Sci. Bull. (2016) 61(1):48–51
DOI 10.1007/s11434-015-0969-7

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News & Views

Neutrino oscillation: discovery and perspectives

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Takaaki Kajita from Japan and Arthur B. McDonald from Canada shared the 2015 Nobel Prize in Physics, "for the discovery of neutrino oscillations, which shows that neutrinos have mass". Neutrinos are elementary particles with zero mass in the Standard Model of particle physics. In 1998, Takaaki Kajita, on behalf of the Super-Kamiokande collaboration, showed a smoking gun evidence of neutrino oscillation with atmospheric neutrinos [1]. In 2001 and 2002, the Sudbury Neutrino Observatory (SNO) collaboration led by Arthur B. McDonald published results showing the solar neutrino oscillation [2, 3]. These two discoveries revealed that neutrinos have mass, which is beyond our understanding of the universe, and thus opened a door to the new physics.

The existence of neutrinos was hypothesized by Pauli in 1930 to explain the continuous energy spectrum in β decay. Neutrinos should be neutral, inert, and have vanishing mass, to be consistent with the β decay phenomena. Although extremely difficult to detect, neutrino was discovered by Reines and Cowan by observing electron antineutrinos released from a nuclear reactor in South Carolina, 26 years after Pauli's hypothesis. Reines won Nobel Prize in 1995 while Cowan passed away in 1974. The second kind of neutrino, muon neutrino, was discovered by Lederman, Schwartz and Steinberger in 1962 with the first accelerator neutrino beam at Brookhaven National Laboratory. They were awarded the Nobel Prize in 1988. Three kinds (or called "flavors") of neutrinos were predicted in the Standard Model developed in 1970s and confirmed by the Z_0 decay experiments in 1989. The last kind, tau neutrino, was only observed very recently in 2000 at Fermi National Laboratory.

Although neutrinos were believed to be massless, inferred from the experimental facts that the Parity symmetry is violated maximumly in weak interaction, Pontecorvo, Maki, Nakagawa and Sakata speculated in 1950s and 1960s that neutrino could change flavor while in flight, called "neutrino oscillation", if neutrinos have mass and mixing exists between flavor and mass eigenstates. Hints were found in early 1970s when Raymond Davis observed a deficit in the solar neutrinos. Another deficit in the atmospheric neutrinos found in 1980s added to the odds. However, both theoretical and experimental difficulties appeared at the beginning when explaining these deficits with neutrino oscillation, until unarguable evidences were presented by the experiments led by the 2015 Nobel Prize Laureates.

Solar neutrinos are electron neutrinos generated in the nuclear fusion in the Sun. The standard solar model (SSM) developed since the middle of the twentieth century predicts the solar neutrino flux to high precision [4]. Detection of the solar neutrino is a certain justification of the fusion mechanism in the Sun and a test of the SSM. Raymond Davis won the Nobel Prize in 2002 for the observation of solar neutrinos in late 1960s. However, the observed solar neutrino fluxes by him and several followed experiments were between 30 % to 50 % of the SSM prediction. This deficit was known as the "solar neutrino anomaly". Neutrino oscillation is a possible explanation that some of solar neutrinos change to other flavors, which cannot be seen by the detector. This explanation was not widely accepted for several reasons. First, various experiments showed different deficits, which cannot be simply explained by oscillation. Second, the deficit should not surpass 50 % since

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what we observed should be an average effect of the oscillation, unless the oscillation circle is larger than the dimension of the fusion area in the sun, which is about 300,000 km. And last, one may suspect the detection efficiency of these experiments since the techniques are very challenging. The solar neutrino problem troubled neutrino physicists for 30 years.

