Neutrino oscillations

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Neutrino oscillations are a quantum mechanical phenomenon predicted by Bruno Pontecorvo whereby a neutrino created with a specific lepton flavor (electron, muon or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies periodically as it propagates. Neutrino oscillation is of theoretical and experimental interest since observation of the phenomenon implies that the neutrino has a non-zero mass, which is not part of the original Standard Model of particle physics.

A zero mass particle would have to travel at the speed of light. At the speed of light, time stands still so no change (and, therefore, no oscillation) is possible. Therefore if particles change, they must have mass.

Contents

Observations

A great deal of evidence for neutrino oscillations has been collected from many sources, over a wide range of neutrino energies and with many different detector technologies.

Solar neutrino oscillation

The first experiment to detect the effects of neutrino oscillations was Ray Davis's Homestake Experiment in the late 1960s, in which he observed a deficit in the flux of solar neutrinos using a chlorine-based detector. This gave rise to the Solar neutrino problem. Many subsequent radiochemical and water Cherenkov detectors confirmed the deficit, but neutrino oscillations were not conclusively identified as the source of the deficit until the Sudbury Neutrino Observatory provided clear evidence of neutrino flavor change in 2001.

Solar neutrinos have energies below 20 MeV and travel an astronomical unit between the source in the Sun and detector on the Earth. At energies above 5 MeV, solar neutrino oscillation actually takes place in the Sun through a resonance known as the MSW effect, a different process from the vacuum oscillations described later in this article.

Atmospheric neutrino oscillation

Large detectors such as IMB, MACRO, and Kamiokande II observed a deficit in the ratio of the flux of muon to electron flavor atmospheric neutrinos (see *muon decay*). The Super Kamiokande experiment provided a very high precision measurement of neutrino oscillations in an energy range of hundreds of MeV to a few TeV, and with a baseline of the diameter of the Earth.

Reactor neutrino oscillations

Many experiments have searched for oscillations of electron anti-neutrinos produced at nuclear reactors. A high precision observation of reactor neutrino oscillation has been made by the KamLAND experiment since 2002. Neutrinos produced in nuclear reactors have energies similar to solar neutrinos, a few MeV. The baselines of these experiments have ranged from tens of meters to over 100 km.

Beam neutrino oscillations

Neutrino beams produced at a particle accelerator offer the greatest control over the neutrinos being studied. Many experiments have taken place which study the same neutrino oscillations which take place in atmospheric neutrino oscillation, using neutrinos with a few GeV of energy and several hundred km baselines. The MINOS experiment recently announced that it observes consistency with the results of the K2K and Super-K experiments.

The controversial observation of beam neutrino oscillation at the LSND experiment in 2006 was tested by MiniBooNE. Results from MiniBooNE appeared in Spring 2007, and appeared to contradict the findings of the LSND experiment.

On 31 May 2010, the INFN and CERN announced[1] having observed a tau particle in a muon neutrino beam in the OPERA detector located at Gran Sasso, 730 km away from the neutrino source in Geneva.

The upcoming T2K experiment will direct a neutrino beam through 295 km of earth, and will measure the parameter θ_{13}. The experiment is scheduled to begin in 2009 and uses the Super-K detector. NOνA is a similar effort. This detector will use the same beam as MINOS and will have a baseline of 810 km.

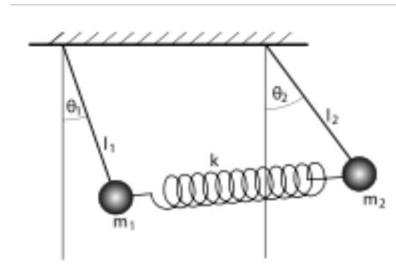
Decay oscillations - GSI anomaly

A study of the decay of radioactive hydrogen-like Praseodymium-140 and Promethium-142 at GSI nuclear physics laboratory in Darmstadt, Germany in 2008 revealed an oscillation superimposed on the otherwise exponential decay of the atomic nuclei. It has been suggested that this oscillation is related to neutrino oscillations[2][3]. However, the theoretical description of this effect in terms of neutrino oscillations has been a source of much debate and there is no clear consensus on whether it is viable or not[4]. Independent experiments are needed to assess if the effect is real and if the process can be used as a supplementary observation method of neutrino oscillations.

