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Neutrino physics for 50 years of the Institute

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Abstract The experiments important for the understanding of week interactions, and neutrino properties are discussed. The unresolved problems of neutrino physics and plans for the experiment in medium and long time scale are presented. Brief description of cosmological ν is given.

Key words neutrino mile stone experiments • astrophysics neutrinos

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Introduction

> *I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.*
>
> Wolfgang Pauli

Pauli was not mistaken – the neutrino exists, but due to the very low cross-section, is extremely difficult to detect. However, neutrino physics is probably one of the most dynamic branches of science in the last several years. There are several reasons for this – an important development of accelerating and detection techniques, discovery of the neutrino oscillations and in a consequence discovery of nonzero neutrino mass. There is also a psychological reason. Neutrino physics is fascinating, whereas hadron accelerator physics is in a kind of stagnation.

Historical remarks

Neutrino is born

In 1930, W. Pauli in his famous letter addressed to "*Dear radioactive ladies and gentlemen*" proposed the existence of ν – particle which should be very light, neutral, weakly interacting, carrying spin $^1/_2$. Such particle was necessary to understand the energy spectrum of electrons observed in nuclear β decay. Pauli was aware that ν will be impossible to observe – and, as it turned out, he was close to the reality.

First observation of antineutrino interactions [10, 33, 34]

In 1956, the existence of ν was experimentally confirmed. A nuclear reactor produces very high fluxes of anti ν from β decays. Anti ν interacting with proton produces neutron and positron: anti ν + p → n + e^+. Covan and Reines observed this reaction in an experiment where a liquid scintillator tank with an admixture of $CdCl_2$ was used as the target. By an annihilation with electrons the positrons produce two 0.5 MeV photons. The neutrons are not observed directly but when absorbed in Cd they produce an excited state which subsequently emits photons: $n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$. This provides a distinctive signature for the anti-neutrino reaction – 2 simultaneous photons from e^+-e^- annihilation in a delayed by about 5 μs coincidence with another photon.

Milestone experiments – understanding of weak interactions

It is not the aim of this talk to list all important experiments which contributed to the understanding of weak interactions. However, in my opinion one should remember three historical experiments: that of Chien-Shiung Wu, that of Maurice Goldhaber and Gargamelle Collaboration under the guidance of André Lagarrigue, André Rousset and Paul Musset.

Chien-Shiung Wu experiment [40]: parity is not conserved in β decay

In 1956, T. D. Lee and C. N. Yang, had proposed that the parity[1] did not hold for weak interactions. However, Lee and Yang could not prove their theory but Chien-Shiung Wu did. Before C. S. Wu's experiment, physicists believed in parity conservation, that is, that nature is not biased toward left-handed or right-handed systems.

In Wu experiment the radioactive ^{60}Co cooled to the temperature of 0.01 K was placed in a strong magnetic field. The angular distribution of electrons emitted by ^{60}Co in the decay ${}^{60}Co \rightarrow {}^{60}Ni + e^- + \nu$ was measured. Electrons were emitted preferentially in the direction opposite to the direction of the magnetic field and, therefore, opposite to the nuclear spin showing parity violation. Wu experiment proved the existence of parity violation, which radically altered modern physics. After the conclusions of this experiment were confirmed, Lee and Yang won the Nobel Prize for Physics; however, Chien-Shiung Wu was overlooked.

Maurice Goldhaber experiment [16]: neutrino is a left-handed particle

During the fifties of last century, first accelerators were starting to produce evidence for the existence of strange particles. They were produced in pairs in a strong interaction, and were slow to disintegrate. Studies of the properties of strange particles were important for understanding the weak interactions which governed the decay of the neutron and "strange" particles. Already in 1935, Fermi formulated the formalism for calculations of the weak interaction processes. In the presence of parity violation the Fermi mechanism of weak interactions should be modified. The question was which combination of couplings describes beta decay.

Either in beta decay[2] neutrino is produced with negative helicity[3]: or, the neutrinos are produced with positive helicity, i.e. spin parallel to the direction of motion ("right-handed" neutrinos).

