Results from MiniBooNE

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The long-awaited experimental results from MiniBooNE have recently been announced. This experiment tests whether neutrino oscillations can occur at a higher mass-squared difference ~1 eV^2 compared to well-established observations of solar and atmospheric neutrinos. The LSND experiment had previously claimed to have observed neutrino oscillations at $\Delta m^2 \sim 1$ eV^2. However, the results being controversial, required independent confirmation. The MiniBooNE results settle this controversy by observing null oscillations at the said mass-squared difference. These results have strong implications on the existence of sterile neutrinos, CPT violation and mass-varying neutrinos. We review the present status of neutrino masses and mixing in the light of this recent result.

Keywords: MiniBooNE, neutrinos, oscillations, results.

IN the Standard Model (SM) of elementary particles there are three neutrinos, one for each flavour: electron type (ν_e), muon-type (ν_μ) and the tau-type (ν_τ). They do not have electric charge and participate only in weak interactions which are responsible for processes like nuclear β-decay, etc. The original SM, not having enough knowledge of the other main physical attribute of the neutrinos, namely their mass, has left them massless. However, starting from 1998, experimental measurements of neutrino oscillations have become robust, implying neutrinos do have masses, however tiny. The neutrino oscillation formula is given in terms of the mass-squared differences and the mixing angle parameters of the neutrinos. For the simplest case of two flavours, denoted by a and b, oscillation probability is given by:

$$P_{ab} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m_{ab}^2(\mathrm{eV}^2)L_\nu(\mathrm{m})}{E_\nu(\mathrm{MeV})}\right), \qquad (1)$$

with θ representing the mixing angle between the two flavours and $\Delta m_{ab}^2 = m_b^2 - m_a^2$, the mass-squared difference between them. L_ν and E_ν represent the distance and energy traversed by the neutrino respectively. Within the standard picture of three neutrinos, which we elaborate below, there can be two independent mass-squared differences responsible for the observed solar and atmospheric neutrino oscillations.

One of the important challenges in this field was whether oscillations would be observed not just in neutrinos produced in astrophysical processes, but also in laboratory-like conditions, for example, neutrinos produced at nuclear reactors or in particle accelerators. These experiments are of two types either short-base line (SBL) or long-base line (LBL), depending on the length the neutrino traverses from the time of production to the time of detection. One of the first claims for the observation of neutrino oscillations in the laboratory was by the Liquid Scintillation Neutrino Detector (LSND) experiment conducted at the Los Alamos National Laboratory, USA. However, this result soon ran into controversy for various technical reasons (see Note 1) as well as for predicting the existence of newer exotic particles called sterile neutrinos. The oscillations observed required a much larger mass difference compared to those required in solar and atmospheric oscillations and thus could only be explained by introducing a new neutrino which does not even participate in weak interactions and hence is sterile.

A second experiment called KARMEN failed to settle this controversy, as it could not probe the entire parameter space of the LSND experiment. The MiniBooNE was designed specifically to settle this controversial issue and prove/refute the simplest and popular explanation of the LSND result, i.e. existence of a sterile neutrino at that mass range. This April, the MiniBooNE collaboration announced its first results after taking data for almost five years. Using statistically robust methods in their data analysis, they have found no positive signal for neutrino oscillations at mass-squared difference $\Delta m^2 \sim 1$ eV^2. This result settles the LSND controversy which has dogged the particle physics community for over a decade. However, caveats still do exist, as we will explain later.

In the present article, we report on this new experimental results and comment on the implications they would have on our understanding of sterile neutrinos. The rest of the article is organized as follows: we summarize the existing standard picture of three neutrino oscillations in the next section. The summary is not necessarily chronological in order, but we will give the dates wherever we can. Next we elaborate on the LSND experimental results and their possible theoretical explanations. We also report on KARMEN's failure to contradict/validate the LSND experiment. We also report on the first results from MiniBooNE and their implications on particle physics scenarios. We close with some remarks on future directions.