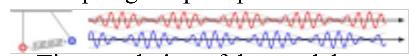
Theory

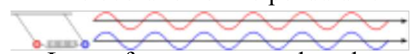
Classical analogue of neutrino oscillation

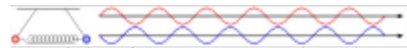
The basic physics behind neutrino oscillation can be found in any system of coupled harmonic oscillators. A simple example is a system of two pendulums connected by a weak spring (a spring with a small spring constant). The first pendulum is set in motion by the experimenter while the second begins at rest. Over time, the second pendulum begins to swing under the influence of the spring, while the first pendulum's amplitude decreases as it loses energy to the second. Eventually all of the system's energy is transferred to the second pendulum and the first is at rest. The process then reverses. The energy oscillates between the two pendulums repeatedly until it is lost to friction.



Spring-coupled pendulums


Time evolution of the pendulums


Lower frequency normal mode


Higher frequency normal mode

The behavior of this system can be understood by looking at its normal modes of oscillation. If the two pendulums are identical then one normal mode consists of both pendulums swinging in the same direction with a constant distance between them, while the other consists of the pendulums swinging in opposite (mirror image) directions. These normal modes have (slightly) different frequencies because the second involves the (weak) spring while the first does not. The initial state of the two-pendulum system is a combination of both normal modes. Over time, these normal modes drift out of phase, and this is seen as a transfer of motion from the first pendulum to the second.

When the pendulums are not identical the analysis is slightly more complicated. In the small-angle approximation, the potential energy of a single pendulum system is $\frac{1}{2}\frac{mg}{L}x^2$, where g is the standard gravity, L is the length of the pendulum, m is the mass of the pendulum bob, and x is the horizontal displacement of the pendulum bob. As an isolated system the pendulum is a harmonic oscillator with a frequency of $\sqrt{g/L}$. The potential energy of a spring is $\frac{1}{2}kx^2$ where k is the spring constant and x is the displacement. With a mass attached it oscillates with a period of $\sqrt{k/m}$. With two pendulums (labeled *a* and *b*) of equal mass but possibly unequal lengths and connected by a spring, the total potential energy is

$$V = \frac{m}{2}\left(\frac{g}{L_a}x_a^2 + \frac{g}{L_b}x_b^2 + \frac{k}{m}(x_b - x_a)^2\right).$$

This is a quadratic form in x_a and x_b, which can also be written as a matrix product:

$$V = \frac{m}{2}\begin{pmatrix}x_a & x_b\end{pmatrix}\begin{pmatrix}\frac{g}{L_a}+\frac{k}{m} & -\frac{k}{m} \\ -\frac{k}{m} & \frac{g}{L_b}+\frac{k}{m}\end{pmatrix}\begin{pmatrix}x_a \\ x_b\end{pmatrix}.$$

The 2×2 matrix is real symmetric and so (by the spectral theorem) it is "orthogonally diagonalizable". That is, there is an angle θ such that if we define

$$\begin{pmatrix}x_a \\ x_b\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}x_1 \\ x_2\end{pmatrix}$$

then

$$V = \frac{m}{2}\begin{pmatrix} x_1 & x_2 \end{pmatrix}\begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

where λ_1 and λ_2 are the eigenvalues of the matrix. The variables x_1 and x_2 describe normal modes which oscillate with frequencies of $\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$. When the two pendulums are identical ($L_a = L_b$), θ is 45°.

The description of the system in terms of the two pendulums (*a* and *b*) is analogous to the flavor basis of neutrinos. These are the parameters that are most easily produced and detected (in the case of neutrinos, by weak interactions involving the W boson). The description in terms of normal modes is analogous to the mass basis of neutrinos. These modes do not interact with each other when the system is free of outside influence. The angle θ is analogous to the Cabibbo angle (though that angle applies to quarks rather than neutrinos).

When the number of oscillators (particles) is increased to three, the orthogonal matrix can no longer be described by a single angle; instead, three are required (Euler angles). Furthermore, in the quantum case, the matrices may be complex. This requires the introduction of complex phases in addition to the rotation angles, which are associated with CP violation but do not influence the observable effects of neutrino oscillation.

