Neutrino Oscillations

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Outline

- History of Neutrino Detection
- Theory of Neutrino Oscillations
- Future Detectors
- Future of Theory

1930: β Decay

A radioactive nucleus, **A** is transformed into a slightly lighter nucleus **B**, with the emission of an electron:

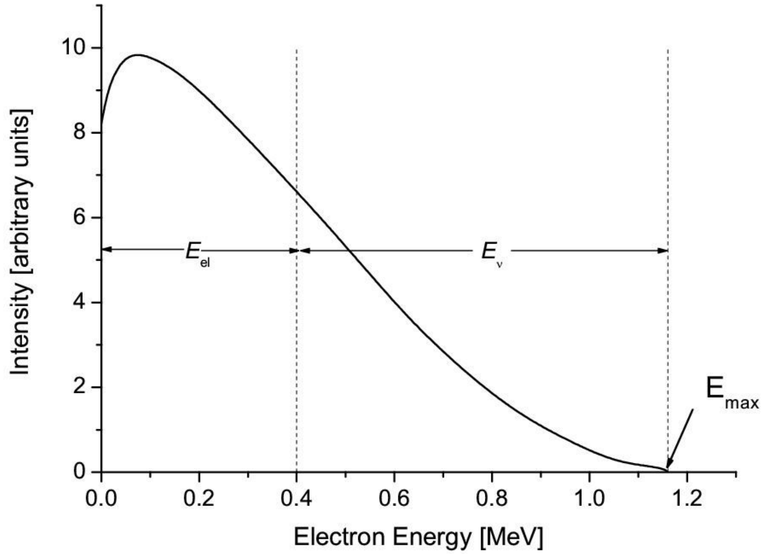
$$A \rightarrow B + e^{-}$$

The energy of the electron was not unique even though the nucleus is transitioning between two discreet energy levels

Pauli theorized the neutrino and Fermi later published his paper on beta decay.

$$\mathrm{n} \rightarrow p^{+} + e^{-} + \overline{\nu}$$

Note, the neutron had not been discovered yet.



A beta spectrum, showing a typical division of energy between electron and neutrino, Hpaul, https://en.wikipedia.org/wiki/Beta_decay

Basics of Neutrinos

6 Neutrinos:

- 3 flavors, e, μ, τ
- Neutrinos are left-handed, have no charge, and only participate in weak interactions
- 3 Antiparticles with opposite lepton number and chirality

How the different flavors were determined:

$$e^- + e^+ \rightarrow \tau^+ + \tau^-$$

$$\rightarrow \mu^- + \overline{\nu_\mu} + \nu_\tau$$

$$\rightarrow e^+ + \nu_e + \overline{\nu_\tau}$$

Scale of Neutrino

$$\sigma_\nu \approx G_f^2 E_\nu \approx 10^{-42} cm^2$$

$$l_\nu \approx \frac{2 \times 10^{20} cm}{\rho}$$

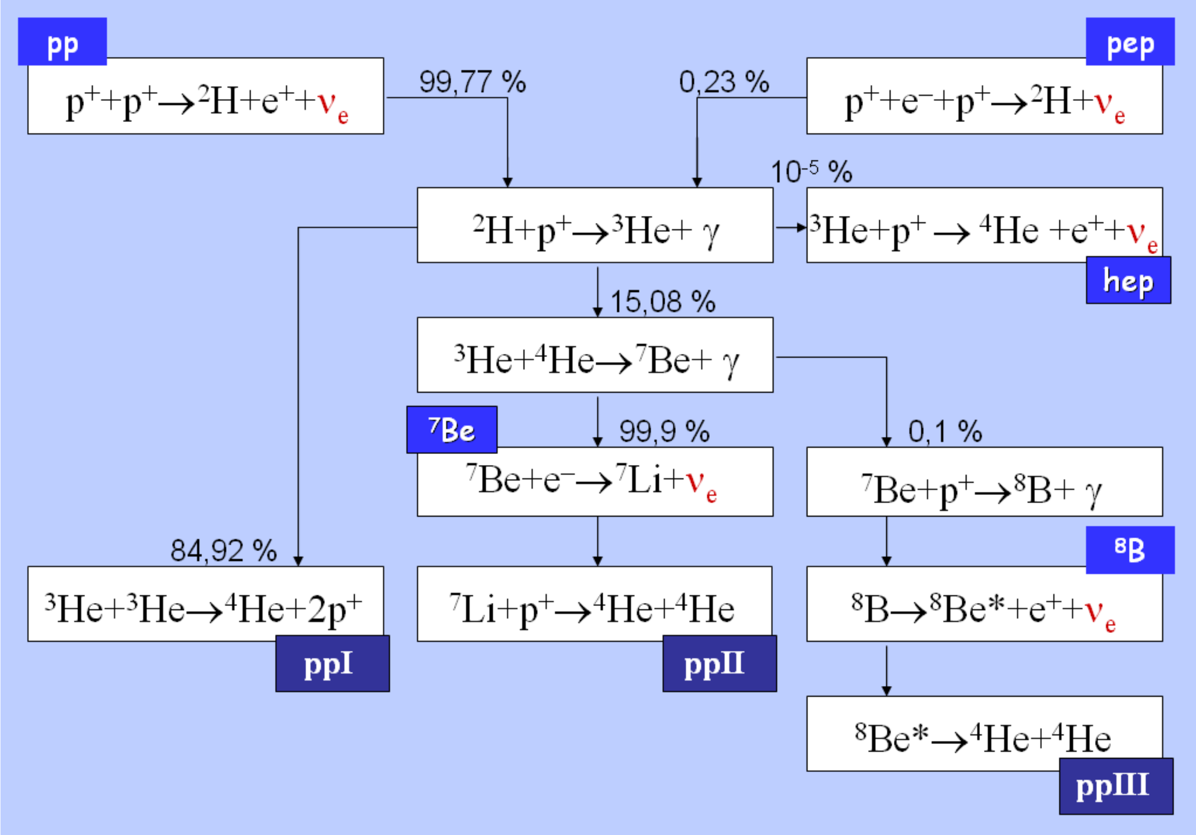
Light travels 10^{18}cm/yr

The weak interaction is on the scale of 10^{-17} to 10^{-16} m

Solar Model

We are only concerned with p+p chain reaction.

$$f_{\nu_e} = 6.7\times10^{10}s^{-1}cm^{-2}$$



Proton–proton and electron-capture chain reactions in a star
https://en.wikipedia.org/wiki/Proton–proton_chain_reaction

Raymond Davis and John Bahcall

The Homestake Solar Neutrino Observatory
Gold Mine in South Dakota
The deepest operating mine in the continental US.
The observatory chamber is located 1478 m from the surface
100,000-gallon tank of perchloroethylene
Pumped in He gas
Threshold is .814Mev