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Standard picture of three neutrino oscillations

Neutrino oscillations were first proposed by Pontecorvo[1] inspired by the observed neutral K-meson oscillations. The first experimental indications of neutrino oscillations came from pioneering experiments of Raymond Davis Jr (Nobel laureate, 2002), measuring neutrino flux from the sun. The sun produces energy through nuclear fusion, which can be summarized by the following equation[2]:

$$4\mathrm{p} + 2\mathrm{e}^- \rightarrow \mathrm{He} + 2\nu_\mathrm{e} + Q, \tag{2}$$

which shows four protons and two electrons fuse to form a helium nucleus giving out energy ($Q = 26.73$ MeV) and two electron-type neutrinos (ν_e). The expected number of ν_e coming from the sun to be observed at the earth can be computed using detailed numerical computations, following the Standard Solar Model. However, the observed number always fell short by about 50% compared to the expected number, giving rise to the so called 'solar neutrino problem' (see Note 2). The simplest solution proposed for this problem was neutrino oscillations of Pontecorvo, which are possible if neutrinos have tiny but non-zero masses. In such a case, the ν_e produced in the sun, gets converted into a ν_μ or ν_τ or more exactly a linear combination of them while traversing the distance from the sun to the detector placed on earth. It should be noted that earlier detectors were sensitive only to ν_e, i.e. they could only detect ν_e but not ν_μ and ν_τ flavours. And hence, experiments could only validate that solar electron neutrinos do convert to ν_μ and ν_τ flavours conclusively only in late 2002. This was done by a combination of experiments at the SNO (Sudbury Neutrino Observatory) in Canada, which was sensitive to all the three flavours, and at the Super-Kamiokande detector located in Japan[3].

However, there was still one more issue to be settled. This was concerned with how and where exactly the electron neutrinos which are produced at the core of the sun get converted to the other flavours while traversing the distance from the centre of the sun to the earth's surface. In particular, taking into consideration the interaction of the neutrino with the dense matter of the sun, another mechanism to convert ν_e to $\nu_{\mu(\tau)}$ called the MSW (Mikheyev, Smirnov and Wolfenstien) mechanism can happen, other than the aforementioned oscillations of the neutrino in vacuum. It was thus important to identify exactly which mechanism was responsible for the conversion of the electron neutrinos from the sun as they reached the earth. This issue was recently settled by the experiment called KamLand, which observed neutrino oscillations on the earth corresponding to the mass differences of the solar neutrinos. Finally, data from all the experiments, namely KamLand, SNO and Super-Kamiokande taken together point out to a large mixing MSW solution to the solar neutrino problem. The mass-squared difference and the mixing angle are determined to be[4]:

$$\Delta m^2_\mathrm{solar} = 7.9^{+0.27}_{-0.28}\left({}^{+1.1}_{-0.89}\right) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\theta_\mathrm{solar} = 33.7 \pm 1.3\left({}^{+4.3}_{-3.5}\right)\mathrm{deg}, \tag{3}$$

where we have shown the error bars in the $1\sigma\,(3\sigma)$ range.

Atmospheric neutrinos have been discovered in India and South Africa in the 1960s as background for proton decay experiments. The origin of these neutrinos was traced to the interactions of cosmic rays with the atmospheric air molecules, which led to the prediction for the ratio

$$\frac{N_{\nu_\mu} + N_{\overline{\nu_\mu}}}{N_{\nu_\mathrm{e}} + N_{\overline{\nu_\mathrm{e}}}} \simeq 2, \tag{4}$$

where N_{ν_f} stands for the total number of the neutrinos corresponding to the flavour f. The bar on the top represents an anti-particle. This ratio is roughly expected to be two, based on simple analysis of pion and kaon decays. Detailed numerical simulations, including earth magnetic field effects also confirm this ratio to be close to two. However, experiments using huge water Cerenkov neutrino detectors like IMB and Kamiokande observed a deviation from the above prediction, which can be best expressed in terms of a double ratio given by