The experiment of Goldhaber is very clever and probably one of the most elegant ever done. The idea of the experiment is based on the angular momentum (spin) conservation. To measure the neutrino helicity Goldhaber with collaborators studied the capture of an inner electron in ^{152}Eu, (a spin 0 radioactive nucleus with short lifetime) and its subsequent decay into an unstable, spin 1, $^{152}Sm^*$ and neutrino: ${}^{152}Eu + e^- \rightarrow {}^{152}Sm^* + \nu_e$. $^{152}Sm^*$ nucleus decays (with the lifetime of 0.07 ps) into ^{152}Sm (spin = 0) + γ. From the angular momentum conservation, the direction of the spin of the photon must be the same as the direction of the neutrino spin. The direction of spin of photons is measured by scattering on electrons in an Fe target polarized by magnetic field. The helicity of neutrinos measured by Goldhaber turned out to be negative.

Under the parity transformation, left-handed particles become right-handed (or *vice versa*), but only left-handed neutrinos exist. This confirms the parity is violation in weak interaction!

Experiment of Gargamelle Collaboration [18] neutrino couples to Z^0, the neutral carrier of weak forces

In 1967–1968, S. Glashow, S. Weinberg and A. Salam developed the Standard Model of Electroweak Interactions (SM), which unifies electromagnetic and weak interactions. SM proposes a theoretical description of the basic constituents of matter and the fundamental forces of nature. A very important prediction of the SM was the existence of a neutral Z-boson, heavy carrier of electroweak interactions. Fermi theory predicted only its charged partner – boson W. The reactions such as $\nu_\mu e^- \rightarrow \nu_\mu e^-$ (neutral current interaction, for which the Z^0-boson is responsible), were not allowed in the Fermi's theory.

In 1973, the experiments with neutrino and antineutrino beams were performed at CERN. Protons were accelerated by the CERN Proton Synchrotron. Neutrinos and antineutrinos were produced in the decays of charged pions and kaons produced in proton interactions with dedicated target. Neutrino interactions were detected in the large bubble chamber – Gargamelle, filled with 15 tons of freon (CF_3Br). Gargamelle Collaboration proved the existence of neutral current – ν interactions (anti ν interactions) without production of a charge lepton.

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[1] Parity – invariance under left-right, i.e. symmetry of mirror image and object.

[2] A neutron decays into a proton, an electron, and an anti-neutrino.

[3] Spin of antineutrino is anti-parallel to the direction of motion ("left-handed" antineutrino).

Milestone experiments – properties of neutrinos

Several people and several detectors contributed to understanding the properties of neutrinos. It is not possible to mention all of them. In my opinion the results of the following experiments should be considered as milestones in the present knowledge of neutrino physics. They answer two important questions – what are the neutrino masses and what is the number of neutrino flavors?

How many neutrinos exist in Nature?

Ledermann–Steinberger–Schwartz experiment – discovery of muon neutrino [11, 26]

In 1962, experiments at Brookhaven National Laboratory and CERN, made a surprising discovery: neutrinos from π decay ($\pi \rightarrow \nu + \mu$) produce only muons. They do not behave in the same way as those produced in association with electrons. Experiment of Ledermann–Steinberger–Schwartz proved the existence of a second flavor of neutrino (ν_μ) after the electron antineutrino was discovered by Covan and Reines.

Discovery of ν_τ – DONUT experiment in FERMILAB [25, 30]

The first two flavors of neutrinos observed were the electron and muon flavors. The existence of tau neutrino was predicted. The production of τ in charge current reaction: $\nu_\tau + N \rightarrow \tau + N'$ is difficult to observe for two reasons: the reaction threshold requires ν_τ of high energy and the exceedingly short lifetime of τ.

In 2000, the direct evidence of the reaction $\nu_\tau + N \rightarrow \tau + N'$ was presented by an experiment done at FERMILAB. A block of emulsions was irradiated by neutrinos produced by high energy (800 GeV) protons dumped on a target. Lepton τ produced in the emulsion block, after traveling about 1 mm decays into charged particles. Emulsion detector gives a unique possibility to observe production and decay vertex. The analysis of both vertices allows the identification of the appearance of τ. DONUT experiment observed ~10 events of τ produced by charge current. No one has previously observed the interactions of ν_τ directly. In this experiment, the existence of the third neutrino was confirmed.

