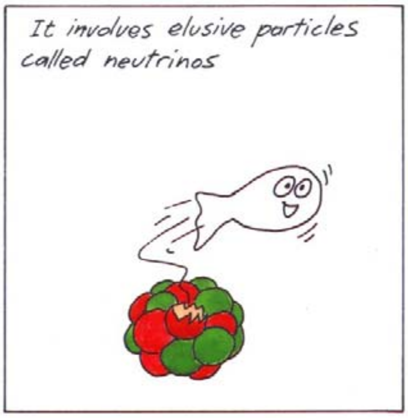
Many physicists believe that the 21st century will be the "neutrino century", when these particles will cease to be just an object of basic research, and will serve as new valuable tools of applied science and technology. It seems fit to mention here that our eminent writer Stanisław Lem used neutrino physics as a base of two of his novels. In "The Master's voice" the cosmic "older brothers" use the neutrino beam to code the message which men strive to decode, and in "Solaris" the "thinking ocean" constructs from neutrinos the stable systems, which imitate the people reconstructed from human thoughts. The first idea is feasible (although unlikely to occur exactly along the lines presented in the novel), the second one seems to contradict the known physics – but who can predict the future...

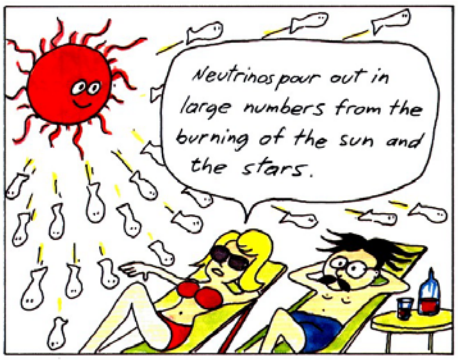
/from *Foton* 92/

About neutrinos from CERN – comic



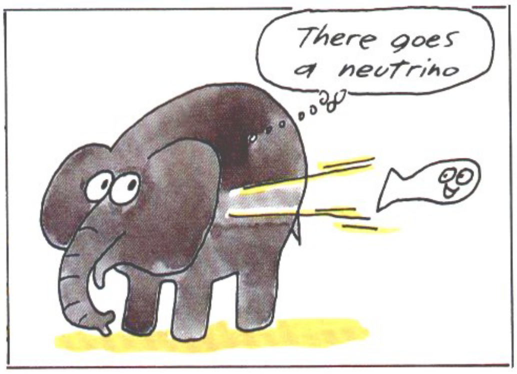







As the stars shine, neutrinos are being made and the weak force is at work


They are so averse to other particles that they can pass through the whole earth without difficulty. Thousands of them are passing through you now


There goes a neutrino