$$R = \frac{(N_{\nu_\mu}/N_{\nu_\mathrm{e}})_\mathrm{data}}{(N_{\nu_\mu}/N_{\nu_\mathrm{e}})_\mathrm{MC}}, \tag{5}$$

where the subscript 'MC' for the ratio in the denominator corresponds to expectations based on Monte Carlo numerical simulations. Both IMB and Kamiokande have found this double ratio, R to be of the order of 0.6 instead of 1, as one would have expected. Neutrino oscillations were again thought to be the culprit for this discrepancy. In 1998, the Super-Kamionkande collaboration announced strong evidence for neutrino oscillations in atmospheric neutrinos with high statistics. This was one of the first evidences of neutrino oscillations with such experimental accuracy and high statistics. These experiments observed an 'up-down' asymmetry (see Note 3) away from zero by about ten standard deviations, putting the phenomenon of neutrino oscillations on firm experimental footing[2].

Soudan-2 and MACRO experiments, both of which are based on iron calorimeters have further confirmed the hypothesis that atmospheric neutrinos do oscillate, hence removing any suspicions regarding this phenomenon being observed only at water Cerenkov detectors, perhaps due to some systematic errors particular to those detectors. In recent years, two experiments, K2K and MINOS, have further reduced errors in the measurement of the oscillation parameters associated with the atmospheric neutrinos. They are now given as[4]:

$$\Delta m^2_{\mathrm{atm}} = 2.6 \pm 0.2(0.6) \times 10^{-3}\ \mathrm{eV}^2,$$
$$\theta_{\mathrm{atm}} = 43.3^{+4.3}_{-3.8}(^{+9.8}_{-8.8})\,\mathrm{deg}, \tag{6}$$

where as before we have quoted the $1\sigma\,(3\sigma)$ error bars.

Given these numbers for the mass-squared differences and the mixing angles, we are now ready to reconstruct from the experimental data the neutrino mass matrix[5]. As mentioned earlier, the SM of particle physics has made no provisions for non-zero neutrino masses. To accommodate non-zero neutrino masses, several extensions of the SM have been considered. Experimentally, however, a few issues still need to be settled. These are (i) whether neutrinos are of Majorana or Dirac nature. This determines whether neutrinos are anti-particles of themselves or not. This important issue could be tested in future neutrino-less double-beta decay experiments, whose transitions are only possible if neutrinos are Majorana (self anti-particles) in nature. This also has implications for the structure of the neutrino mass matrix as, in the Majorana case, the mass matrix is complex symmetric, whereas in the Dirac case it is complex generic. (ii) The second issue is related to the point that we have so far measured only the mass-squared differences of the neutrinos, but not their absolute masses. With three neutrinos, we can have the observed mass-squared differences in three different hierarchies (a) Normal Hierarchy (NH) $m_{\nu_1} \ll m_{\nu_2} \ll m_{\nu_3}$; (b) Inverted Hierarchy (IH) $m_{\nu_3} \ll m_{\nu_1} \ll m_{\nu_2}$; (c) Degenerate $m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3}$. Future experiments based on cosmology, long-base line neutrino propagation and perhaps even neutrino-less double-beta decay are expected to shed light on this important aspect of neutrino mass hierarchy. (iii) We have not yet measured the third neutrino mixing angle θ_{13}, which appears in the three-neutrino mixing scheme. At present there is only an upper bound from the CHOOZ experiment in France and its present limits are given as $\theta_{13} = 0^{+5.2}_{-0.0}(^{+11.5}_{-0.0})$ deg. Future experiments like Double CHOOZ in France and Daya Bay in China are expected to improve this limit by at least an order of magnitude. (iv) Finally we have the question whether CP (a product of Charge conjugation symmetry and Parity; see Note 4) is a good symmetry or not in the leptonic sector. Experimentally, this question is quite challenging and it crucially depends on the value of unknown neutrino mixing angle θ_{13}. Future experiments will hopefully be able to uncover this mystery.