Invisible width of Z^0 – results of the LEP experiments [1–3, 9, 14]

The measurement of the total number of neutrino flavors is based on a completely different principle. This number is obtained from the measurement of the energy dependence of the cross-section for Z^0 production: $e^+e^- \rightarrow Z^0$ with the subsequent Z^0 decay into VISIBLE fermion–antifermion pair. The dependence of the cross-section on the energy of e^+e^- has the resonance behavior with characteristic width, which depends of the number of all decay channels of Z^0.

In 1989, the accelerator LEP collided for the first time the e^- and e^+ beams at the energy close to the Z^0 mass. The experiments ALEPH, DELPHI, OPAL and L3 determined the number of ν flavors from the width of Z^0 cross-section energy dependence. Number of ν flavors determined by LEP experiments is $N_\nu = 2.984 \pm 0.008$.

Probably no fundamental fermions remain to be discovered.

In 1995, F. Reines got the Nobel Prize for Physics for the detection of the electron antineutrino. (Cowan had died some years before.) For discovering the muon neutrino, L. Lederman, M. Schwartz, and J. Steinberger won the Nobel Prize in 1988.

The neutrino physics is a very dynamical field of research – several excellent experiments contributed to understanding a very important fact – neutrinos are not massless. The results of "solar neutrino deficit" experiment, atmospheric neutrino experiment of Super-Kamiokande collaboration and the most recent heavy water SNO experiment greatly contributed to understanding neutrino properties.

Are the neutrinos massless?

Pauli postulated that the neutrinos are massless. This fact was included by E. Fermi in his theory of weak interactions and in the Standard Model of Electroweak Interactions. If the neutrino masses are different from zero, the Standard Model would not be sufficient to describe the reality.

Solar neutrino deficit – experiment of R. Davis [12, 23]

Inside a star such as our Sun, the conditions are such that the hydrogen nuclei fuse: $4\,^1H \rightarrow {}^4He + 2e^+ + 2\nu$. In the chain of hydrogen burning reactions heavier elements are produced. One of them is ^8B which decays into $^8Be + e^+ + \nu$.

The difficulty of the experiment to detect solar neutrinos consist in the very small ν cross-section – from 10^{11} neutrinos/s hitting each cm^2 of Earth surface the large majority of them pass through Earth without interacting. The first attempt to measure the solar neutrino flux was made by Davis. The detector of Davis's experiment (1960) consisted of a pool of 600 t of C_2Cl_4. To avoid the background from cosmic ray it was set-up in the old, deep gold mine. Only ^8B neutrinos have enough energy to produce ^{37}Ar nuclei in reaction $\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$. The reaction rate was very small, but after a long time of exposure the Ar atoms were detected.

The results of Davis's experiment, and of several others designed to detect solar neutrinos, were unexpected. They found about half of the number of neutrinos expected by Standard Solar Model. There were two possible explanations of solar neutrino deficit: either the models of the Sun are wrong, or some physical process changes the solar electron neutrinos during their flight from the Sun to Earth and they became undetectable.

Super-Kamiokande studies of atmospheric neutrinos [37–39]

The Super-Kamiokande (SK) detector placed in an underground laboratory consists of a huge 50 kt tank of ultra pure water, which is observed by ~10,000 large photomultipliers. Charged particles traveling at a speed greater than the speed of light in water emit the Cerenkov light. The timing, intensity and pattern of light signal registered by the phototubes allow determining the particle's direction, energy and most important the nature of charged particle.

On June 5, 1998, the SK collaboration announced the historical discovery: their data show the evidence for nonzero ν mass. The analysis was based on "atmospheric" neutrinos with energies >500 MeV. By classifying the neutrino interactions according to the type of charged lepton produced (electron or muon) and measuring the angular distributions (the angle is a function of the distance ν traveled from the creation point in the atmosphere to the detection point) SK team concluded that the ν_μ traversing the long distances are disappearing. This disappearance was explained by the phenomena of "oscillations" into undetectable ν ($\nu_\mu \to \nu_\tau$ and/or a sterile, non interacting ν_s).

