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NEUTRINO OSCILLATIONS: NON-ACCELERATOR RESULTS*

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In the past decade non-accelerator experiments have discovered neutrino oscillations and made precise measurements of neutrino mixing parameters. I will review the phenomenon of neutrino oscillation and describe what non-accelerator experiments have revealed about neutrino masses and mixings.

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1. Introduction

In the Standard Model each charged lepton (e, μ, or τ) is associated with one massless neutrino, and lepton flavour is rigorously conserved, so that for example the total number of "electron"-type leptons (charged or otherwise) is unchanged in all interactions. Interestingly, although no Standard Model process violates lepton flavour number, there is no associated symmetry of the Lagrangian that requires this to be so — that is, the absence of lepton-flavour-changing terms in the Lagrangian seems to be "accidental", and not the result of a deeper symmetry.

Neutrino oscillation supposes in analogy with quark mixing that neutrino flavour eigenstates such as ν_e or ν_μ do not correspond to the neutrino mass eigenstates [1]. That is, the particle we call "ν_e", produced when an electron couples to a W, might actually be a linear superposition of two mass eigenstates ν_1 and ν_2. In the case of 2-flavour mixing, we can write:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} +\cos\theta & +\sin\theta \\ -\sin\theta & +\cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} . \tag{1}$$

While the formalism exactly parallels that used for quark mixing, with angle θ in Eq. (1) playing the role of a Cabibbo angle for leptons, the resulting

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phenomenology is somewhat different. In the case of quarks, mixing between generations can be readily seen by producing hadrons through strong interactions, and then observing them through weak interactions. Neutrinos, however, have *only* weak interactions, and so we cannot produce neutrinos with one kind of interaction and then detect them with another. A rotation between neutrino flavour eigenstates and neutrino mass eigenstates such as in Eq. (1) has no direct impact on weak interaction vertices themselves. W bosons will still always couple an e to a ν_e and a μ to ν_μ even if there is a rotation between the flavour and mass eigenstates.

If the mass eigenstates have different masses, then neutrino oscillation can occur. Consider a ν_e produced at $x = 0$, $t = 0$. As this state propagates in vacuum, each term of the linear superposition picks up the standard quantum mechanical phase factor for plane wave propagation (with $\hbar \equiv 1$):

$$|\nu(\vec{x}, t)\rangle = \exp(i(\vec{p} \cdot \vec{x} - E_1 t)) \cos\theta |\nu_1\rangle + \exp(i(\vec{p} \cdot \vec{x} - E_2 t)) \sin\theta |\nu_2\rangle \,. \quad (2)$$

At some time $t > 0$, the neutrino's state will be proportional to the following superposition: $|\nu(t)\rangle \propto \cos\theta|\nu_1\rangle + e^{i\phi} \sin\theta|\nu_2\rangle$, where ϕ is a phase difference that arises due to the different masses of the eigenstates. The net result is that at time t, the ν that originally was in a pure ν_e state is no longer in a pure ν_e state, but due to the phase difference ϕ will have acquired a non-zero component of ν_μ! We therefore can determine the probability that our original ν_e will interact as a ν_μ by projecting out the ν_μ component:

$$\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= |\langle \nu_\mu | \nu(t) \rangle|^2 \\ &= \sin^2 2\theta \sin^2 \left[1.27 \left(\frac{\Delta m^2}{1 \text{ eV}^2} \right) \left(\frac{L}{1 \text{ km}} \right) \left(\frac{1 \text{ GeV}}{E} \right) \right] . \end{aligned} \quad (3)$$

The oscillation probability in Eq. (3) has a characteristic dependence on both L and E that is a distinctive signature of neutrino oscillations.

The presence of matter alters the oscillation. The reason is that ordinary matter contains electrons but not μ's or τ's. As a result, ν_e's traveling through matter can interact with leptons in matter by both W and Z boson exchange, while ν_μ or ν_τ can interact only by Z exchange. Hence ν_e's pick up an extra interaction term, proportional to the density of electrons N_e in matter, that acts as a matter-induced potential for ν_e's but not for other flavours. The time evolution of the superposition in the flavour basis is altered to:

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2} G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} . \quad (4)$$

This matter effect, known as the MSW effect [2], gives rise to a rich phenomenology in which oscillation probabilities in dense matter, such as the interior of the Sun, can be markedly different from those seen in vacuum. Of the experimental results to date, only in solar neutrino oscillations does the MSW effect play a significant role. The generalization of neutrino oscillation to three flavours is straightforward and described in Section 5.