One of the most popular and simplest extensions of the SM gives neutrino masses through the so-called see-saw mechanism. In this mechanism, right-handed neutrinos are added to the SM particle spectrum. Given that these particles do not obey SM symmetries, they can have very large masses, however, breaking lepton number. At the same time, they can couple with the SM (left-handed) neutrinos resulting in a lepton number conserving (Dirac) mass, which can be expected to be close to one of the masses of the other SM particles like top quark, bottom quark or tau lepton, etc. The interplay between the large Majorana mass and the Dirac mass leads to a small non-vanishing mass ~eV to the SM left handed neutrinos, just as what is expected from the experiments. It would be instructive to see what the structure of the neutrino mass matrix is as demanded by the data. We will now assume that neutrinos are Majorana in nature (as indicated by the see-saw mechanism) and further follow NH. In such a scheme, the neutrino mass matrix is given by:

$$\mathcal{M}_\nu = U^*_{\mathrm{PMNS}} \mathcal{M}_{\mathrm{diag}} U^\dagger_{\mathrm{PMNS}}, \tag{7}$$

where $\mathcal{M}_{\mathrm{diag}} = \mathrm{Diag}\{m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\}$, with $m_{\nu_1} \le (\Delta m^2_{\mathrm{solar}})^{1/2}$, $m_{\nu_2} \sim (\Delta m^2_{\mathrm{solar}})^{1/2}$, $m_{\nu_3} \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$. Neglecting the phases, the U_{PMNS} has the form (at 3σ level) given by[4]:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 0.79\text{–}0.86 & 0.50\text{–}0.61 & 0.0\text{–}0.20 \\ 0.25\text{–}0.53 & 0.47\text{–}0.73 & 0.56\text{–}0.79 \\ 0.21\text{–}0.51 & 0.42\text{–}0.69 & 0.61\text{–}0.83 \end{pmatrix}. \tag{8}$$

Considering the values for the individual neutrino masses depending on the scheme, one can reconstruct the neutrino mass matrix. This summarizes the present status of three-neutrino mixing and oscillations as we understand now.

LSND and KARMEN: Indications for a sterile neutrino

LSND

While the search for a robust signal in solar and atmospheric neutrino oscillations was going on, simultaneously experimentalists have been on the lookout for neutrino oscillations at other frequencies (i.e. at Δm^2 other than those relevant for solar and atmospheric neutrino oscillations). Most of these earlier experiments had short-base lines, typically about few tens of metres (see Note 5) and are thus sensitive to $\Delta m^2 \gtrsim 1\ \mathrm{eV}^2$. The LSND was one such experiment. Another important characteristic of the LSND experiment was that it was an appearance experiment. Typically, we can think of two types of strategies while looking for neutrino oscillations:

(a) Disappearance experiments: Here, we look for a reduction in the expected number of the neutrinos (which are detected) of a particular flavour. Then this disappearance is explained in terms of neutrino oscillations (into undetected flavours).

(b) Appearance experiments: Here, we look for neutrino flavours which are either not present or very weakly produced at the neutrino source. Again this appearance is explained in terms of neutrino oscillations. It should be noted that earlier short based-lined experiments have not found any evidence for neutrino

> oscillations. The initial indications for oscillations in both the solar and atmospheric sectors have come from various disappearance experiments.

The LSND was based at Los Alamos National Laboratory (LANL) in the United States. LSND, had a base-line of 30 m and was looking for an excess of ν_e, $\bar{\nu}_e$, starting from a beam which was mainly made up of ν_μ (and $\bar{\nu}_\mu$). The LSND has collected data from 1993 up to 1998. The Collaboration first reported 'evidence' for anti-neutrino oscillations in 1995, thus becoming the first experiment to report observation of neutrino oscillations using appearance-type strategy.