The SK experiment did not determine the masses of neutrinos, but under the hypothesis of oscillations the difference of neutrino masses. The rate of disappearance of ν_μ allowed concluding that the difference in masses between the oscillating types of neutrinos is very small.

Oscillation – short introduction

The changing of a neutrino's flavor as it travels through vacuum and/or matter has an oscillating character. Observation of this phenomenon would indicate a nonzero neutrino mass, nonzero mixing angle and the non-degeneration of neutrino mass states.

In 1957, the idea of neutrino-antineutrino oscillation was first considered by B. Pontecorvo and later the possibility of neutrino oscillation was pointed out by Pontecorvo [31] and Z. Maki, M. Nakagawa, and S. Sakata [27]. If the neutrinos have nonzero mass then it is possible that the mass, states and the weak states are not the same. If the observed neutrinos are not quantum states of well defined mass they would be the mixture of different mass eigenstates[4].

Weak interactions produce neutrinos with well defined flavors. Mass states propagate through vacuum (and/or matter) with different velocities producing neutrinos of different flavors which weakly interact. It was experimentally confirmed that leptons form doublets (ν_e produces an electron; ν_μ produces μ, ν_τ and τ) therefore, if the interaction is mediated by the charge current the flavor of interacting neutrino would be known.

For the sake of clarity, I will discuss the formalism of oscillations in a model with 2 neutrino eigenstates of mass (ν_1 and ν_2) and 2 flavors (ν_α and ν_β).

Neutrinos of a given flavor are the mixture of eigenstates of mass neutrinos

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} * \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The probability of transformation of ν_α into ν_β is given by: $P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - \sin^2 2\theta * \sin^2 (1.27\ \Delta m^2\ L/E)$, where θ is the mixing angle; $\Delta m^2_{12} = m^2_1 - m^2_2$ [eV^2]; L [km] is the distance from the source, where ν_α is produced to the detector where ν_β is observed and E [GeV] is the energy of neutrino.

In a realistic case of 3 neutrino flavors the number of oscillation parameters increase and the formulae became more complicated. In the simplest case the mixing matrix (known as Pontecorvo, Maki, Nakagawa, Sakata – PMNS matrix) is defined by 3 mixing angles $\theta_{12,}$ θ_{13} and θ_{23} and a phase δ responsible for CP violation. The probabilities of oscillations are the functions of mixing angles and 2 mass differences Δm^2_{12} and Δm^2_{23} The message is basically the same as in a case of 2 neutrino oscillations – the frequency of oscillation probability depends on Δm^2_{ij}, and L/E ratio, the amplitude is a function of mixing angle (angles). The ratio L/E can be controlled experimentally and the choice of its value is very important in "long base line" experiments.

Sudbury Neutrino Observatory (SNO) [35] experiment

In the presence of oscillations, the solution of the solar neutrino deficit requires independent measurements of the fluxes of all neutrino flavors.

Filled with heavy water the SNO detector could measure the ν_e component, $\Phi(\nu_e)$, of the ^{8}B solar neutrino flux of all neutrinos, $\Phi(\nu_x)$. The flux of non-electron neutrinos is given by the difference, i.e. $\Phi(\nu_\mu) + \Phi(\nu_\tau) = \Phi(\nu_x) - \Phi(\nu_e)$. SNO can measure these fluxes via the different ways in which neutrinos interact with the D_2O:

1) Measurement of $\Phi(\nu_e)$. Proportional to this flux is the number of charged current events: $\nu_e + d \to p + p + e^-$. In this reaction a W boson is exchanged. The electron gets most of the neutrino energy and emits the Cerenkov radiation which is detected by the photomultipliers.
2) Measurement of the flux of neutrinos with all flavors ν_x:$\Phi(\nu_x)$. Proportional to this flux is the number of neutral current events $\nu_x + d \to p + n + \nu_x$. In this "neutral current reaction", the neutral Z^0 boson is exchanged. This reaction is equally sensitive to all three neutrino flavors. The signatures of it are photons emitted when the neutron is captured by another nucleus. Neutrons can be captured directly on deuterium, but to increase the efficiency of neutron detection ^{35}Cl (NaCl) has been added to the heavy water. The photons will scatter electrons which produce detectable Cerenkov light.
3) The cross-section for electron scattering $\nu_x + e^- \to \nu_x + e^-$ is sensitive to 3 neutrino flavors, but it is