Pontecorvo–Maki–Nakagawa–Sakata matrix

Main article: Pontecorvo–Maki–Nakagawa–Sakata matrix

The idea of neutrino oscillations was put forward in 1957 by Bruno Pontecorvo, in analogy with a similar phenomenon observed in the neutral kaon system. The quantitative theory described below was developed by him in 1967. One year later the solar neutrino deficit was first observed, that was followed by the famous paper of Gribov and Pontecorvo published in 1969 titled "Neutrino astronomy and lepton charge".

Solar and atmospheric neutrino experiments have shown that neutrino oscillations are due to a mismatch between the flavor and mass eigenstates of neutrinos. The relationship between these eigenstates is given by

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

where

- $|\nu_\alpha\rangle$ is a neutrino with definite flavor. α = e (electron), μ (muon) or τ (tauon).
- $|\nu_i\rangle$ is a neutrino with definite mass. i = 1, 2, 3.

- The asterisk (*) represents a complex conjugate. For antineutrinos, the complex conjugate should be dropped from the first equation, and added to the second.

$U_{\alpha i}$ represents the *Pontecorvo–Maki–Nakagawa–Sakata matrix* (also called the *PMNS matrix*, *lepton mixing matrix*, or sometimes simply the *MNS matrix*). It is the analogue of the CKM matrix describing the analogous mixing of quarks. If this matrix were the identity matrix, then the flavor eigenstates would be the same as the mass eigenstates. However, experiment shows that it is not.

When the standard three neutrino theory is considered, the matrix is 3×3. If only two neutrinos are considered, a 2×2 matrix is used. If one or more sterile neutrinos are added (see later) it is 4×4 or larger. In the 3×3 form, it is given by:[5]

$$\begin{aligned} U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. The phase factors α_1 and α_2 are physically meaningful only if neutrinos are Majorana particles — i.e. if the neutrino is identical to its antineutrino (whether or not they are is unknown) — and do not enter into oscillation phenomena regardless. If neutrinoless double beta decay occurs, these factors influence its rate. The phase factor δ is non-zero only if neutrino oscillation violates CP symmetry. This is expected, but not yet observed experimentally. If experiment shows this 3x3 matrix to be not unitary, a sterile neutrino or some other new physics is required.

Propagation and interference

Since $|\nu_i\rangle$ are mass eigenstates, their propagation can be described by plane wave solutions of the form

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})}|\nu_i(0)\rangle,$$

where

- quantities are expressed in natural units $(c = \hbar = 1)$
- E_i is the energy of the mass-eigenstate i,
- t is the time from the start of the propagation,
- $\vec{p_i}$ is the 3-dimensional momentum,
- $\vec{x}$ is the current position of the particle relative to its starting position

In the ultrarelativistic limit, $|\vec{p}_i| = p_i \gg m_i$, we can approximate the energy as

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E},$$

This limit applies to all practical (currently observed) neutrinos, since their masses are less than 1eV and their energies are at least 1MeV, so the Lorentz factor γ is greater than 10^6 in all cases. Using also $t \approx L$, where L is the distance traveled and also dropping the phase factors, the wavefunction becomes:

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E} |\nu_i(0)\rangle,$$

Eigenstates with different masses propagate at different speeds. The heavier ones lag behind while the lighter ones pull ahead. Since the mass eigenstates are combinations of flavor eigenstates, this difference in speed causes interference between the corresponding flavor components of each mass eigenstate. Constructive interference causes it to be possible to observe a neutrino created with a given flavor to change its flavor during its propagation. The probability that a neutrino originally of flavor α will later be observed as having flavor β is

$$P_{\alpha\to\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E} \right|^2 .$$

This is more conveniently written as

$$\begin{aligned} P_{\alpha\to\beta} = \delta_{\alpha\beta} \quad &- \quad 4 \sum_{i>j} Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\tfrac{\Delta m_{ij}^2 L}{4E}) \\ &+ \quad 2 \sum_{i>j} Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\tfrac{\Delta m_{ij}^2 L}{2E}), \end{aligned}$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$. The phase that is responsible for oscillation is often written as (with c and $\hbar$ restored)[6]

$$\frac{\Delta m^2\, c^3\, L}{4\hbar E} = \frac{\mathrm{GeV\,fm}}{4\hbar c} \times \frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E} \approx 1.267 \times \frac{\Delta m^2}{\mathrm{eV}^2}\frac{L}{\mathrm{km}}\frac{\mathrm{GeV}}{E},$$

where 1.267 is unitless. In this form, it is convenient to plug in the oscillation parameters since:

- The mass differences, Δm^2, are known to be on the order of $1\mathrm{eV}^2$
- Oscillation distances, L, in modern experiments are on the order of kilometers
- Neutrino energies, E, in modern experiments are typically on order of MeV or GeV.

If there is no CP-violation (δ is zero), then the second sum is zero.

Two neutrino case

The above formula is correct for any number of neutrino generations. Writing it explicitly in terms of mixing angles is extremely cumbersome if there are more than two neutrinos that participate in mixing. Fortunately, there are several cases in which only two neutrinos participate significantly. In this case, it is sufficient to consider the mixing matrix

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Then the probability of a neutrino changing its flavor is

$$P_{\alpha\rightarrow\beta, \alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)\ \mathrm{(natural units)}$$

Or, using SI units and the convention introduced above

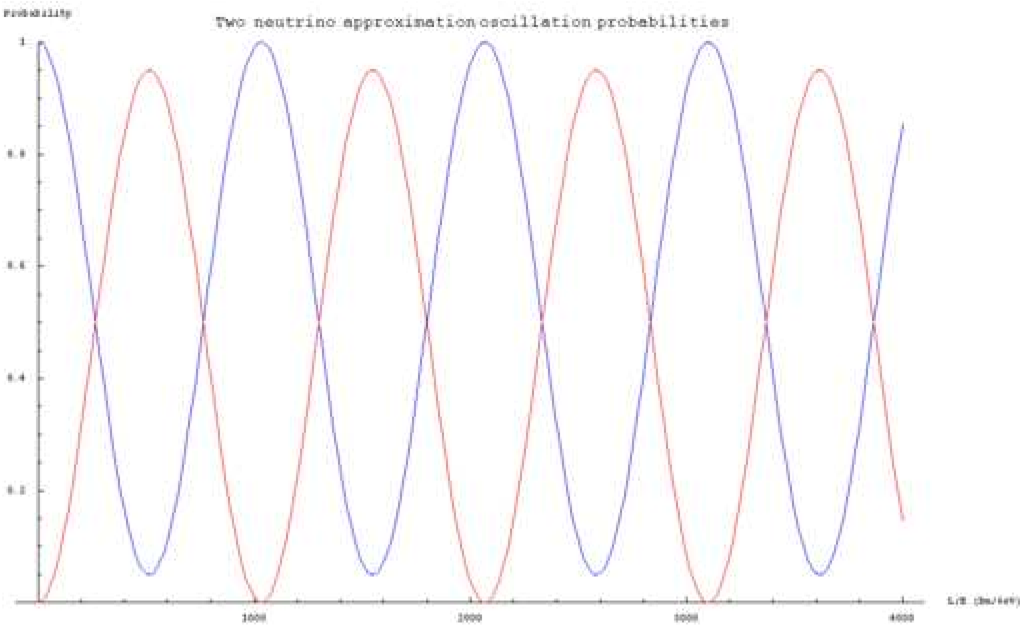
$$P_{\alpha\rightarrow\beta, \alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{\mathrm{GeV}}{\mathrm{eV}^2\,\mathrm{km}}\right)$$

This formula is often appropriate for discussing the transition $\nu_\mu \leftrightarrow \nu_\tau$ in atmospheric mixing, since the electron neutrino plays almost no role in this case. It is also appropriate for the solar case of $\nu_e \leftrightarrow \nu_x$, where ν_x is a superposition of ν_μ and ν_τ. These approximations are possible because the mixing angle θ_{13} is very small and because two of the mass states are very close in mass compared to the third.

