Neutrino oscillations

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Neutrinos are massless as proposed in the Standard Model of particle physics. However, neutrino experiments in the last few decades have revealed that neutrinos flavour oscillate, a scenario possible only if they have mass and mixing. Existence of neutrino mass was the first conclusive evidence of physics beyond the Standard Model, and explaining the smallness of the neutrino masses and peculiar mixing angles still remains a challenge for model-builders proposing beyond Standard Model scenarios. We give a brief introduction to the phenomenon of neutrino oscillations and showcase some recent work where we look for physics beyond the three-generation neutrino oscillation paradigm and its impact on future experiments.

Keywords: Beta decay, flavour transformation, neutrino oscillations, particle physics.

Introduction

NEUTRINOS were proposed by Wolfgang Pauli in 1930 in favour of the principle of energy conservation which had come under question following the measurement of the beta decay spectrum that was seen to be continuous. Therefore, the neutrino was proposed as the chargeless, massless, spin-half partner of the electron which carries away the balance energy and spin during the beta decay process, without being detected. Pauli called it the neutron, since it carried no electric charge. James Chadwick discovered the neutron in 1934 and it was soon understood that this was not Pauli's proposed particle since it was almost as heavy as the proton. Enrico Fermi then renamed Pauli's particle as neutrino, which in Italian means the little neutral particle, to distinguish it from the particle discovered by Chadwick. In 1934, Fermi wrote down the theory of beta decay and in 1942 Wang Ganchang suggested that neutrinos could be detected via the inverse beta decay process. The rate of the inverse beta decay process when calculated using Fermi's theory turned out to be extremely small. However, this did not deter physicists from attempting to detect this elusive particle and a variety of ideas were proposed, culminating in the discovery of the neutrino by Fred Reines and Clyde Cowan in 1956. Reines and Cowan had successfully detected the electron anti-neutrinos coming from nuclear reactors through the inverse beta decay process in a scintillator detector. This landmark discovery was awarded the Nobel Prize 40 years later in 1995.

Another 'flavour' of neutrino was discovered in 1962 by Lederman, Melvin and Steinberger, for which they were awarded the Nobel Prize in 1988. This was the muon flavour neutrino, meaning the neutrino that is associated with the muon. This discovery also established that there were more than one 'type' of neutrinos. Finally, the tau flavour neutrino was discovered in 2000 by the Donut Collaboration at Fermilab in USA. In another complimentary experiment at the Large Electron Positron Collider (LEP) in CERN, Europe, it was observed that only three light neutrinos are coupled to the Z-boson, the intermediate gauge boson that mediates neutral current weak interactions. Thus the existence of the three so called 'active' neutrinos was confirmed, as predicted by the Standard Model of particle physics.

The Standard Model has been put to stringent precision tests at the collider experiments at CERN and Fermilab. All particles predicted in the Standard Model have been discovered, and their masses measured. The interaction strengths of elementary particles have been measured to unprecedented precision and they agree with the predictions of the Standard Model. So far there are no significant deviations from the Standard Model reported in any experiment, which includes both collider experiments as well as experiments involving exotic mesons. The only missing link of the Standard Model, the Higgs particle, was finally discovered in 2012 at the Large Hadron Collider (LHC). Since then, the LHC has been collecting more and better data, and so far all results pertaining to the Higgs boson appear to be compatible with the Standard Model, with no significant signal of any new physics. Despite this fairytale-like success of the Standard Model, physicists have many reasons to believe that it cannot be the fundamental theory of elementary particles and that there exists a more complete theory at a higher scale whose low-scale manifestation emerges as the Standard Model. The reasons for such a belief are both theoretical as well as observational. Our understanding of the neutrino is one of them.