$$\nu + {}^{37}Cl \rightarrow e^{-} + {}^{37}Ar$$

Solar Flux and Detectors

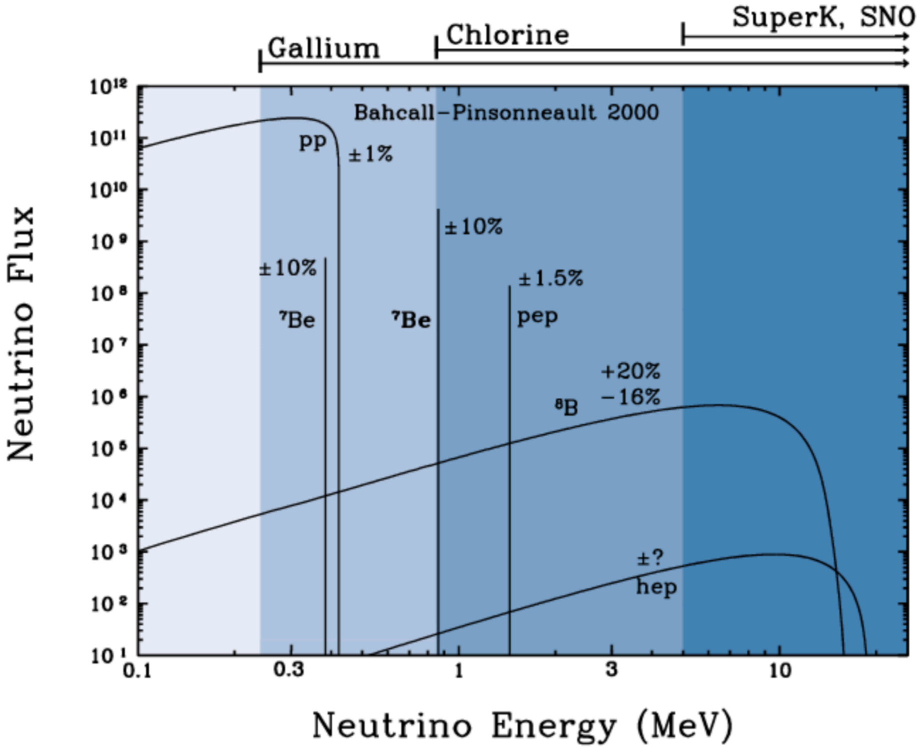


Figure 1. The solar neutrino spectra predicted by the SSM. The neutrino fluxes at one astronomical unit from continuum sources are given in units of $\mathrm{cm^{-2}\,s^{-1}\,MeV^{-1}}$, and the line fluxes are given in $\mathrm{cm^{-2}\,s^{-1}}$. Courtesy of J.N. Bahcall from http://www.sns.ias.edu/∼jnb/.

Results of Davis's Experiment 1968

$1SNU = 10^{-36}$ per target atom s^{-1}

Measured: 2.56 ± 0.16(statistical)± 0.16(systematic) SNU

Predicted:$\approx 6.36 - 9.3SNU$

Why?

- Theoretical Calculations (Solar model)? - NO!
- The Experiment could have a flaw? ------ NO!
- New Physics?

Super-Kamiokande Experiment

It consists of a cylindrical stainless-steel tank about 40 m (131 ft) in height and diameter

50,000 tons of ultrapure water

13,000 photomultiplier tubes

Neutrino interaction with the electrons of nuclei of water

Produces an electron or positron that moves faster than the speed of light in water

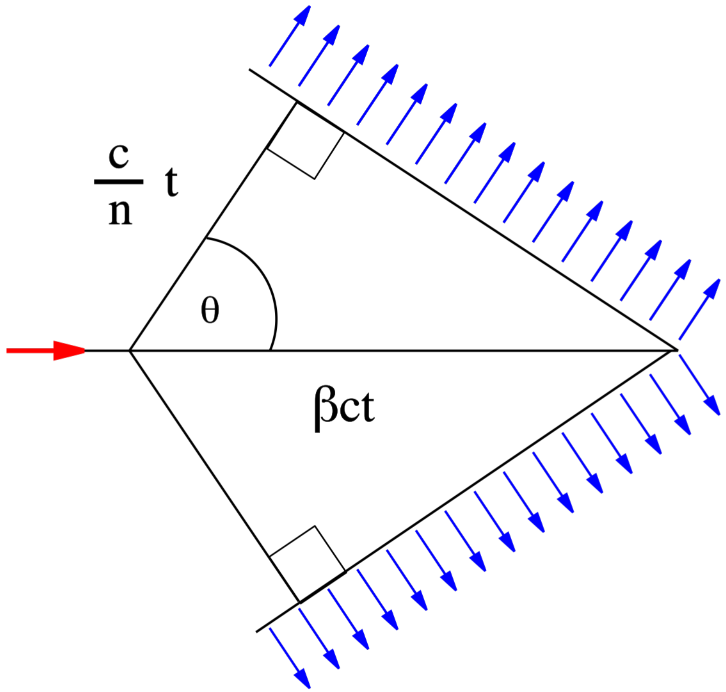
The Cherenkov light is recorded by the photomultiplier tube.