2. Atmospheric neutrinos

The first conclusive demonstration of neutrino oscillation came from studies of atmospheric neutrinos. Atmospheric ν's are produced when cosmic rays collide in the upper atmosphere to make hadronic showers. These showers contain $\pi^{\pm}$, which decay leptonically by $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$. The muons in turn decay in flight by $\mu^{\pm} \to e^{\pm}\nu_{\mu}\nu_{e}$, where I've ignored differences between ν and $\bar{\nu}$ states. A robust conclusion that follows from the decay sequence is that the ratio of ν_{μ} to ν_{e} in the atmospheric neutrino flux should be 2:1.

In 1998 the Super-Kamiokande Collaboration reported results showing that ratio of the flux of ν_{μ} to ν_{e} in fact is not 2:1, but is closer to 1:1 [3]. Closer examination revealed that while the ν_{e} flux in fact is in good agreement with Monte Carlo predictions, the ν_{μ} flux shows a marked deficit. The size of this deficit varies with neutrino energy, and with the zenith angle of the event. This latter point is significant in that down-going neutrinos are produced in the atmosphere just overhead, and have traveled < 10 km before reaching Super-Kamiokande, while up-going neutrinos are produced in the atmosphere on the far side of the Earth, and have traveled $\sim$13,000 km before reaching the detector. As seen in figure 1, the deficit between the expected and measured number of ν_{μ} is largest at low energy and at negative $\cos\theta$ (upward-going events) [3]. This dependence on energy and on the distance traveled by the neutrino is characteristic of neutrino oscillations, and excludes a simple normalization error. The oscillation seems to be of the type $\nu_{\mu} \to \nu_{\tau}$, based on the fact that apparently no additional ν_{e} are produced, while ν_{τ} will generally be below the threshold for τ production and so are not detected. Oscillation to a sterile neutrino would introduce a matter effect due to the differing interactions of $\nu_{\mu\tau}$ and $\nu_{sterile}$, but is strongly disfavoured by the angular distribution of the surviving ν_{μ}, which shows no evidence for such a matter effect. The atmospheric neutrino effect has been confirmed by a number of other experiments [4].

Fitting a two-flavour oscillation model to the data gives $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2 and, surprisingly, a maximal mixing angle of $\theta \approx 45^{\circ}$ [3].

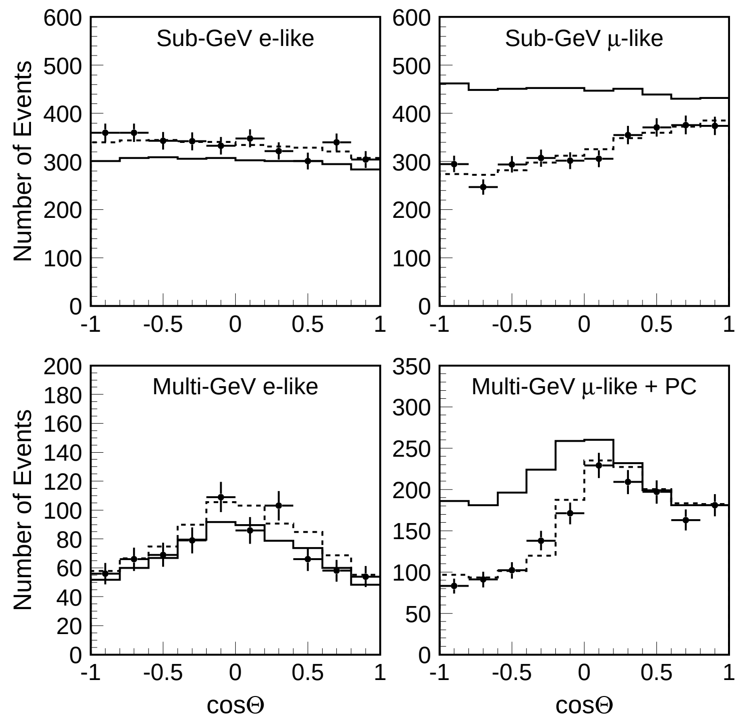

Fig. 1. Fluxes of atmospheric ν_e and ν_μ as a function of zenith angle, as measured by Super-Kamiokande [3]. The solid lines show the no oscillation prediction, while the dashed line passing through the data points is the best-fit oscillation prediction.

3. The solar neutrino problem

The Sun is a prolific source of ν_e's with energies in the $\sim$0.1–20 MeV range, produced by the fusion reaction

$$4p + 2e^- \rightarrow^4 \mathrm{He} \ + \ 2\nu_e \ + \ 26.731 \ \mathrm{MeV}\,. \qquad (5)$$

The reaction in Eq. (5) actually proceeds through a chain of sub-reactions called the *pp* chain, consisting of several steps [5]. Each neutrino-producing reaction in the *pp* chain produces a characteristic neutrino energy spectrum that depends only on the underlying nuclear physics, while the rates of the reactions must be calculated through detailed astrophysical models of the Sun [6]. Experimentally the *pp*, ^{8}B, and ^{7}Be reactions are the most important neutrino-producing steps of the *pp* chain.

