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Neutrino Oscillations: Evidence, Parameters and Open Questions in Neutrino Physics

Vimala George

Associate Professor, Deptartment of Physics, At. Xavier's College for Women (Autonomous), Aluva, India

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Abstract
Neutrinos change flavour as they propagate, and this behaviour requires them to carry non-zero mass, a property the original Standard Model did not provide. This review sets out the quantum-mechanical description of flavour mixing, summarises the observations that established it, and assesses what remains unresolved. Atmospheric measurements at Super-Kamiokande, the neutral-current measurement of the solar flux at the Sudbury Neutrino Observatory, and the reactor antineutrino deficit recorded by KamLAND together fixed the two dominant mass-squared splittings and their mixing angles. Short-baseline reactor experiments later measured the third mixing angle with percent-level precision, which opened the search for leptonic charge-parity violation now pursued by long-baseline accelerator beams. Global analyses constrain five of the six oscillation parameters to a few percent, while the sign of the larger splitting, the octant of the atmospheric angle, and the value of the charge-parity phase remain uncertain. Oscillation data fix only mass differences, so the absolute scale is bounded instead by tritium endpoint spectroscopy and by cosmological structure. Whether the neutrino is its own antiparticle is being tested through searches for neutrinoless double beta decay. Experiments now under construction should settle the mass ordering and provide a first measurement of the phase.

Keywords: Neutrino Oscillation, PMNS Matrix, Mass Ordering, Leptonic CP Violation, Neutrino Mass.

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1. INTRODUCTION

The neutrino was introduced as a bookkeeping device to rescue energy conservation in beta decay and remained, for four decades, a particle assumed to be massless. That assumption was written into the Standard Model of particle physics, which contains no right-handed neutrino field and therefore no renormalisable mass term for neutral leptons. The first sign of trouble came from the Homestake experiment, which counted roughly a third of the electron neutrinos that solar models predicted should arrive from the core of the Sun.[1] For thirty years the deficit was attributed by many to shortcomings in astrophysical modelling rather than to particle properties.

A second anomaly appeared in underground detectors built to look for proton decay. Cosmic-ray interactions in the upper atmosphere produce muon and electron neutrinos in a ratio close to two to one, a prediction that follows from the pion and muon decay chain and is insensitive to the details of the primary cosmic-ray flux. Detectors consistently recorded fewer muon neutrinos than expected, and the deficit grew with the distance travelled through the Earth. In 1998 the Super-Kamiokande collaboration reported a zenith-angle dependence of that deficit which no detector systematic could reproduce and which matched the pattern expected from flavour oscillation .[2]

Confirmation from the solar sector followed. The Sudbury Neutrino Observatory measured both the electron-neutrino flux and the flux of all three active flavours from boron-8 decay in the Sun, and found that the total agreed with the solar model while the electron component did not.[3] The neutrinos had not disappeared; they had changed flavour. The reactor experiment KamLAND then observed the same parameters at work in a laboratory beam of electron antineutrinos, recording an energy-dependent deficit over baselines of about 180 km .[4] The three results together closed the argument.

This paper reviews the formalism that describes flavour change, the measurements that determine its parameters, and the questions that remain. The emphasis is on what the data now establish, what they constrain only weakly, and which of the experiments under construction are expected to resolve each remaining ambiguity.