The experimental set-up is quite simple[6]. The source of neutrinos was an intense proton beam at the Los Alamos Meson Physics Facility (LAMPF), whose kinetic energy was 800 MeV (~1 mA current). This beam was made to hit a water target, followed by a water-cooled copper (Cu) beam dump. This produces a large number of pions, mostly π^+. The π^+ decays into a μ^+ and ν_μ and $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$. Not many electron anti-neutrinos ($\bar{\nu}_e$) are expected from such a source (small amounts of π^- are produced, but are immediately absorbed, a few of them decay to μ^-, which are also absorbed before decaying). As mentioned earlier, the LSND detector itself was situated about 30 m from the source. The detector was approximately a cylindrical tank 8.3 m long and 5.7 m in diameter. It contained 167 t of mineral oil (CH_2) and 0.031 g/l b-PBD (butyl-phenyl-biphenyl-oxydiazole), which acted as the organic scintillating medium filling the detector. The detector was lined up with phototubes (1220 in number, 8 inches in size, Hamamatsu-make) inside the tank to detect the Cherenkov radiation as well as the scintillation light emitted from the propagating particle inside the detector. Further the detector was adequately shielded from cosmic rays by an overburden of roughly 2 kg/cm^2.

Data were collected in two batches from 1993 to 1995 using the water target in the neutrino source described above and later replacing the water target with a closely packed high atomic number element (Z) from 1996 to 1998. Data from two types of decay patterns of muons were collected: (i) μ decay at rest: used for the analysis of anti-neutrinos and (ii) μ decay in flight: used for the analysis for neutrinos. A total of 18×10^{22} protons were made to hit the LSND target during this period. The following reactions were used to detect the $\bar{\nu}_e$ emanating from μ decays at rest:

$$\bar{\nu}_e + p \rightarrow e^+ + n, \tag{9}$$

and the 2.2 MeV γ from the reaction

$$n + p \rightarrow d + \gamma. \tag{10}$$

In the case of μ decays in flight, the experiment looked for electron neutrinos which are expected to be present after oscillations of the muon neutrinos during flight. The reaction used to detect the electron neutrino was

$$\nu_e + {}^{12}C \rightarrow e^- + X, \tag{11}$$

the signal being the single electron, where X stands for the residue of the ^{12}C atom due to this inelastic scattering.

In the data analysis, the energy range was taken to be $20 < E_e < 60$ MeV for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search and $60 < E_e < 200$ MeV for the $\nu_\mu \rightarrow \nu_e$ oscillation search. In the anti-neutrino oscillation search, a total excess of $87.9 \pm 22.4 \pm 6.0$ events (3.8σ) consistent with $\bar{\nu}_e + p \rightarrow e^+ + n$ scattering was observed above the background. This excess corresponds to an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$, assuming the two anti-neutrino oscillation hypothesis. The neutrino oscillation search, in addition to the anti-neutrino search also found an excess of events, though statistically this excess was not significant. It amounted to $8.1 \pm 12.2 \pm 1.7$ events corresponding to an oscillation probability of $(0.10 \pm 0.16 \pm 0.04)\%$. To summarize, the LSND data suggested that (anti)neutrino oscillation occurred with a Δm^2 in the range of 0.2–10 eV^2/c^4. At 90% C.L. analysis of the μ^+ decay at rest data showed that $\sin^2 2\theta \in [10^{-3}$ to $10^{-1}]$.

The implications of the LSND result are many fold. First, it indicates that the standard three flavour picture which we have summarized earlier, would no longer hold true as with three neutrinos, one can have only two independent mass-squared differences. This can be easily seen as follows: the mass-squared differences Δm^2_{ab} as defined earlier, satisfy the following equation in three generations: $\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = 0$, which shows that there are only two independent mass-squared differences in three generations. Secondly, if there is another neutrino responsible for the oscillations observed at the LSND, this neutrino cannot be a part of the SM families, as it would violate the experimental result from the LEP experiment at CERN, which showed that three are only three families of neutrinos which take part in the SM (more precisely weak) interactions. Thus the new neutrino has to be a inert under these interactions and was thus named as a sterile neutrino.