Ray Davis's chlorine experiment in the Homestake mine measured solar neutrinos by observing the rate of Ar atom production through the reaction $\nu_e + ^{37}\mathrm{Cl} \rightarrow ^{37}\mathrm{Ar} + e^-$ [7]. By placing 600 tons of tetrachloroethylene deep underground (to shield it from surface radiation), and using radiochemistry techniques to periodically extract and count the number of argon atoms in the tank, Davis inferred a solar neutrino flux that was just $\sim$1/3 of that predicted by solar model calculations [6, 7].

When scrutiny of both the Davis experiment and the solar model calculations failed to uncover any clear errors, other experiments were built to measure solar neutrinos in other ways. The Kamiokande and Super-Kamiokande water Cherenkov experiments have measured elastic scattering of electrons by ^{8}B solar neutrinos, using the directionality of the scattered electrons to confirm that the neutrinos in fact are coming from the Sun [8]. The measured elastic scattering rate is just $\sim$47% of the solar model prediction. The SAGE and GNO/GALLEX experiments have employed a different radiochemical technique to observe the $\nu_e + {}^{71}\mathrm{Ge} \rightarrow {}^{71}\mathrm{Ge} + e^-$ reaction, which is primarily sensitive to *pp* neutrinos, and have measured a rate that is $\sim$55% of the solar model prediction [9].

Multiple experiments using different techniques have therefore confirmed a deficit of solar ν_e's relative to the model predictions. While it was realized early on that neutrino oscillations that converted solar ν_e to other flavours (to which the various experiments would not be sensitive) could explain the observed deficits, merely observing deficits in the overall rate was generally considered insufficient grounds upon which to establish neutrino oscillation as a real phenomenon. It was left for the Sudbury Neutrino Observatory (SNO) to provide the conclusive evidence that solar neutrinos change flavour by directly counting the rate of all active neutrino flavours, not just the ν_e rate to which the other experiments were primarily sensitive.

SNO is a water Cherenkov detector that uses 1000 tonnes of D_2O as the target material [10]. Solar neutrinos can interact with the heavy water by three different interactions:

$$
\begin{aligned}
&(\mathrm{CC}) \qquad \nu_e + d \;\rightarrow\; p + p + e^- \,, \\
&(\mathrm{NC}) \qquad \nu_x + d \;\rightarrow\; p + n + \nu_x \,, \\
&(\mathrm{ES}) \qquad \nu_x + e^- \;\rightarrow\; \nu_x + e^- \,.
\end{aligned} \tag{6}
$$

Here ν_x is any active neutrino species. The reaction thresholds are such that SNO is only sensitive to ^{8}B solar neutrinos[1]. The charged current (CC) interaction measures the flux of ν_e's coming from the Sun, while the neutral current (NC) reaction measures the flux of all active flavours. The elastic scattering (ES) reaction is primarily sensitive to ν_e, but ν_μ or ν_τ also elastically scatter electrons with $\sim$ 1/6th the cross section of ν_e.

[1] The tiny flux of higher-energy neutrinos from the `hep` chain may be neglected here.

SNO has measured the effective flux of ^{8}B neutrinos inferred from each reaction. In units of 10^6 neutrinos/cm^2/s the most recent measurements are [10]:

$$\begin{aligned}\phi_{\rm CC} &= 1.68 \pm 0.06\ (\text{stat.})^{+0.08}_{-0.09}\ (\text{sys.})\,,\\ \phi_{\rm NC} &= 4.94 \pm 0.21\ (\text{stat.})^{+0.38}_{-0.34}\ (\text{sys.})\,,\\ \phi_{\rm ES} &= 2.34 \pm 0.22\ (\text{stat.})^{+0.15}_{-0.15}\ (\text{sys.})\,. \end{aligned} \tag{7}$$

In short, the NC flux is found to be in good agreement with the solar model predictions, while the CC and ES rates are each consistent with just $\sim 35\%$ of the ^{8}B flux being in the form of ν_e's.

This direct demonstration that $\phi_e < \phi_{\rm total}$ provides dramatic proof that solar neutrinos change flavour, resolving the decades-old solar neutrino problem in favour of new neutrino physics. The neutrino oscillation model gives an excellent fit to the data from the various solar experiments, with mixing parameters of $\Delta m^2 \approx 10^{-4}$–$10^{-5}$ eV^2 and $\tan^2\theta \approx 0.4$–0.5. This region of parameter space is called the Large Mixing Angle solution to the solar neutrino problem. In this region of parameter space, the MSW effect plays a dominant role in the oscillation, and in fact ^{8}B neutrinos are emitted from the Sun in an almost pure ν_2 mass eigenstate. The Borexino experiment has recently measured the flux of ^{7}Be ν's and finds a result consistent with the LMA prediction [11].