A new detection method using heavy water was proposed by Herbert Chen in 1985 to measure all of the three flavor neutrinos at the same time [5]. The detection is sensitive to solar neutrinos of relatively high energies, called ^8B neutrinos, via three reactions:

$$\begin{aligned} \nu_e + d &\rightarrow p + p + e^- && \text{(CC)}\,, \\ \nu_x + d &\rightarrow p + n + \nu_x && \text{(NC)}\,, \\ \nu_x + e^- &\rightarrow \nu_x + e^- && \text{(ES)}\,, \end{aligned}$$

where ν_e denotes the electron neutrino, ν_x denotes any of the three flavors of neutrinos, and d, p, n and e^- denote deuteron, proton, neutron and electron, respectively. CC, NC and ES stand for three interaction processes, charge current, neutral current and elastic scattering, respectively. Only electron neutrinos participate the CC process; thus, the measured flux $\phi_{\mathrm{CC}} = \phi_e$. All flavors participate the NC process with the same cross section; thus, $\phi_{\mathrm{NC}} = \phi_e + \phi_\mu + \phi_\tau$. All flavors participate the ES process but electron neutrinos have six times larger cross section than the other two; thus, $\phi_{\mathrm{ES}} = \phi_e + (\phi_\mu + \phi_\tau)/6$. Here, ϕ_e, ϕ_μ and ϕ_τ stand for the flux of electron, μ and τ neutrinos, respectively.

Adopting this method, SNO experiment was constructed and started operation in 1999, which used 1,000 ton (1 ton = 1,000 kg) heavy water contained in an acrylic vessel of 12 m in diameter and viewed by 9,456 photomultipliers. When a neutrino is captured in the heavy water, a flash of Cherenkov light will be produced and seen by the photomultipliers. The three processes can be distinguished by different photon numbers corresponding to the particle energies and different hit patterns. In 2001, SNO measured the electron neutrino flux via CC and found a similar deficit as past experiments. In 2002, total neutrino flux was measured via all three processes,

$$\begin{aligned} \phi^{\mathrm{SNO}}_{\mathrm{CC}} &= 1.76^{+0.06}_{-0.05}(\mathrm{stat.})^{+0.09}_{-0.09}\,(\mathrm{syst.}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \\ \phi^{\mathrm{SNO}}_{\mathrm{ES}} &= 2.39^{+0.24}_{-0.23}(\mathrm{stat.})^{+0.12}_{-0.12}\,(\mathrm{syst.}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}, \\ \phi^{\mathrm{SNO}}_{\mathrm{NC}} &= 5.09^{+0.44}_{-0.43}(\mathrm{stat.})^{+0.46}_{-0.43}\,(\mathrm{syst.}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}. \end{aligned}$$

While solar neutrino is pure electron neutrino at production, the comparison of the CC and NC measurements showed the appearance of new neutrinos, μ and/or τ neutrinos, at a significance of 5.3 standard deviations. The total neutrino flux measured via NC is consistent with the SSM prediction $\phi_{\mathrm{SSM}} = 5.05^{+1.01}_{-0.81}$. The SNO measurements provide strong evidence for neutrino flavor transformation.

On the other hand, theoretical progresses provided a surprising answer to the inconsistence of different experiments. Wolfenstein [6] suggested in 1978 that electrons in matter will change the energy levels of the mass eigenstates of neutrinos. Mikheyev and Smirnov [7] applied this idea to the solar neutrino problem in 1985 and realized that the solar neutrino deficit is not due to oscillation during the flight from the Sun to the Earth. Instead, the flavor conversion mostly happens in the Sun. This matter effect, called “MSW effect”, depends on neutrino energy. Different types of solar neutrino experiments, such as chloride capture, gallium capture and elastic scattering, have sensitivity to different energy regions, thus see different deficits. The puzzle of the solar neutrino disappearance was thus solved.

Actually, atmospheric neutrinos provided a “smoking gun” evidence of neutrino oscillation before the solar neutrinos, although the problem was found later. In 1980s, Kamiokande experiment and IMB experiment were built to search for proton decay. Atmospheric neutrinos are important background for the anticipated proton decay signal and were carefully studied. They are produced by high-energy cosmic rays interacting with the atmosphere of the Earth. Electron and muon (anti)neutrinos are generated through the cascade decay of mesons:

$$\begin{aligned} &\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu) \\ &\mu^\pm \rightarrow e^\pm + \overline{\nu}_\mu(\nu_\mu) + \nu_e(\overline{\nu}_e) \end{aligned}$$

In 1988, 29-year-old Takaaki Kajita and his two supervisors, Masatoshi Koshiba and Yoji Totsuka, found a deficit of muon neutrinos comparing to the expectation in the Kamiokande experiment. This deficit was confirmed by IMB and known as the “atmospheric neutrino anomaly”.