Theory, graphically

Two neutrino probabilities in vacuum

In the approximation where only two neutrinos participate in the oscillation, the probability of oscillation follows a simple pattern:



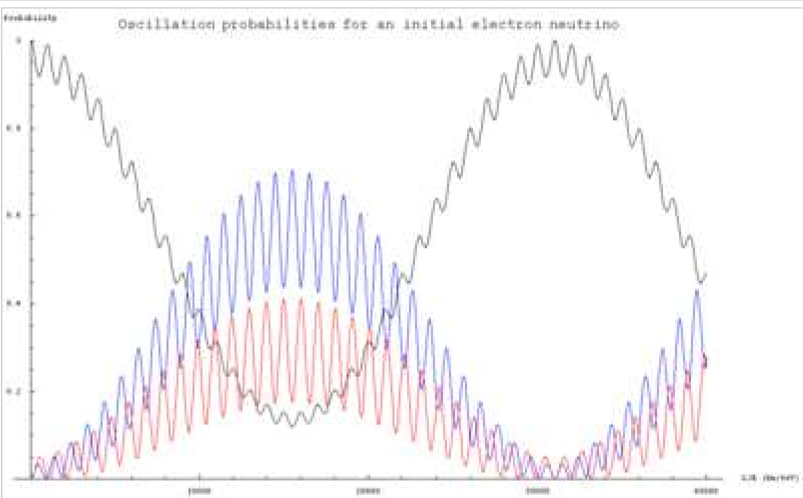
The blue curve shows the probability of the original neutrino retaining its identity. The red curve shows the probability of conversion to the other neutrino. The maximum probability of conversion is equal to $\sin^2 2\theta$. The frequency of the oscillation is controlled by Δm^2.

Three neutrino probabilities

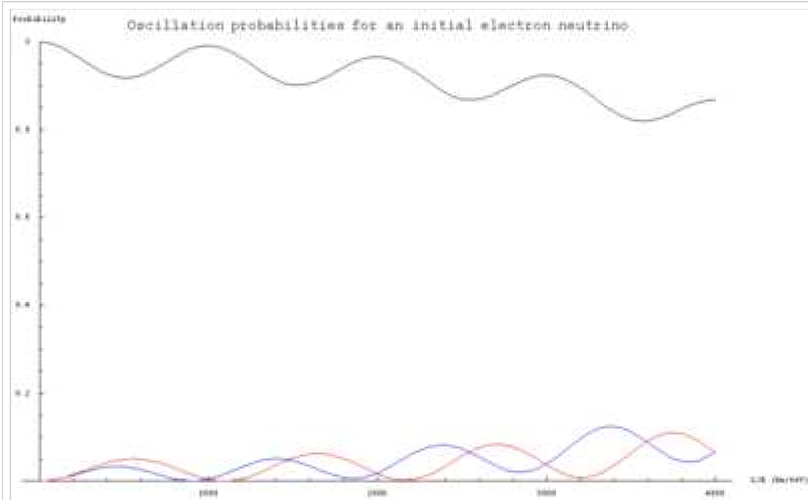
If three neutrinos are considered, the probability for each neutrino to appear is somewhat complex. Here are shown the probabilities for each initial flavor, with one plot showing a long range to display the slow "solar" oscillation and the other zoomed in to display the fast "atmospheric" oscillation. The oscillation parameters used here are consistent with current measurements, but since some parameters are still quite uncertain, these graphs are only qualitatively correct in some aspects. These values were used:

- $\sin^2 2\theta_{13} = 0.08$. (If it turns out to be much smaller or zero, the small wiggles shown here will be much smaller or non-existent, respectively.)
- $\sin^2 2\theta_{23} = 0.95$. (It may turn out to be exactly one.)
- $\sin^2 2\theta_{12} = 0.86$.