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[4] The neutrino with the highest electron neutrino content is called ν_1, the neutrino with the next to-highest electron neutrino content is ν_2 and the neutrino with the smallest electron neutrino content is called ν_3.

dominated by the σ (ν_e e). The number of events of electron scattering is proportional to the flux $\Phi(\nu_e) + 0.15(\Phi(\nu_\mu) + \Phi(\nu_\tau))$, because ν_e can interact with electrons via Z^0 or via W exchange, whereas ν_μ and ν_τ only via W exchange. This reaction can also be measured in light water detectors.

The total flux of solar neutrinos as measured by SNO equals to $\Phi(\nu_x) = 5.09{*}10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ in an excellent agreement with Standard Solar Model predictions. The electron neutrino flux measured by SNO is in agreement with the earlier measurements.

Oscillations – present knowledge

The oscillation parameters θ_{23}, θ_{12} and Δm^2_{12} and Δm^2_{23} were measured in several experiments with different neutrino flavors, distances detector – source and ν energies.

The experiments were performed with atmospheric neutrinos (mixture of ν_e and ν_μ), solar neutrinos, reactor electron antineutrinos and accelerator electron and muon neutrinos (antineutrinos).

The distance source – detector changed from ~100 km for reactor antineutrino KAMLAND [6, 15] experiment, ~15,000 km in Super-Kamiokande experiment where the atmospheric neutrinos traversing Earth were observed, up to the distance Sun–Earth in SNO, Super-Kamiokande and "solar deficit neutrino experiments".

The energies varied from ~MeV (reactor antineutrinos, solar neutrinos) to few GeV (atmospheric neutrinos). Up to now K2K [21] is the first and unique "long base line" accelerator experiment which published the results. Neutrino beam of ~1 GeV energy after traveling the distance of 250 km is observed in the detector Super-Kamiokande. The results K2K [4, 5] confirmed those of SK obtained in studies of interactions of atmospheric neutrinos.

To summarized [17]: here are the main results obtained in the neutrinos experiments: two mass differences – Δm^2_{12} and Δm^2_{23} where measured. The present value of $\Delta m^2_{23} = 2.2 \times 10^{-3}\ \mathrm{eV}^2$ and $\Delta m^2_{12} = 8.1 \times 10^{-5}\ \mathrm{eV}^2$. The values of neutrino masses and the relation between the values of m_1, m_2 and m_3 (mass hierarchy) are not known.

In neutrino mixing matrix 2 angles are large (θ_{23} is close, or equal, to the maximum value of 45°, $\theta_{12} \sim 33°$). Angle θ_{13} is very small and only the value of its upper limit is known. There is no experimental information about the value of phase δ.

The oscillation experiments are not able to measure the masses of neutrino eigenstates.

The following upper limits of effective masses were obtained from the direct measurement: $m(\nu_e) < 3$ eV, $m(\nu_\mu) < 0.19$ MeV, $m(\nu_\tau) < 18.2$ MeV [29].

What is the nature of ν – is ν its own antiparticle – double β decay

The Standard Model considers ν as massless particle. It exists in the form of a left-handed ν or a right-handed anti ν. Anti ν is distinguished from ν by lepton number, (+1 for ν and –1 for anti ν of a given flavor). According to the Standard Model, weak interactions conserves the lepton number. The charged particles can be described as Dirac particles (a particle and an antiparticle have the opposite sign of the electrical charge). The neutrino is electrically neutral and the distinction between a particle and its antiparticle is not obvious. Very important is the question whether the ν is its own antiparticle. It is possible that the anti ν and the ν are the same particle (i.e. Majorana particles), with different helicity.