Kamiokande added new data in the form of timing and direction

Can Detect all three flavors of Neutrinos (Primarily Atmospheric)

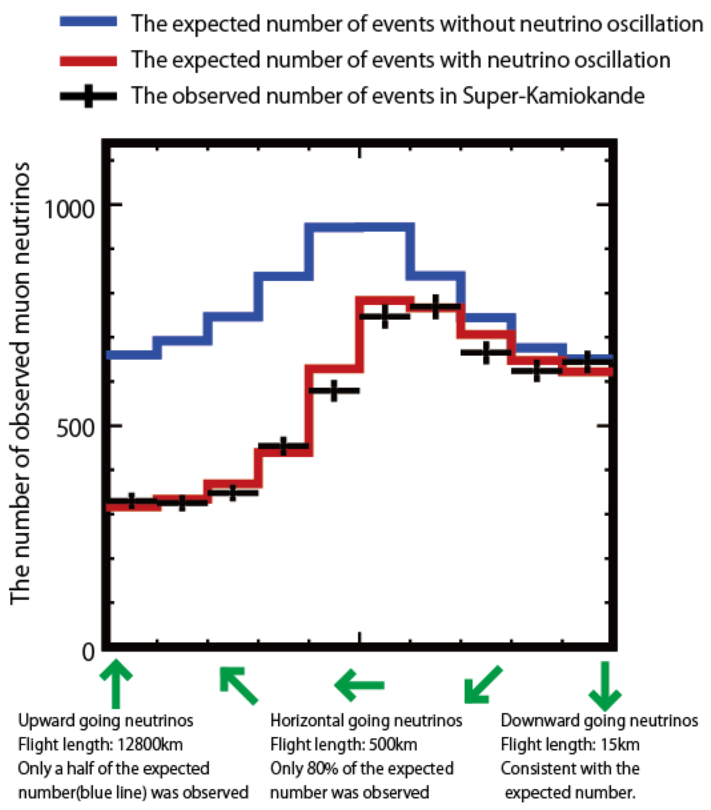
Cherenkov Radiation

$c/n < v_p < c$
$\beta = v_p/c$
$v_p t = \beta c t$
$v_{emitted} t = c/n$
The particle travels: $x_p = v_p t = \beta c t$
The emitted wave travels: $x_{emitted} = v_{emitted} t = \frac{c}{n} t$
The emission angle results in $cos\ \theta = \frac{1}{n\beta}$

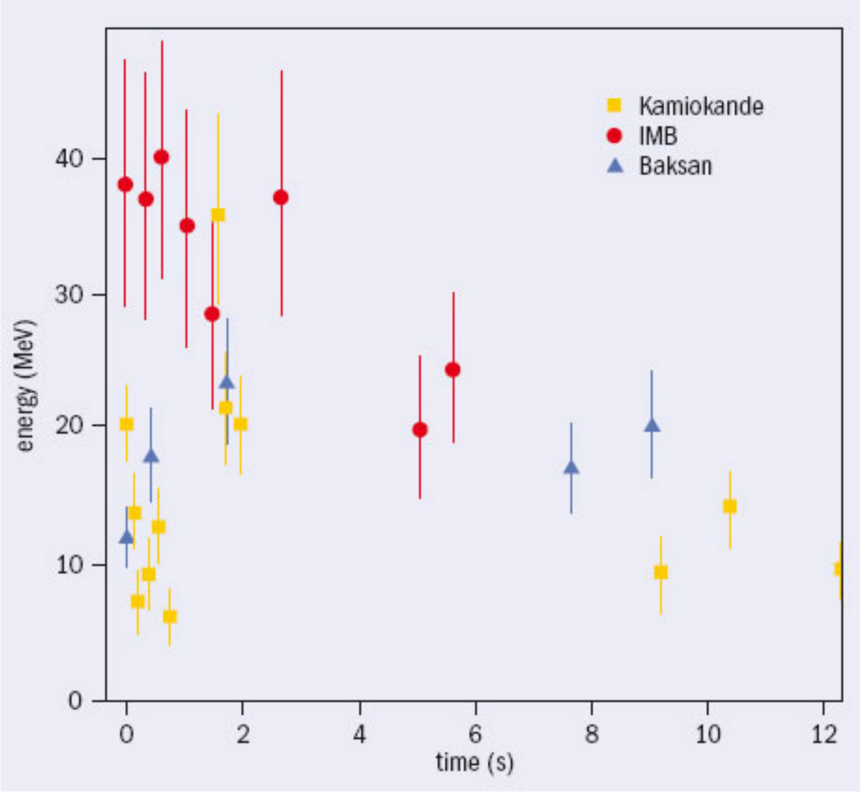


https://en.wikipedia.org/wiki/Cherenkov_radiation

Important Results



The observed number of the muon neutrinos
http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/neutrino-e.html