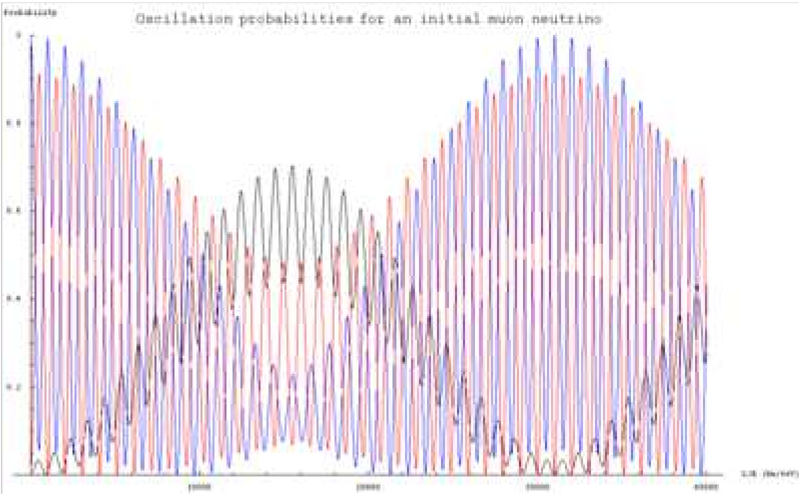
- $\delta = 0$. (If it is actually large, these probabilities will be somewhat distorted and different for neutrinos and antineutrinos.)
- $\Delta m^2_{12} = 8 \times 10^{-5} \mathrm{eV}^2$.
- $\Delta m^2_{23} \approx \Delta m^2_{13} = 2.4 \times 10^{-3} \mathrm{eV}^2$.



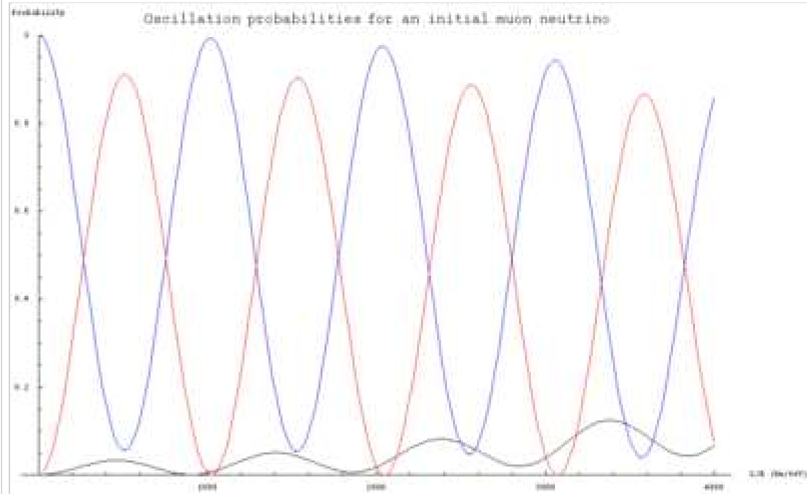
Electron neutrino oscillations, long range. Here and in the following diagrams black means electron neutrino, blue means muon neutrino and red means tau neutrino.



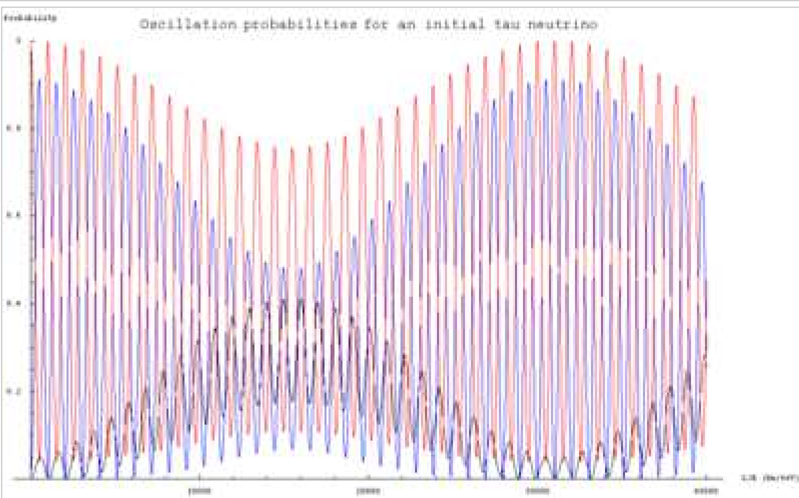
Electron neutrino oscillations, short range