2. THEORETICAL DESCRIPTION OF FLAVOUR CHANGE

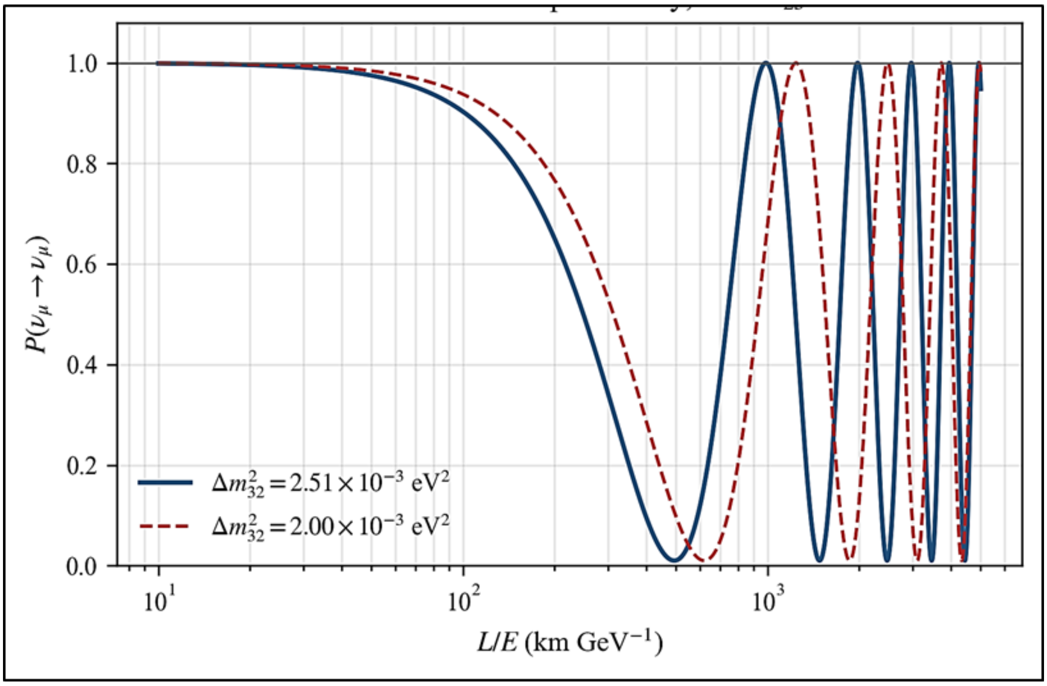
Flavour oscillation follows from a single assumption: the neutrino states produced in weak interactions are not states of definite mass. The idea was proposed by Pontecorvo in the context of neutrino and antineutrino transitions and developed for flavour mixing by Maki, Nakagawa and Sakata.[5,6] A neutrino created together with a charged lepton of flavour a is a superposition of mass states, related by a unitary matrix now named after those authors and Pontecorvo.

Because the mass states carry slightly different phases as they propagate, the superposition that arrives at a detector is no longer the state that was produced. For two flavours the survival probability takes a compact form in which the oscillation phase depends on the mass-squared difference, the distance travelled and the neutrino energy through the ratio of baseline to energy. Written in practical units, the phase equals 1.267 times the mass-squared difference in square electronvolts multiplied by that ratio in kilometres per gigaelectronvolt. Fig. 1 shows the resulting survival probability for muon neutrinos at two values of the atmospheric splitting; the position of the first minimum is what a long-baseline experiment measures most precisely, and a ten percent change in the splitting moves it visibly.

The three-flavour description requires three mixing angles, two independent mass-squared differences and one phase that can generate charge-parity violation in the lepton sector. If neutrinos are their own antiparticles, two further phases enter, but these do not affect oscillation probabilities. The two splittings differ by a factor of roughly thirty, which conveniently separates the experimental programme: the smaller splitting governs solar and long-baseline reactor measurements, and the larger one governs atmospheric and accelerator measurements.

Propagation through matter modifies the picture. Electron neutrinos undergo coherent forward scattering on electrons through the charged current, which the other flavours do not, and the resulting potential shifts the effective mixing angle. Wolfenstein derived the effect, and Mikheyev and Smirnov showed that a neutrino crossing a region of falling density can convert almost completely if it passes through a resonance. [7,8]The solar neutrino deficit is the clearest example: high-energy boron-8 neutrinos leave the Sun predominantly in the second mass state, so their survival probability is set by the mixing angle rather than by an oscillation phase. The same effect makes the sign of the larger splitting accessible to experiments with long baselines through the Earth.

Fig 1: Muon-neutrino survival probability as a function of baseline divided by energy, computed for two values of the atmospheric mass-squared splitting. Long-baseline experiments tune their beam energy and baseline to sit near the first minimum.



3. THE EXPERIMENTAL RECORD

Atmospheric neutrinos provided the first compelling evidence. Super-Kamiokande, a 50 kiloton water Cherenkov detector, exploited the fact that neutrinos arriving from above travel some tens of kilometres while those arriving from below travel up to the diameter of the Earth. The upward-going muon-neutrino rate was suppressed by about half, the downward rate was not, and the electron-neutrino rate matched expectation in both directions .[2] The pattern identified the dominant channel as transitions from muon to tau flavour.

The solar programme reached its conclusion through a measurement that was insensitive to flavour. Neutral-current interactions on deuterium occur with equal strength for all three active flavours, so the Sudbury Neutrino Observatory could compare the total active flux with the electron-flavour flux measured through charged-current interactions in the same detector. The total agreed with the standard solar model while the electron component accounted for roughly a third of it .[3] KamLAND then detected reactor antineutrinos from the Japanese power network and observed a spectral distortion consistent with the same parameters, which demonstrated that the phenomenon is a property of neutrinos and not of the Sun .[4]

The third mixing angle was the last to be measured. Its size sets the amplitude of electron-neutrino appearance in an accelerator beam and therefore controls access to the charge-parity phase. Daya Bay used eight functionally identical detectors at several distances from six reactor cores, which cancelled the flux uncertainty that had limited earlier attempts, and reported a non-zero value with high significance in 2012 .[9] RENO published a consistent result within weeks.[10] The angle turned out to be large enough that appearance experiments became practical, which reshaped the field.