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Neutrino oscillations

The neutrinos were predicted to be massless in the Standard Model. However, a series of experiments spanning six decades have finally established that neutrinos have a mass, albeit tiny. Existence of massive neutrinos was proposed as an explanation of the so-called solar neutrino problem way back in the 1960s. A huge flux of electron flavour neutrinos is created during the thermonuclear burning of hydrogen inside the sun and these can be detected on earth. John Bahcall, using his Standard Solar Model (SSM) had calculated the number of expected events in terrestrial detectors coming from solar neutrinos. These events were first observed by Ray Davis in his experiment in the Homestake mine in South Dakota[1], where he used cleaning liquid to capture these neutrinos on chlorine. The number of events observed in Davis' experiment turned out to be only about a third of that predicted by Bahcall's SSM[2]. This discrepancy, popularly known as the solar neutrino problem, can be explained in terms of the quantum mechanical phenomenon known as neutrino flavour oscillations as proposed by Pontecorvo[3], wherein if neutrinos were to be massive and if they had flavour mixing, then the electron flavour neutrino produced inside the sun could flavour-transform into another neutrino flavour in its journey from inside the sun to the detector. A simple way to understand neutrino oscillations is as follows. The fact that neutrino flavours 'mix' implies that the neutrinos which appear as a part of the weak interaction process are not the physical neutrino states or the mass eigenstates. Rather, the neutrino flavour states ν_α that are associated with weak interactions can be expressed as a linear combination of the mass eigenstates ν_i. In other words

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle,$$

where $U_{\alpha i}$ are the elements of the mixing matrix U which relate the flavour eigenstates to the mass eigenstate[3,4]. For three generations of neutrinos, the mixing matrix is a 3×3 unitary matrix which can be parametrized in terms of three mixing angles θ_{12}, θ_{23}, θ_{13} and one CP-violating phase δ_{CP}. Suppose neutrinos of energy E produced in flavour ν_α in a weak interaction process travel a distance L to be finally detected in a neutrino detector. The time-evolution of the neutrino state can be understood in the plane-wave approximation and the probability to detect flavour ν_β in the detector can be calculated as

$$P_{\nu_\alpha \nu_\beta} = \delta_{\alpha\beta}$$

$$-4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} L/4E)$$

$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} L/4E),$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$, m_i being the mass of ν_i. In the case of solar neutrinos, this would mean that the electron flavour neutrino from the sun would get converted to muon and/or tau neutrinos during flight. Since Davis' experiment was sensitive to only electron flavour neutrinos, the other neutrinos would go undetected giving fewer events than predicted by the SSM.

It was also realized that neutrinos while travelling in matter undergo 'matter effects' due to coherent forward scattering on ambient electrons in matter[5]. This coherent forward scattering results in an effective potential which the propagating neutrinos feel, and which changes their masses and mixing in matter. Therefore, presence of matter could bring a drastic change to the neutrino flavour transformation probabilities depending on the density of matter and neutrino energy. For the matter density in the sun and solar neutrino energies, it was expected that solar neutrinos experience maximal matter effects in the sun[6] and some matter effects on earth. If the hypothesis of neutrino masses and mixing was indeed true and in the range that was suggested by the solar neutrino experiments, then the data on solar neutrinos should show signal for matter effects.

More experiments were built using gallium in Baksan (Russia) and Gran Sasso (Italy) which could detect solar neutrino of even lower energies. The Kamiokande and Super-Kamiokande detectors in Japan used water to observe the solar neutrinos. Davis was awarded the Nobel Prize in 2002 along with Koshiba (Kamiokande) for observing neutrinos from outer space (Kamiokande had seen neutrinos from supernova SN1987A). Finally, the SNO experiment in Sudbury, Canada[7] settled the issue and confirmed beyond doubt that the solar neutrinos though produced purely in electron flavour, arrive on earth as a mixture of neutrinos of different flavours. SNO could do this by measuring the flux of solar neutrinos simultaneously using a charged current process and a neutral current process. The charged current interaction is flavour-dependent and observes neutrinos of only electron flavour, while the neutral current interaction is flavour-independent and hence measures the total solar neutrino flux. The number of neutral current events observed by SNO was in agreement with that predicted by SSM, while the number of charged current events was seen to be about one-third of that predicted by SSM, consistent with earlier solar neutrino experiments. Matter effects in neutrino flavour transformation were also confirmed from the solar neutrino data. Art McDonald, who led the SNO experiment was awarded the Nobel Prize in 2015 along with Takaaki Kajita of the Super-Kamiokande collaboration for finally establishing neutrino flavour oscillations.