Theoretically, the existence of a sterile neutrino would require deeper understanding of such particles[5]. Further newer mechanisms might be required to generate masses to them, which can sometimes lead to complicated model-building beyond the SM. Phenomenologically too, simplest extensions from the three-neutrino scheme to the four-neutrino scheme, including a sterile neutrino to accommodate the LSND data, have run into rough weather with improving measurements of solar and atmospheric data, which have serious implications on such schemes. This is because little room is left to accommodate a sterile neutrino either in the solar data or in the atmospheric data. Finally, the sterile neutrino can only be tested indirectly. Indications can come from neutrino oscillations and perhaps through cosmology, where sterile neutrinos can play a role in structure formation. Sterile neutrinos also have severe constraints from astrophysical processes like supernovae cooling, etc.[7]. While all these would pose new and exciting challenges, the existence of a sterile neutrino experimentally relied only on the LSND data.

The sterile neutrinos are not the only solution offered to understand LSND data. Several new, exotic ideas as well as some well-motivated theories were used to explain the LSND data. For example, within supersymmetric extensions of the SM, new kinds of interactions which violate lepton number can be used to explain the LSND excess events. On the other hand, well-motivated models based on theories of extra space dimensions also have a natural way of incorporating sterile neutrinos and LSND data[8]. In addition, more exotic ideas like CPT violation[9], which advocate different masses for particles and antiparticles and ideas of mass-varying neutrinos which propose that neutrino masses vary with time over cosmological timescales, have been put to use explain to the LSND data in the recent years.

The KARMEN experiment

The LSND result ran into controversy when some experimentalists raised objections on the estimation of systematical errors of the experiment. The LSND Collaboration has responded to these concerns by changing the target (from water to a closely packed high-Z target) and further explaining that there could not be large errors introduced into the systematics due to the presence of other sources of electron anti-neutrinos in the experiment. The KARMEN experiment, which was studying neutrino–nucleus cross-sections around that time was expected to provide an independent confirmation or verification of the LSND observations after some modifications to their existing experimental set-up.

This experiment, whose acronym reads KARMEN (KArlsruhe Rutherford Medium Energy Neutrino), was located at the highly pulsed spallation neutron source ISIS of the Rutherford Laboratory, UK. The experiment was most sensitive to the search of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation channel.

In this case, a rapid-cycle synchrotron was used to accelerate the protons up to 800 MeV with a design beam current of 200 μA. The protons were made to hit a target of water-cooled Ta-D_2O, which produced π^+, that then decays into μ^+; the subsequent decays of μ^+ act as a source of anti-muon neutrinos. The detector which is a segmented high-resolution liquid scintillation calorimeter, was located at a mean distance of 17.7 m from the target. The liquid scintillator consisted of a mixture of paraffin oil (75% by volume), pseudocumene (25% by volume) and 2 g l^{-1} of the scintillating active 1-phenyl-3-mesityl-2-pyrazoline (PMP). Appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu \to \bar{\nu}_e$ flavour oscillation was detected by the classical inverse beta-decay reaction:

$$\bar{\nu}_e + \mathrm{p} \to \mathrm{n} + \mathrm{e}^+, \quad Q = -1.804 \text{ MeV}$$
$$n_{\mathrm{th}} + {}^1\mathrm{H} \to {}^2\mathrm{H} + \gamma$$
$$n_{\mathrm{th}} + \mathrm{Gd} \to \mathrm{Gd} + \mathrm{n}\gamma, \tag{12}$$

where the average number of photons emitted $\langle n \rangle = 3$. In total, 15 candidates fulfilled all conditions for the $\bar{\nu}_e$ signature. This agreed with the background expectation of 15.8 ± 0.5 events. Hence there was no signature of oscillations. Analysis of the data yielded the following results: $\sin^2 2\theta < 1.7 \times 10^{-3}$ for $\Delta m^2 \geq 100 \text{ eV}^2$ and $\Delta m^2 < 0.055 \text{ eV}^2$ for $\sin^2 2\theta = 1$ at 90% CL. The implications are that at large Δm^2, KARMEN results exclude the region favoured by LSND. At low Δm^2, there is a restricted parameter region statistically compatible with both the experimental results. A joint analysis with LSND shows that these results are 64% compatible with each other[10].