Double beta decay allowed by the Standard Model $(Z,A) \rightarrow (Z + 2,A) + 2e^- + 2\nu(2\nu\ \beta\beta$ decay) is a rare process with half-live time of about 10^{18} (or greater) years. Neutrinoless double β decay $(Z,A) \rightarrow (Z + 2,A) + 2e^-$ ($0\nu\ \beta\beta$ decay) is forbidden in the Standard Model because of total lepton number conservation. Studies of $0\nu\ \beta\beta$ decay seem to be the only realistic method for determining if the ν is a Majorana or Dirac particle.

The experiment Heidelberg–Moscow reported the first observation of neutrinoless double β decay of ^{76}Ge → ^{76}Se. The Authors [24] claim an effect of 4.2σ. Their value of lifetime for this decay channel is: $T^{0\nu}(1/2) = (1.19 + 0.37–0.23) \times 10^{25}$ years. This would be the slowest nuclear decay ever observed in Nature.

Future of ν accelerator physics

What should be measured?

Some of the parameters of PMNS mixing matrix are very difficult to measure and they remain either unknown (phase δ) or only the upper limit was measured (θ_{13}) [19]. Unknown remains also the neutrino mass hierarchy. Several long base line experiments aiming at the measurement of mixing parameters are in a different stage of realization. The most important goal of new generation of long base line experiments will be the measurement of the transition of muon neutrino into electron neutrino. The probability of this process is controlled by the mixing angle θ_{13}. This angle is either very small or zero.

Keeping in mind that the neutrino interaction rate is proportional to the mass of the target, and the flux of the neutrinos, whereas the oscillation probabilities are the function of L/E ratio – the interconnected problems which should be discuss simultaneously are the unresolved physics questions, the detectors, their distance from the neutrino source and neutrino beams.

What next

Short term projects

In a reasonable future, accelerator neutrino physics will be studied in the detectors either existing or being under construction. All of them are placed in laboratories deep under the Earth surface to decrease the cosmic ray background. The masses of the detectors vary from ~2 kT (ICARUS) to 50 kT (SK).

The detector MINOS (5.4 kT) is irradiated by NUMI – low energy neutrino beam from FERMILAB to SUDAN mine at a distance of 735 km. It started to take data very recently – it is therefore difficult to judge its performance, but the technology applied is a very safe and classical for ν calorimeters. The observation of probability $P(\nu_\mu \to \nu_x)$ as a function of L/E ratio (which will probably be measured by MINOS) would confirm the understanding of oscillation picture.

In 2006, CNGS (high energy neutrino beam from CERN to Gran Sasso at a distance of 730 km) should send neutrinos to two detectors. These detectors: OPERA and ICARUS are being installed in the underground laboratory of Gran Sasso.

OPERA (1 kT) experiment will eventually observe ν_τ by detection of the decays of taons produced by neutrinos in emulsion blocks. The very severe limitation of OPERA data would be statistic.

Completely new technique is used in the construction of ICARUS a Time Projection Chamber filled with liquid argon (LAr). The cosmic ray test of a 300 t module of ICARUS turned out to be satisfactory. The final mass of ICARUS should be 1.8 kt of LAr. Its principal experimental advantage would be the prefect energy and a good spatial resolution.

In 2009, J-PARC low energy, very high intensity, neutrino beam would be aiming at a Super-Kamiokande distant of 290 km (T2K [21] experiment). SK is the water Cerenkov detector which is well understood, and had proven its merits in studies of atmospheric neutrinos, solar neutrinos and in K2K experiment. T2K experiment will probably be able to measure θ_{13}.

- Polish Neutrino Group – consists of physicists and students from the Academy of Mining and Metallurgy in Kraków, Institute of Nuclear Physics in Kraków, and Institute for Nuclear Studies in Warsaw, Silesia University, Warsaw University, Wroclaw University and Warsaw Technical University. We are member of ICARUS Collaborations. Some of us are members of Super-Kamiokande, K2K and MINOS Collaborations. In the near future we would like to join T2K Collaboration which is planning to construct LAr detector 2 km from the accelerator target. We believe that our expertise in understanding LAr detector gained when analyzing the ICARUS data will be valuable.