Indeed the Super-Kamiokande collaboration led by Kajita was the first experiment to provide an unambiguous confirmation of neutrino flavour oscillation. In 1998, the Super-Kamiokande presented data on atmospheric neutrinos, where neutrinos travelling from under the earth showed signal for flavour oscillations, while those coming from directly above had not oscillated[8]. This was a distance-dependent flavour composition of neutrinos and hence a direct signal for neutrino oscillations. It established that neutrinos were massive and mixed, and therefore constituted the first confirmed signal of physics beyond the Standard Model.

Since as many as seven different experiments have data on solar neutrinos and Super-Kamiokande has data on atmospheric neutrinos, a major undertaking in the field of neutrino oscillations is the global analysis of all these experiments taken together. In addition to these pioneering experiments that detected neutrino oscillations using neutrinos from natural sources, a series of experiments using man-made neutrino beams have independently checked the existence of neutrino masses and mixing, and have also provided precise measurement of the neutrino oscillation parameters. The main experiments in this category are KamLAND, K2K and T2K in Japan, MINOS and NOνA in USA, Daya Bay in China, RENO in Korea, and Double Chooz in France. Together with my collaborators, one of whom is also an Indian woman scientist and a leading expert in the field of high-energy physics, we have been involved in the global analysis of world neutrino data and have published a series of top-cited papers on this subject[9–13]. We performed a state-of-the-art statistical analysis of the data from different neutrino experiments, and showed areas allowed in the neutrino oscillation parameter space. The Indian group was one amongst only a few international collaborations that were involved in this kind of analysis. These papers received a lot of attention worldwide. The most recent global analyses[14,15] of the world neutrino data yield the following values for the two mass-squared differences $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2 and $|\Delta m^2_{31}| = 2.5 \times 10^{-5}$ eV^2, while the best-fit values of the three mixing angles $\sin^2\theta_{12} = 0.306$ and $\sin^2\theta_{13} = 0.022$. The best-fit value of $\sin^2\theta_{23} = 0.44(0.59)$ for the normal (inverted) mass ordering.

Beyond three-generation oscillations

While neutrino oscillations are well-established as the solution to the solar neutrino and atmospheric neutrino anomalies, any other kind of new physics that could change the flavour ratio of the solar and atmospheric neutrinos could also play a role in these analyses, albeit subdominant. Amongst the most widely studied new physics scenarios beyond the vanilla three-generation mass and mixing paradigm are: neutrino decay, non-standard interactions (NSI) and sterile neutrinos. Each of these new physics scenarios impacts the neutrino oscillation probabilities and changes the predicted number of events at the neutrino experiments. A lot of work has been done in these areas of neutrino physics. Here I give a brief glimpse of some of the works in which I have been involved in recent times.

The Standard Model of particle physics has to be extended to explain the non-zero neutrino masses and the peculiar mixing pattern observed in the neutrino experiments. Any such extension might give rise to new effective interaction(s) between the neutrino and the other Standard Model fermions. These additional interactions are called NSI, and could be both charged current-like and neutral current-like. The charged current-like NSI usually impact the production and detection of neutrinos. Thus, the parameters that drive the charged current-like NSI are called source/detector NSI. On the other hand, the parameters that drive the neutral current-like NSI play a role in changing the matter effects during neutrino propagation, and hence are popularly known as matter NSI. While both source/detector as well as matter NSI change the neutrino oscillation probabilities, the impact of matter NSI is usually larger since the source/detector NSI are constrained more by the current data.

We have studied[16] the impact of NSI on the physics reach of the Deep Underground Neutrino Experiment (DUNE)[17]. This is a forthcoming experiment in USA, where a very intense neutrino beam will be produced at Fermilab in Illinois, and sent to a ~40 ktonne liquid argon detector at Sanford Under-ground Research Facility in South Dakota, covering a distance of 1300 km. This expensive and ambitious neutrino experiment is being proposed to measure the hitherto unknown neutrino oscillation parameters. It will also improve the precision of the already measured neutrino parameters. We took both source/detector as well as matter NSI and performed a thorough analysis of the physics reach of DUNE using a Markov chain Monte Carlo method which allows us to explore the full parameter space. We showed that DUNE could improve the limits on matter NSI by factors of up to 15, while no significant improvement is expected for the source/detector NSI. We also found that the sensitivity of DUNE to standard neutrino parameters is reduced in the presence of NSI. In particular, there are degenerate solutions in the mixing angle θ_{23} and CP phase δ_{CP} plane. We have shown that some of the degeneracies come from correlations between the source/detector and matter NSI.