4. Reactor neutrino experiments

Although ν oscillations with an MSW effect are the most straightforward explanation for the observed flavour change of solar neutrinos, the solar data by itself cannot exclude more exotic mechanisms of inducing flavour transformation. However, additional confirmation of solar ν oscillation has recently come from a terrestrial experiment called KamLAND.

KamLAND is an experiment in Japan that counts the rate of $\bar{\nu}_e$ produced in nuclear reactors throughout central Japan [12]. If neutrinos really do oscillate with parameters in the LMA region, then the standard oscillation theory predicts that reactor $\bar{\nu}_e$'s, with a peak energy of ~ 3 MeV, should undergo vacuum oscillations over a distance of ~ 200 km.[2] By integrating the flux from multiple reactors, KamLAND achieves sensitivity to this effect. The observed flux is lower than the "no oscillation" expectation on average by $\sim 1/3$, with an energy-dependent suppression of the $\bar{\nu}_e$ flux. The energy-dependent pattern of the flux suppression is in good agreement with the ν oscillation hypothesis with oscillation parameters in the LMA region.

[2] At these low energies matter effects inside the Earth are negligible.

The solar experiments and KamLAND provide complementary constraints on the mixing parameters. Solar ν experiments provide reasonably tight constraints on the mixing parameter $\tan^2\theta$, while the addition of KamLAND data sharply constrains the Δm^2 value [10]. This is because in the LMA region the solar ν survival probability determines the mixing angle through

$$|U_{e2}|^2 \approx \sin^2\theta_{12} \approx \frac{\phi_{\rm CC}}{\phi_{\rm NC}} \tag{8}$$

while the observation of a distortion in the reactor antineutrino energy spectrum fixes Δm^2_{21}. Here the subscripts on θ_{12} and Δm^2_{21} reflect the fact that solar ν oscillations involve the first and second mass eigenstates.

5. Conclusions: the three-flavour picture

In the previous sections, the solar and atmospheric ν oscillation effects were each analyzed separately in terms of oscillations between two ν mass eigenstates. In reality, we know there are (at least) three flavour eigenstates, and so three mass eigenstates. Properly speaking we need to consider the 3×3 mixing matrix, which can be parameterized as:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{9}$$

Here $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.

The θ_{12} term in this parameterization controls solar ν oscillations, which involve the first and second mass eigenstates. Experimentally $\theta_{12} \approx 32°$ [10]. Similarly, θ_{23}, which determines the amplitude of atmospheric ν oscillations, is consistent with maximal mixing ($\theta_{23} \approx 45°$). It is unknown at present by how much θ_{23} actually deviates from maximal mixing angle, or whether this value is indicative of some kind of flavour symmetry between the second and third generations.

By comparison, the middle part of Eq. (9) is poorly constrained. Limits on oscillations of reactor neutrinos at short baselines (~ 1 km) tell us only that $\theta_{13} < 9°$ [13]. Presently nothing is known about the complex phase δ in the matrix, which if non-zero would result in different oscillation patterns for neutrinos than for antineutrinos.

Measurements of atmospheric and solar ν oscillations also partially determine the pattern of the ν masses. Solar and reactor ν data show that $\Delta m^2_{21} \equiv m^2_2 - m^2_1 \approx 8.0 \times 10^{-5}$ eV^2 [10], while atmospheric ν experiments [3] fix $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}$ eV^2. The solar ν experiments have successfully inferred the sign of Δm^2_{21} because the sign of the MSW effect in the Sun, which dominates in solar ν oscillations, depends on the sign of Δm^2. The atmospheric ν data however has no significant sensitivity at present to matter effects, and therefore it is not known whether $m_2 < m_3$ or rather $m_2 > m_3$. The result is that there are two possible mass hierarchies for the ν mass eigenstates. The so-called "normal" hierarchy has two light states and one heavier state, with $m_1 < m_2 < m_3$, while in the "inverted" hierarchy m_3 is the lightest state, with m_1 and m_2 being almost degenerate in mass.

In conclusion, non-accelerator ν experiments not only were the first to discover ν oscillations, but have also proven very successful in measuring the mixing parameters. Determination of the ν mass hierarchy, θ_{13}, and $\delta_{\rm CP}$, as well as precision checks of the predictions of the oscillation framework, remain outstanding problems in ν oscillation which future ν experiments (both accelerator and non-accelerator based) will strive to address.

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