Long term future

The decisions concerning future experiments must take into account several factors. The decisive would be the results obtained in running experiments and in those being in preparation (especially important would be the value of θ_{13}). The most important studies would be the CP non conservation in leptonic sector (phase angle δ).

In planning the future, among the factors which should be taken into account there is a choice of *L*/*E*, *E*, effects of matter, detector design, ratio signal to background, statistics and costs.

- Detectors planned should be very large, reliable; with appropriate performance and what is very important have an acceptable cost. The very large scale of future detectors requires an intensive R&D.

It should be stressed than in charge current interactions flavor of outgoing lepton tags flavor of neutrino, whereas charge of outgoing lepton determines if it was an interaction of a neutrino or antineutrino.

Several technologies are under discussion, the main of them are:

1. Low-Z Calorimetry
2. Water Cerenkov
3. Magnetized Iron Sampling Calorimetry
4. Liquid Argon TPC

Low-Z calorimetry, applied in (the project of) the detector NOvA [32] is an evolution of a proven technique. NOvA mass should be 30 kt, i.e. ~10* that of MINOS, however different and cheaper materials would be used. If the construction of NOvA starts in the late 2006, as foreseen, 30 kt should be fully operational in 2011. Main issue of the construction is to improve performance and to reduce cost of trackers. For accelerator operation, NOvA does not need an underground location, since the sensitive time would be ~100 s/year. I believe that NOvA is the only project approved already. For this reason, I am going to mention the other potential techniques of large scale detectors, without going in any details.

Water Cerenkov detectors is a proven technique. SK – large water Cerenkov is a detector the performance of which has been simulated AND observed. It is, therefore, not surprising that there is a lot of discussions concerning the construction of HYPER K (mass 2*500 kt) and/or UNO detectors [36]. The draw back of water Cerenkov detectors is relatively low performance at high energy due to the difficulty in the analysis of higher multiplicity events with several rings of Cerenkov light.

The technique of magnetized iron sampling calorimeter was proven on a smaller scale. One probably can reach target mass of the order of 10* mass of MINOS. This technique has a great advantage. It allows the measurements of the sign of a muon charge.

Liquid argone time projection chambers is proven to work on a small scale. There are a number of projects to build a detector containing to ~100 kt of LAr. This requires the solution of several cryogenic problems. In particular, the purity of LAr should be such as to allow the sufficient life time of drift electrons.

- Beams. The construction of a further neutrino beams is an open problem. The most classical solution is a "super beam". The intensity of ν beam results from the enormous power of initial proton beam dumped on a target. An example of a super beam would be ν line at the J-PARC. In the second stage of operations the initial value of 0.75 MW of proton beam would be increased to 4 MW.

Large effort has been made in R&D area for studying the feasibility of "neutrino factories", based on storage and acceleration of muon beam. The muon beam should be produced, cooled, bunched and accelerated within the muon (Lorenz boosted) lifetime. There is not much time to do that. Neutrinos of 2 flavors will be produced by the muon decays. Intensity of such a beam could be very high; however this technology seems to be extremely difficult.

Other possibility is a neutrino beam produced in beta decay of radioactive, short lifetime, ions. The β decays of accelerated ions will produce narrow, pure electron neutrino (antineutrino) beam.

At the moment it is not clear which solution will prevail.

- Accelerator – detector distances. In the future accelerator experiments the distances source – detector would vary from 300 km to 3000 km. J-PARC beam to SK detector (experiment T2K) has a length of ~300 km. Hyper-Kamiokande, if it would ever be built, would be close to Super-Kamiokande. From Brookhaven National Laboratory to the site in New Mexico the distance is ~3000 km. An interesting possibility for Europe would be the organization of the underground laboratory in the old salt mine in Sieroszowice (Poland) 900 km from CERN. The radioactive background measured in this mine is very low.

Neutrinos in the Universe

In the Universe, neutrinos with a very broad energy spectrum should exist.

Studies of neutrinos can answer several important and fascinating questions about the mechanisms of processes taking place in the Universe and of particle acceleration.