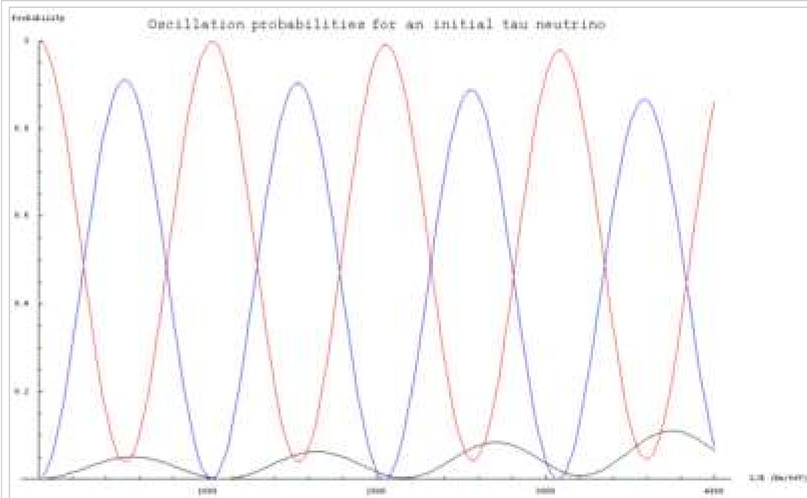
Muon neutrino oscillations, long range



Muon neutrino oscillations, short range



Tau neutrino oscillations, long range



Tau neutrino oscillations, short range

Observed values of oscillation parameters

- $\sin^2(\theta_{13}) < 0.032$ at 95% confidence level ($\theta_{13} < 10.3°$) [5]

- $\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07}$. This corresponds to $\theta_{12} \equiv \theta_{\rm sol} = 33.9^{\circ}{}^{+2.4^\circ}_{-2.2^\circ}$ ("sol" stands for solar) [7]
- $\sin^2(2\theta_{23}) = 1^{+0}_{-0.1}$, corresponding to $\theta_{23} \equiv \theta_{\rm atm} = 45 \pm 7^\circ$ ("atm" for atmospheric)[8]
- $\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5} {\rm eV}^2$ [7]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3} {\rm eV}^2$[8]
- δ, α_1, α_2, and the sign of Δm^2_{32} are currently unknown

Solar neutrino experiments combined with KamLAND have measured the so-called solar parameters $\Delta m^2_{\rm sol}$ and $\sin^2\theta_{\rm sol}$. Atmospheric neutrino experiments such as Super-Kamiokande together with the K2K first long baseline accelerator neutrino experiment have determined the so-called atmospheric parameters $\Delta m^2_{\rm atm}$ and $\sin^2 2\theta_{\rm atm}$. An additional experiment, MINOS, is expected to reduce the experimental errors significantly thereby increasing precision.[9]

For atmospheric neutrinos (where the relevant difference of masses is about $\Delta m^2 = 2.5 \times 10^{-3}~{\rm eV}^2$ and the typical energies are ~1 GeV), oscillations become visible for neutrinos travelling several hundred km, which means neutrinos that reach the detector from below the horizon.

From atmospheric and solar neutrino oscillation experiments, it is known that two mixing angles of the MNS matrix are large and the third is smaller. This is in sharp contrast to the CKM matrix in which all three angles are small and hierarchically decreasing. Nothing is known about the CP-violating phase of the MNS matrix.

If the neutrino mass proves to be of Majorana type (making the neutrino its own antiparticle), it is possible that the MNS matrix has more than one phase.

Since experiments observing the neutrino oscillations measure the squared mass difference and not absolute mass, one can claim that the lightest neutrino mass is exactly zero, without contradicting observations. This is however regarded as unlikely by theorists.

Origins of neutrino mass

The question of how neutrino masses arise has not been answered conclusively. In the Standard Model of particle physics, fermions only have mass because of interactions with the Higgs field (see *Higgs boson*). These interactions involve both left- and right-handed versions of the fermion (see *chirality*). However, only left-handed neutrinos have been observed so far.

Neutrinos may have another source of mass through the Majorana mass term. This type of mass applies for electrically-neutral particles since otherwise it would allow particles to turn into anti-particles, which would violate conservation of electric charge.

The smallest modification to the Standard Model, which only has left-handed neutrinos, is to allow these left-handed neutrinos to have Majorana masses. The problem with this is that the neutrino masses are implausibly smaller than the rest of the known particles (at least 500,000 times smaller than the mass of an electron), which, while it does not invalidate the theory, is not very satisfactory.