Sterile neutrinos were proposed to explain the so-called LSND anomaly in neutrino physics. The LSND experiment in 1996 reported a 3.8σ excess in the electron neutrino data[18]. This could be explained in terms of neutrino oscillations, if the mass-squared difference $\Delta m^2 \sim 1$ eV^2. Since the three-generation paradigm of neutrinos allows only two independent mass-squared differences and since the solar neutrino data demand $\Delta m^2 \sim 7.5 \times 10^{-5}$ eV^2 and the atmospheric neutrino data demand $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2, there is no further room to accommodate the $\Delta m^2 \sim 1$ eV^2 needed to explain neutrino oscillations claimed by LSND. There is an easy way to circumvent this problem by increasing the number of neutrino generations to four (or more). However, since the number of light neutrinos coupled to the Z-boson was measured to be three by the LEP experiment at CERN, this additional neutrino should not couple to the Standard Model gauge bosons, and hence is called sterile. Subsequently, many attempts have been made to test the LSND anomaly; however, this issue still remains unresolved. A large number of dedicated experiments have been proposed recently to test the LSND anomaly.

We have looked at the prospects of testing LSND at DUNE[19]. There is a proposal to build a near detector at a distance of a few hundred metres from the DUNE beamline. The main purpose of the near detector will be to measure the unoscillated neutrino flux with very high precision. This is required in order to achieve the extremely low systematic uncertainties needed to perform the precision measurements at DUNE. We have pointed out that for the DUNE beam energy and the baseline distance of the proposed near detector, the LSND anomaly could be tested to a very high precision at nearly no additional costs.

There also exists the possibility that the neutrinos are not stable particles, as assumed in the Standard Model, and could decay into invisible states via some new exotic physics scenario. If such were the case, then the neutrinos would decay during flight from the source to the detector, and hence would give a lower count rate. Solar neutrino experiments indeed observe a lower rate of the electron-type neutrino and are hence consistent with this observation. The same is true for atmospheric neutrinos, which would show more depletion for neutrinos travelling over longer distances, partly in agreement with the observed data. However, the spectral shape predicted by neutrino flavour oscillations is unique and different from any new physics scenario in general, including neutrino decay. This can be used to distinguish any new physics scenario such as neutrino decay from neutrino oscillations. Indeed the solar neutrino spectrum observed on earth has a certain shape, which is given from spectral measurements at Super-Kamiokande and SNO, as well as from a comparison of solar neutrino experiments sensitive to different regimes of the solar neutrino spectrum. We have studied[20] the solar neutrino data in the context of a framework which incorporated both neutrino oscillations as well as neutrino decay scenarios, and put bounds on the neutrino lifetime, which still stands as one of the best bounds on the lifetime of the second neutrino mass eigenstate.

Just like the lifetime of the second neutrino mass eigenstate is best constrained by the solar neutrino data which concern the electron-type neutrino, the lifetime of the third neutrino eigenstate is constrained best by data sensitive to muon-type neutrinos. The atmospheric neutrino gives one of the best bounds for the lifetime of the third mass eigenstate. The other experiments that give comparable or better constraints are T2K and MINOS, which work with muon beams produced in accelerators.

Conclusion

Neutrino physics has seen a lot of activity in the past decades and the field continues to attract young researchers worldwide. Neutrino oscillations are today a well-established phenomenon with many of the neutrino oscillation parameters determined to high precision. Nonetheless, there are some missing links in our understanding of the neutrino properties. Bigger and better experiments are being planned to measure the mixing neutrino parameters. With the improvement of our understanding of the neutrino sector, we hope to learn more about how the Standard Model needs to be extended in order to alleviate or solve some of the other issues that plague the Standard Model.

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