MiniBooNE

In order to address the LSND anomaly the MiniBooNE (BooNE is an acronym for the Booster Neutrino Experiment) experiment was proposed. The MiniBooNE collaborators have kept the *L*/*E* the same as in LSND, but have changed the systematics, energy and event signature. This way, one has access to the entire parameter space accessed by LSND.

MiniBooNE is located at the Fermi National Accelerator Laboratory in the United States. The experiment made use of the Fermilab Booster neutrino beam. Protons with energies of 8 GeV were incident on a beryllium target; such a choice of target solely being dictated by the need of a source with far more μ^+s than μ^-s. To increase the flux, a magnetic focusing horn which encloses the target has been used (this increases the flux almost six-fold). A total 6.3×10^{12} POT were delivered[11], while the actual result of the experiment corresponded to $(5.58 \pm 0.12) \times 10^{12}$ POT.

This experiment was also based on the 'appearance' principle; it had looked for an excess of ν_e in a purely ν_μ beam. After the protons hit the target, the produced (positively charged) pions and kaons pass through a collimator of about 60 cm long and then through a tunnel towards the detector which is about 50 m long. These particles decay along the way producing neutrinos. The 'intrinsic' $\nu_e + \bar{\nu}_e$ sources are: $\mu^+ \to \mathrm{e}^+ + \nu_e + \bar{\nu}_\mu$ (52%), $K^+ \to \pi^0 + \mathrm{e}^+ + \nu_e$ (29%), $K^0 \to \pi + \mathrm{e} + \nu_e$ (14%), others (5%); $\nu_e/\nu_\mu = 0.5\%$ and the anti-neutrino content about 6%.

The detector was placed about 541 m downstream in front of the target. It had the shape of a sphere, 12.2 m in diameter. This spherical tank was filled up with 800 t of pure mineral oil (fiducial volume = 450 t; see Note 6). An optical barrier separated the detector into two regions: (a) an inner light-tight volume of radius 575 cm and (b) an optically isolated outer volume, 35 cm thick known as veto region. The optical barrier was lined with 1280 inner photomultiplier tubes (PMT) (8 in) providing 10% photocathode coverage. An additional 240 veto phototubes were lined in the inner volume detecting particles entering or leaving the detector.

The produced neutrinos traverse along the tunnel, enter the detector, and interact with the medium in the detector. Depending on the pattern of light observed in the PMTs, one can determine the kind of interaction the neutrino went through in the detector. Two signatures, (a) Cherenkov radiation and (b) scintillation (fluorescence) light were used to detect the kind of neutrino interaction. Neutrinos interact through both charged current and neutral current channels here and both were used in the detection process. The main interactions were (1) charged-current scattering (39%), (2) neutral current (NC) elastic scattering (16%), (3) charged current (CC) single pion production (29%), (4) NC single pion production (12%), (5) Multi-pion and deep-inelastic scattering (less than 5%). The list of all possible interactions and the corresponding signature in the PMT can be found in the research paper put out by the collaboration[11]. For example, in the CC quasi-elastic events, a neutrino interaction in the detector will produce the lepton partner of the neutrino. Electrons multiple-scatter along their way and so travel for a short time before their velocity falls below that required for Cherenkov radiation. Hence a fuzzy Cherenkov ring in the detector is their signature. Muons, being heavier, have much longer tracks. As they slow down, the angle at which the Cherenkov light is being emitted shrinks. Muons also emit scintillation light. The signature is a sharp outer ring with fuzzy inner region. Neutral pions decay into two photons which then pair-produce (an electron and a positron). Evidently their signature in the detector consists of two fuzzy rings.