Neutrinos From SuperNova 168,000 ly away
https://cerncourier.com/a/sn1987a-heralds-the-start-of-neutrino-astronomy/

Acclaim

- The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos. Koshiba's work was showing the results from SN 1987A.

- The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita (SK) and Arthur B. McDonald (Sudbury Neutrino Observatory (SNO) in Canada) for the discovery of neutrino oscillations, which shows that neutrinos have mass.

Neutrino Oscillations

Nature Creates Neutrinos in a specific lepton flavor:
electron, muon, tau

The flavor states are not states of a definite mass

The flavor states are linear combinations of the more basic mass eigenstates

Linear Combinations

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$|\nu_\alpha\rangle$ is a neutrino with definite flavor $\alpha =$ e (electron), μ (muon), τ (tau)
$|\nu_i\rangle$ is a neutrino with definite mass $i = 1, 2, 3$
U is a unitary matrix:

At a later time:

$$|\nu(t)\rangle = \sum_i U_{\alpha i} e^{-iE_i t} e^{i\vec{p}\cdot\vec{x}}|\nu_i\rangle$$

Intensity

Now, we assume ν interacts weakly at time t and the state is the lepton flavor eigenstate $|\nu_\beta\rangle$. Looking at the intensity of the process:

$$I_{\beta\alpha} = |\langle \nu_\beta | \nu(t) \rangle|^2 = \left| \sum_i U_{\alpha i} U^*_{\beta i} e^{-iE_i t} \right|^2$$

In the ultra-relativistic limit:

$$E_i = p + \frac{m_i^2}{2p}$$

So that

$$I_{\beta\alpha} = \left| \sum_i U_{\alpha i} U^*_{\beta i} e^{-iE_i \frac{m_i^2 t}{2p}} \right|^2$$

Simplified Oscillations

Now, we'll look at a simplifying case of two types of Neutrinos. Now,

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

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The orthonormal wavefunctions:

$$\nu_\mu = \nu_1 \cos\theta + \nu_2 \sin\theta \text{ and } \nu_e = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

Simplified Oscillations

The neutrinos are created in the states ν_μ and ν_e. The propagation through space-time is determined by the characteristic frequencies of the mass eigenstates:

$$\nu_1(t) = \nu_1(0)e^{-iE_1 t}$$
$$\nu_2(t) = \nu_2(0)e^{-iE_2 t}$$

So now we set $t = 0$ and muon flavor, $\nu_\mu(0) = 1$ and $\nu_e(0) = 0$

$$\nu_1(0) = \nu_\mu(0)e^{-iE_1 t}$$

$$\nu_2(0) = \nu_\mu(0)e^{-iE_2 t}$$

and

$$\nu_\mu(t) = \cos\theta\nu_1(t) + \sin\theta\nu_2(t)$$

Intensity

Now we look at

$$\frac{\nu_\mu(t)}{\nu_\mu(0)} = \cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}$$

The Intensity:

$$\frac{I_\mu(t)}{I_\mu(0)} = \left|\frac{\nu_\mu(t)}{\nu_\mu(0)}\right|^2 = 1 - \sin^2 2\theta \sin^2\left[\frac{(E_2 - E_1)t}{2}\right]$$

Probabilities

We write $\Delta m^2 = m_2^2 - m_1^2$ and look at the probability of finding ν_μ or ν_e