Long-baseline accelerator experiments now dominate the search for the remaining unknowns. T2K directs a beam from the Japan Proton Accelerator Research Complex to Super-Kamiokande, 295 km away, and compares neutrino with antineutrino running; its data disfavour a substantial region of the phase near the charge-parity conserving values.[11] NOvA observes a beam from Fermilab over a baseline of 810 km and provides complementary sensitivity to the mass ordering through the matter effect.[12] The two experiments prefer somewhat different regions of parameter space, and reconciling them is an active question.

4. PRESENT PARAMETER DETERMINATIONS

Global analyses combine solar, atmospheric, reactor and accelerator data with a common treatment of systematic uncertainties. Table 1 lists representative values from one such analysis for the normal mass ordering.[13] Five quantities are known to a few percent. The solar angle and the smaller splitting are fixed mainly by solar data combined with KamLAND; the third angle is fixed almost entirely by short-baseline reactor experiments; and the atmospheric splitting is constrained by both accelerator and atmospheric samples.

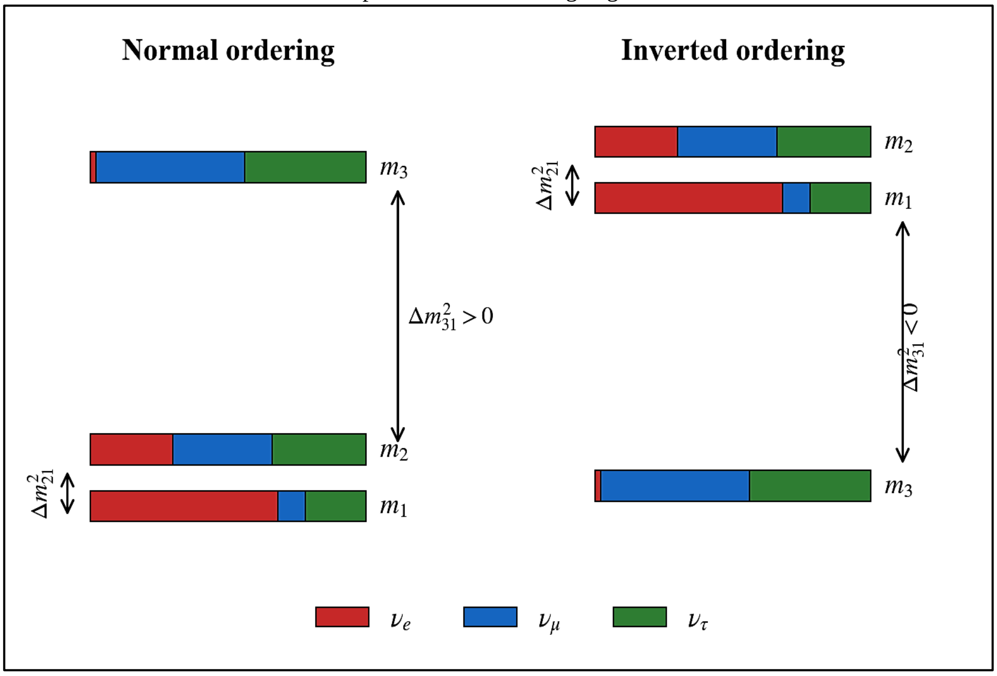
Two features of the table deserve comment. First, the atmospheric angle is consistent with maximal mixing, and whether it lies above or below 45 degrees, the so-called octant question, is not resolved. Second, the phase that governs charge-parity violation is quoted with an uncertainty of many tens of degrees, and its allowed region depends noticeably on which data sets are included. Values differ modestly between the published global fits, and quoted intervals should be read as analysis-dependent rather than as settled numbers.

Table 1. Representative global-fit values of the three-flavour oscillation parameters for the normal mass ordering Values follow the global analysis of reference.[13]

Parameter	Best fit	Three-sigma range	Principal constraint
$\sin^2\theta_{12}$	0.303	0.270 to 0.341	Solar data with KamLAND
$\sin^2\theta_{23}$	0.572	0.406 to 0.620	Atmospheric and accelerator
$\sin^2\theta_{13}$	0.02203	0.02029 to 0.02391	Short-baseline reactors
Δm^2_{21} (10^{-5} eV^2)	7.41	6.82 to 8.03	KamLAND with solar data
Δm^2_{31} (10^{-3} eV^2)	+2.511	+2.428 to +2.597	Accelerator and atmospheric
δ (degrees)	197	108 to 404	Accelerator appearance channels

The sign of the larger splitting remains open. Two arrangements are possible, illustrated in Fig. 2. In the normal ordering the state with the smallest electron content is the heaviest; in the inverted ordering it is the lightest. The distinction matters well beyond oscillation physics, because the inverted arrangement implies a minimum effective mass for neutrinoless double beta decay that current detectors are close to reaching, whereas the normal ordering allows that observable to be arbitrarily small.