Data were collected for about five years starting from 2002. After the data were taken, the MiniBooNE Collaboration performed a 'blind' analysis. This means the experimentalists did not have access to all information in the data. This is one of the hallmarks of the work done by this Collaboration. For oscillation search, two different types of analysis were performed: one which depended on likelihood variables (called the 'track based', TB analysis), and one which depended on a boosted decision tree. In this way, each analysis would cross-check the other. In the published analysis, the former algorithm was chosen as the primary result because it had a better sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation. In the analysis, the electron neutrino events were isolated and then a comparison made between the observed number of events to the expected number of events (that is, the sum of the intrinsic electron neutrino and the fake events) as a function of the 'reconstructed' neutrino energy. An excess of the observed data over expected data (or an excess of ν_e events) as a function of the energy indicates oscillation.

After the complete analysis was done 'the box' was opened. It was found that there was no significant excess of events ($22 \pm 19 \pm 35$ events) for $475 < E_\nu^{\mathrm{QE}} <$ 1250 MeV. The oscillation fit in the $475 < E_\nu^{\mathrm{QE}} < 1250$ MeV range yielded a χ^2 probability of 93% for the null hypothesis, and a probability of 99% ($\sin^2\theta = 10^{-3}$, $\Delta m^2 = 4\ \mathrm{eV}^2$) for the best-fit point. The probability that both MiniBooNE and LSND are due to two-neutrino oscillations is only 2%.

Implications of MiniBooNE and future directions

The MiniBooNE results will have strong implications for most of the sterile neutrino models which are constructed as extensions of the SM. However, there are still some points to be understood about the MiniBooNE analysis. The experiment has reported that an excess of events ($96 \pm 17 \pm 20$ events) (deviation = 3.7σ) was observed below 475 MeV above the expected background. Presently, there is little understanding about the source of this excess. It is not clear whether it is an experimental systematical error or whether it signals the existence of new physics.

One of the major implications of the MiniBooNE result is that simplest sterile neutrino schemes, like 3 + 1 or 2 + 2 with single sterile neutrino are ruled out, as they are not compatible with both LSND and MiniBooNE data. However, the exploiting CP violation present in much larger schemes like 3 + 2 with two sterile neutrinos can still accommodate LSND and MiniBooNE data making them compatible[12].

Mass-varying neutrinos have been proposed as means of generating cosmological dark energy in recent years. Here the neutrinos have couplings to an acceleron field which varies over cosmological times scales. This idea has been applied to explain the LSND data. Just as in the three-neutrino case, here too one would need to add another neutrino to accommodate the LSND data, as we would need at least one more mass-squared difference in addition to the ones required. It has been pointed out that in this particular model[13], there could be positive signal at LSND, whereas a null result for MiniBooNE. How far this idea would remain viable with future long-based experiments remains to be seen.

While the need for CPT violation is not completely understood within the context of quantum field theory, in the neutrino sector it can be incorporated by assuming that neutrinos and anti-neutrinos have different masses and mixing angles, and thus the oscillation frequencies of neutrinos and anti-neutrinos would be different. This has been utilized to explain the LSND data. However, after the KamLand experiment, there has been some skepticism, though it was shown that statistically the fits could be still reasonable. The fate of a four[14] or high number of neutrino-generation CPT violating models needs to be known.

Thus, at present the last word has not yet been said about the fascinating world of sterile neutrinos. As MiniBooNE continues to take data, we expect more severe constraints from them.

Notes

1. The LSND evidence soon was termed as the LSND anamoly as questions were raised regarding the accuracy about background estimates, etc. The LSND collaboration has responded to most of the criticisms with elaborate checks. The evidence still persists.
2. This problem persisted for over thirty years.
3. The up-down asymmetry is expected to be zero if there are no oscillations.
4. This symmetry plays an important role in the understanding of the origins of matter and anti-matter asymmetry in our world.
5. To probe solar and atmospheric neutrino oscillations on earth, one would need much larger base-lines.
6. Actual volume relevant in the detection process.

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