Kamiokande and IMB observed supernova neutrinos for the first time in 1987, which provided strong evidence to the theory that supernova explosion could be driven by neutrinos. Masatoshi Koshiba, the leader of the Kamiokande experiment, was awarded the 2012 Noble Prize for this discovery. With this big achievement, the Super-Kamiokande experiment, a 50 kton pure water detector, was approved as an upgrade of the 3 kton Kamiokande. It started operation in 1996. Two years later, Kajita reported the discovery of neutrino oscillation with high-precision measurement of the atmospheric neutrinos.

In Super-Kamiokande, muon neutrinos and electron neutrinos produce muons and electrons, respectively, via the CC reaction. They can be distinguished by the different patterns of the Cherenkov light. The energy and direction of neutrinos are determined by the arrival time and the intensity of Cherenkov light. Super-Kamiokande found an asymmetry of the number of down-going and up-going muon neutrinos, while the electron neutrinos were almost isotropic. The asymmetry can be explained as that a part of muon neutrinos transformed to tau neutrinos during their thousands-of-kilometers propagation in the Earth. The observed deficit as a function of distance, the critical characteristic of oscillation, is in good agreement with the oscillation prediction.

Besides the solar and atmospheric neutrino experiments, the neutrino oscillation was also confirmed by reactor neutrino experiment KamLAND [8] and accelerator neutrino experiment K2K [9] in 2002 and 2003.

Neutrino oscillation can be described by six parameters. The solar and reactor experiments measured a pair of them, $\Delta m^2_{21} \sim 8 \times 10^{-5}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{12} \sim 0.86$, where Δm^2 is the difference of mass square between two mass eigenstates and determines the oscillation frequency, and $\sin^2 2\theta$ determines the oscillation amplitude. The atmospheric and accelerator experiments measured another pair, $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{23} \sim 1$. The unknown parameters include $\sin^2 2\theta_{13}$, the CP phase δ_{CP}, and the sign of Δm^2_{32} (usually called as the neutrino mass hierarchy). The CP phase could introduce asymmetry between neutrino and antineutrino oscillations and thus very likely relate to the mystery of the missing antimatter in the Universe. The mass hierarchy relates to the mechanism for neutrino mass generation [10] and determines the prospects of neutrinoless double β decay experiments. The mixing angle θ_{13} determines the size of observable effects of the CP phase and the mass hierarchy.

Oscillation among three types of neutrinos is complex. However, since Δm^2_{32} is 30 times larger than Δm^2_{21}, oscillation can often be decoupled and simplified as that between two types. The survival probability P_{sur} of a neutrino of energy E after traveling distance L can be described as

$$P_{\mathrm{sur}} \approx 1 - \sin^2 2\theta \sin^2\left(\Delta m^2 L/4E\right).$$

In 2012, Daya Bay Reactor Neutrino Experiment in China discovered a new oscillation besides the solar and atmospheric neutrino oscillations and measured the oscillation amplitude $\sin^2 2\theta_{13} = 0.092$ [11, 12]. This value is unexpectedly large comparing to what neutrino physicists speculated around 2003. A large θ_{13} paved the way to measure the mass hierarchy and δ_{CP} by the next generation of neutrino oscillation experiments. Daya Bay will continue running until 2020 and measure $\sin^2 2\theta_{13}$ to 3 % precision. Besides Daya Bay, another two similar reactor experiments RENO and Double Chooz are running with the same physics goal but less precision.

Combining the high precision θ_{13} measured by Daya Bay and the ν_e appearance measured recently by the accelerator experiment T2K, an interesting hint for a maximum CP violation showed up with $\delta_{\mathrm{CP}} = -\pi/2$. Another accelerator experiment NOvA just starting operation also showed a similar sign and preferred normal mass hierarchy, i.e., $m_3 > m_2$. Although the current signals are not significant, T2K and NOvA could determine the mass hierarchy and δ_{CP} to $3\,\sigma$ significance in a few years if they are really at these lucky values.

To determine the mass hierarchy and δ_{CP}, a bunch of new experiments has been launched or planned, including JUNO in China, RENO-50 in Korea, INO in India, DUNE in USA, Hyper-K in Japan, PINGU in the Antarctic and ORCA in the Mediterranean.