Neutrino is an obvious candidate for being an excellent messenger carrying the information from the Universe – as it is neutral its direction is not influenced by magnetic fields. Neutrinos interact weakly and, therefore, they can carry information from the very dense and/or very distant sources. Unfortunately, they are difficult to observe.

Relict neutrinos

If our understanding of the development of the Universe in first few seconds after the Big Bang is correct, very low energy (<< 1 eV) relict neutrinos would exist. They are decoupled from the rest of the Universe 1 s after the Big Bang, and cooled down during 13 Gy of the Universe expansion. Relict neutrinos are not observed, and because of their very low energies it is doubtful that they ever would.

Solar neutrinos

Few MeV ν_e are produced mostly in the fusion $4p \rightarrow 4He + 2e + 2\nu$. This "H burning" reaction chain takes place in star nuclei. It lasts as long as a star belongs to the main sequence. For a star with a mass of the order of the mass of our Sun, this period is ~10 Gy. The properties of solar neutrinos were studied by several researchers, and are well known. The flux of solar neutrinos is correctly described by the Standard Solar Model.

Supernova neutrinos

In a gravitational core collapse of a supernova (SN type II) 90% of energy is carried out by neutrinos and antineutrinos of all flavors with the average energy in the 10–20 MeV range. Burst of SN neutrinos is short – it should last about 10–20 s. Such a burst was probably produced by the explosion of SN 1987A (a blue super giant Sanduleak –69° 202) as several close in time ν interactions was observed by 3 detectors (IMB [8], Kamiokande [20] and Baksan). At present, few large neutrino detectors are waiting to register a ν burst produced in an SN explosion. It could be observed provided the distance to SN is of the order of several kpc.

Extragalactic neutrinos

Very high energy neutrinos (with energies >> 1 TeV) pointing towards the extragalactic sources are searched for. Such neutrinos would be an unambiguous signature of proton accelerating region in the Universe. Protons could be accelerated in Supernova Remnants, Active Galactic Nuclei, or Gamma Ray Bursts.

Accelerated protons can, for example, interact with photons (e.g. microwave background) producing the resonance Δ, which decays into a proton and a pion. Neutrinos are created either in pion decays or in a subsequent muon decays. On average, ν carries ~5% of proton energy. The following ratios of neutrinos fluxes result from Δ decay chain: $\phi(\nu_e):\phi(\nu_\mu):\phi(\nu_t) = 1:2:0$. Due to the oscillations (at a very long distance L), this ratio would change into $\phi(\nu_e):\phi(\nu_\mu):\phi(\nu_t) = 1:1:1$ on Earth.

Characteristic is the appearance of high energy tau neutrinos. In the study of the Universe they can play a very interesting role. Due to the rise of neutrino cross-section with energy, ν_e and ν_μ of a very high energy would be absorbed by Earth. Because of a very short lifetime of τ, the ν_τ's have the property of regeneration and at very high energy they can traverse the Earth. Their energy would decrease, whereas neutrinos with other flavors would be absorbed. Therefore, in the detectors the interactions of ν_τ can be observed as coming from "below".

Detector – present and future: Ice Cube

Several models predict different values of high energy ν fluxes, attributed to different point sources. However, none of the presently working large scale neutrino detectors (Baikal, Amanda II, Antares, and Nestor) observed high energy extragalactic neutrino signal. The construction of several larger scale detectors of neutrinos is discussed; some of them are being constructed. Probably the most advanced is the detector Ice Cube.

The experience gain in the construction of Amanda, which is a system of phototubes, immerged in the depth of the South Pole ice, allows an application of this technology to a much larger scale (10 times the size of Amanda). In the Ice Cube [22] 1 km^3 of ice would be equipped with phototubes. The sensibility of Ice Cube would be such that if the model estimations of fluxes of high energy neutrino from extragalactic sources are realistic, the signal could be observed.

Ice Cube is a detector with high threshold – it would detect muons produced by very high energy neutrinos. It could, however, observe an SN explosion. The SN low energy neutrino (antineutrino) burst would produce in ice a burst of electrons (positrons). Due to the very low noise of phototubes immerged in ice, the neutrino flux from SN explosion would be seen as a fast change in noise frequency. Provided that the explosion of SN is close enough.

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