The next simplest addition would be to add right-handed neutrinos into the Standard Model, which interact with the left-handed neutrinos and the Higgs field in an analogous way to the rest of the fermions. These new neutrinos would interact with the other fermions solely in this way, so are not phenomenologically excluded. The problem of the disparity of the mass scales remains.

Seesaw mechanism

Main article: Seesaw mechanism

The most popular conjectured solution currently is the *seesaw mechanism*, where right-handed neutrinos with very large Majorana masses are added. If the right-handed neutrinos are very heavy, they induce a very small mass for the left-handed neutrinos, which is proportional to the inverse of the heavy mass.

If it is assumed that the neutrinos interact with the Higgs field with approximately the same strengths as the charged fermions do, the heavy mass should be close to the GUT scale. Note that, in the Standard Model there is just one fundamental mass scale (which can be taken as the scale of $SU(2)_L \times U(1)_Y$ breaking) and all masses (such as the electron or the mass of the Z boson) have to originate from this one.

There are other varieties of seesaw and currently it is not clear which, if any, nature has chosen.[10]

The apparently innocent addition of right-handed neutrinos has the effect of adding new mass scales, completely unrelated to the mass scale of the Standard Model. Thus, heavy right-handed neutrinos look to be the first real glimpse of physics beyond the Standard Model. It is interesting to note that right-handed neutrinos can help to explain the origin of matter through a mechanism known as leptogenesis.

Other sources

There are alternative ways to modify the standard model that are similar to the addition of heavy right-handed neutrinos (e.g., the addition of new scalars or fermions in triplet states) and other modifications that are less similar (e.g., neutrino masses from loop effects and/or from suppressed couplings). One example of the last type of models is provided by certain versions supersymmetric extensions of the standard model of fundamental interactions, where R parity is not a symmetry. There, the exchange of supersymmetric particles such as squarks and sleptons can break the lepton number and lead to neutrino masses. These interactions are normally excluded from theories as they come from a class of interactions that lead to unacceptably rapid proton decay if they are all included. These models have little predictive power and are not able to provide a cold dark matter candidate but they are considered interesting since they would be compatible with new observable signals in particle colliders.

See also

- MSW effect
- Majoron
- Neutral kaon mixing

Notes

1. ^ http://press.web.cern.ch/press/PressReleases/Releases2010/PR08.10E.html
2. ^ A new way to measure neutrinos (http://www.symmetrymagazine.org/breaking/2008/06/13/a-new-way-to-measure-neutrinos/)
3. ^ Nuclear physics: A neutrino's wobble? (http://www.nature.com/nature/journal/v453/n7197/full/453864a.html)
4. ^ See Hendrik Kienert et al., *The GSI anomaly*, arXiv:0808.2389 (http://arxiv.org/abs/0808.2389) and references therein.
5. ^ ***a b*** S. Eidelman et al. (2004). "Particle Data Group - The Review of Particle Physics" (http://pdg.lbl.gov) . *Physics Letters B* **592** (1). http://pdg.lbl.gov. Chapter 15: *Neutrino mass, mixing, and flavor change (http://pdg.lbl.gov/2005/reviews/numixrpp.pdf)* . Revised September 2005.
6. ^ "A Simple Parameterization of Matter Effects on Neutrino Oscillations", M. Honda, Y. Kao, N. Okamura and T. Takeuchi, 2006. (http://arxiv.org/pdf/hep-ph/0602115)
7. ^ ***a b*** Limit from the Solar and KamLAND Experiments, Phys. Rev. C 72, 055502 (2005)
8. ^ ***a b*** Evidence for an oscillatory signature in atmospheric neutrino oscillation. Apr 2004. Published in Phys. Rev. Lett. 93, 101801 (http://arxiv.org/pdf/hep-ex/0404034)
9. ^ Double Chooz Letter of Intent (http://doublechooz.in2p3.fr/0405032.pdf)
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External links

- Maury Goodman, "The Neutrino Oscillation Industry (http://neutrinooscillation.org/) " (2006). *(Provides links to many other neutrino oscillation websites.)*
- Review Articles on arxiv.org (http://xstructure.inr.ac.ru/x-bin/revtheme3.py?level=3&index1=-155642&skip=0)

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