Jiangmen Underground Neutrino Observatory (JUNO) [13] was started in 2013. A 20 kton liquid scintillator detector will be built at 700 m underground to detect the reactor neutrinos from the Yangjiang and Taishan nuclear power plants, both at 53 km distance to the detector. It will start operation at 2020 and determine the mass hierarchy at 3–4 σ confidence level in 6 years. Meanwhile, JUNO will provide the most precise measurements of three oscillation parameters, θ_{12}, Δm^2_{21} and Δm^2_{31}, to sub-percent level. JUNO can also serve as a neutrino telescope to observe the supernova neutrino, solar neutrino and geoneutrino and to search for dark matter, proton decay, and so on [14]. RENO-50 is a similar proposal as JUNO to be approved.

Among new atmospheric neutrino experiments, PINGU and ORCA will measure the mass hierarchy to $3\,\sigma$ in 4 years. They are waiting for approval and might start operation around 2020. INO has been approved but has less sensitivity. Hyper-Kamiokande, a further upgrade of Super-Kamiokande to 1,000 kton, might be launched around 2025 and has similar sensitivity as PINGU and ORCA.

The CP violation associated with the matter–antimatter asymmetry can be studied with accelerator neutrinos. By switching the focusing magnetic field, neutrinos or antineutrinos can be selected and directed to the detector at 100 or a 1,000 km away. The difference of their oscillation probabilities is proportional to $\sin \delta_{\mathrm{CP}}$. There are two new accelerator experiments planned. DUNE is a 10 kton liquid argon detector to detect the neutrinos produced 1,300 km away at Fermilab. It is planned to take data in 2024. It can determine the mass hierarchy to $5\,\sigma$ for most parameter space and exclude $\sin \delta_{\mathrm{CP}} = 0$ at $3\,\sigma$ for about half of the parameter space. T2HK uses the Hyper-Kamiokande detector to detect neutrinos produced 295 km away at J-Parc. Due to the short baseline and thus small matter effect, it cannot measure mass hierarchy with accelerator neutrinos, but can exclude $\sin \delta_{\mathrm{CP}} = 0$ at $3\,\sigma$ for 76 % of the parameter space.

With these new experiments, it is very likely that we will establish a comprehensive picture of the neutrino oscillation in the next 15 years, with all parameters known.

The unitarity of the neutrino mixing matrix can be examined to sub-percent level, which could hint new physics beyond our reach.

Neutrino oscillation is the most promising and productive field in neutrino studies. Nevertheless, neutrino has much more puzzles existing [15]. Unlike other Dirac particles, neutrino could be Majorana particle, which means that neutrino could be its own antiparticle. Many experiments are going on to determine its particle nature by searching for the neutrinoless double β decay. Neutrino oscillation is the most sensitive probe to the tiny mass of neutrino. However, it relates to the mass square differences but not the mass itself. We need at least another absolute measurement to solve the mass. It could come from the precision measurement of β decay, or from neutrinoless double β decay if neutrinos are Majorana particles, or from cosmology. There are also many exotic searches, such as the sterile neutrino, neutrino abnormal magnetic moment and decoherence effect.

Beyond particle physics, neutrino serves as a unique probe in astrophysics and cosmology. Neutrino is the only particle that could penetrate massive celestial bodies due to its inert nature. It could provide us interior information of the Sun, the Earth, the supernova, as well as the origin of ultra-energetic cosmic rays. Enormous neutrinos were produced in the first second at the birth of the Universe. They carry the information of the very early Universe while the cosmic microwave background only produced 380,000 years later. Pioneer experiments have been started to search for these neutrinos.

In summary, neutrino researches have been awarded the Nobel Prize for four times. Neutrino oscillation is still the most active area in neutrino studies. Many new experiments are launched or planned to explore the mass hierarchy, CP violation, and precision measurements that might lead to new physics. Neutrinoless double β decay, absolute mass measurement, as well as neutrino astronomy, are getting prosperous. More amazing discoveries could be ahead in near future.

Acknowledgments This work was supported partly by the National Natural Science Foundation of China (11225525, 11390380 and 11575226).

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