Fig 2: The two possible mass orderings. Bar shading shows the approximate flavour content of each mass state, computed from the mixing angles in Table 1.



5. QUESTIONS THAT OSCILLATION DATA CANNOT ANSWER

Oscillation probabilities depend on differences of squared masses, so they say nothing about the absolute scale. Three independent approaches bound it. Kinematic measurements examine the endpoint of the tritium beta spectrum, where a non-zero mass removes the last few electronvolts of phase space. The KATRIN spectrometer has pushed this method below the electronvolt level and reported an upper limit of 0.8 eV at 90 percent confidence, with later analyses of larger data sets tightening the bound further .[14] The method is model independent, which is its main strength.

Cosmology provides a much tighter but model-dependent constraint. Massive neutrinos stream freely in the early universe and suppress the growth of structure on small scales, so the sum of the masses can be inferred from the cosmic microwave background combined with measurements of galaxy clustering. Analyses of Planck data with baryon acoustic oscillation measurements give an upper bound of about 0.12 eV on the sum.[15] The number assumes the standard cosmological model, and it would relax if that model were extended.

Whether the neutrino is a Dirac particle, distinct from its antiparticle, or a Majorana particle that is its own antiparticle, is the deepest of the open questions. A Majorana mass term violates lepton number and would allow a nucleus to undergo double beta decay without emitting neutrinos. No such decay has been seen. GERDA reported no candidate events in germanium-76 with essentially zero background , and KamLAND-Zen has set the strongest limits using xenon-136 dissolved in liquid scintillator, reaching into the region of effective masses predicted for the inverted ordering .[16,17] Interpretation of these limits in terms of mass depends on nuclear matrix elements, which differ between calculations by roughly a factor of three.

A separate question concerns whether additional neutrino states exist that do not couple to the weak interaction. The LSND experiment reported an excess of electron antineutrinos consistent with a splitting near one square electronvolt , and MiniBooNE later reported an excess of low-energy events in a similar region . [18,19] MicroBooNE, using liquid-argon imaging that separates electrons from photons event by event, found no corresponding excess of electron-neutrino interactions.[20] The tension is not fully resolved, and a global sterile-neutrino interpretation now sits uncomfortably with reactor and atmospheric disappearance data.

6. EXPERIMENTS NOW UNDER CONSTRUCTION

Three facilities are expected to resolve most of what remains. The Deep Underground Neutrino Experiment will send a wide-band beam from Fermilab to liquid-argon detectors 1300 km away in South Dakota. The baseline is long enough for the matter effect to separate the two orderings decisively, and the wide spectrum allows the oscillation pattern to be measured at several energies at once, which breaks degeneracies between the phase and the ordering .[21] Hyper-Kamiokande, a detector with roughly eight times the fiducial volume of its predecessor, will use the existing Japanese beam over a shorter baseline where matter effects are small, so its measurement of the phase is comparatively clean.[22]

JUNO takes an entirely different route. A 20 kiloton liquid scintillator detector placed 53 km from two reactor complexes will resolve the fine interference between the two splittings in the antineutrino energy spectrum. That interference pattern depends on the ordering without any reliance on matter effects or on the value of the phase, which makes the measurement complementary to the accelerator programme.[23] The experiment will also improve the precision on the solar parameters by roughly an order of magnitude.

For the Majorana question, the next generation of double beta decay searches aims at tonne-scale isotope masses with backgrounds low enough to cover the whole inverted-ordering region. If the ordering turns out to be normal and the lightest mass is small, a null result would remain compatible with Majorana neutrinos, so a definitive answer may require both a positive signal and independent information on the mass scale.

7. CONCLUSION

Flavour oscillation is now measured rather than inferred. The mixing angles and the two mass-squared splittings are known with a precision that would have seemed implausible when the solar deficit was first reported, and the framework that describes them requires only the assumption that flavour states mix. What remains unknown is structurally important: the ordering of the masses, the size of charge-parity violation among leptons, the absolute mass scale, and the Dirac or Majorana character of the particle. Each of these bears on why neutrino masses are so much smaller than those of the charged fermions, and the last two bear on whether lepton number is conserved at all. The experiments now being built address them directly, and the next decade should convert several of these open questions into measurements.

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