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

$$P(\nu_\mu \to \nu_e) = 1 - P(\nu_\mu \to \nu_\mu)$$

Δm^2 is in units of $(eV/c^2)^2$, L is in units of meters and E, the energy of the beam is in MeV. This show the intensities oscillate as a function of distance. If $E \simeq 1$ MeV, and $\Delta m \simeq 1$ eV$/c^2$, L will be about a few meters. Data shows:

$$\left| \Delta m_{12}^2 \right| \simeq 6.9 \times 10^{-5} \mathrm{eV}^2$$

$$\left| \Delta m_{23}^2 \right| \simeq 2.5 \times 10^{-3} \mathrm{eV}^2 \qquad \text{and} \qquad \theta \simeq 45^\circ$$

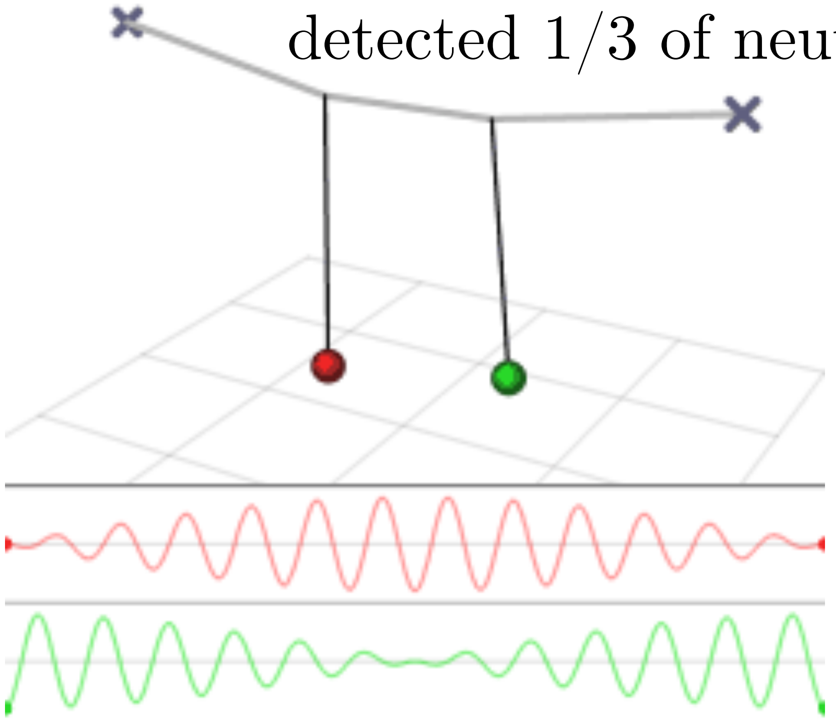
The Full Matrix From Data

From the data we approximate the matrix U:

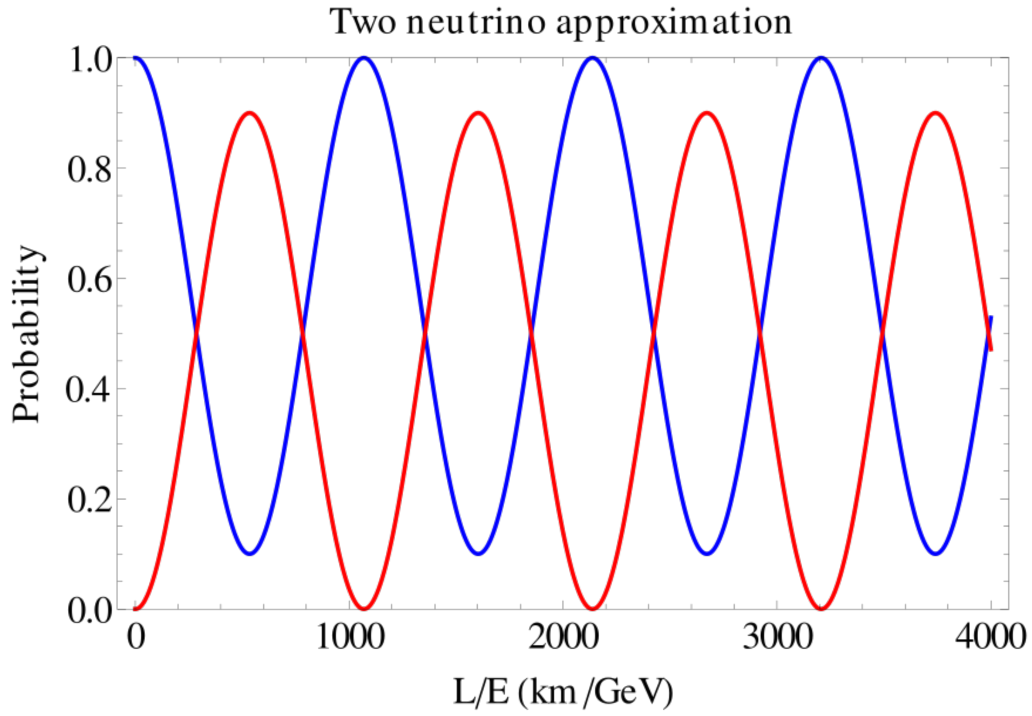
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & \theta_{13}e^{i\delta} \\ -\sin\theta_{12}\cos\theta_{23} & \cos\theta_{12}\cos\theta_{23} & \sin\theta_{23} \\ \sin\theta_{12}\sin\theta_{23} & -\cos\theta_{12}\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Here θ_{12} is $\approx 35°$, θ_{23} is $\approx 45°$,θ_{13} is $\leq 10°$. δ is the CP violating phase

The Flavor state is a linear combination of propagating mass states. If the masses are different, they will propagate with different velocities. The flavor state oscillates. This is why Davis only detected 1/3 of neutrinos.

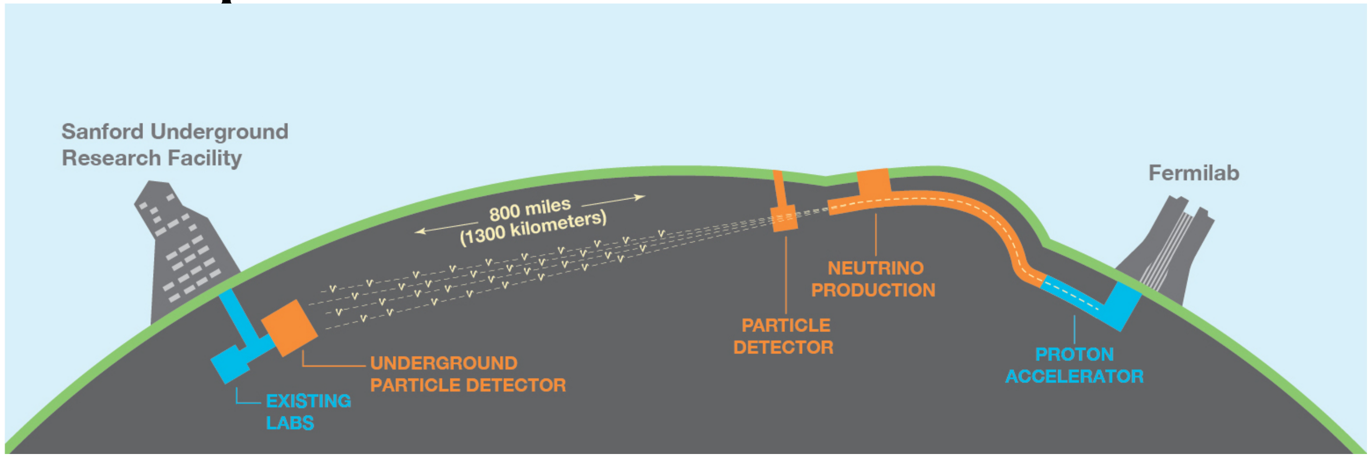


https://upload.wikimedia.org/wikipedia/commons/4/43/Coupled_oscillators.gif



https://en.wikipedia.org/wiki/File:Oscillations_two_neutrino.svg

Future Experiments



https://www.dunescience.org

The neutrino is the most abundant mass particle in the universe.

Two neutrino detectors
The world's most intense neutrino beam.
One detector will record particle interactions
near the source of the beam
at Fermi National Accelerator
Laboratory in Batavia, Illinois
A second, much larger, detector will be
more than a kilometer underground at the Sanford Underground Research Laboratory in Lead, South Dakota
1,300 kilometers downstream of the source.

Future Research

What are the masses of a single neutrino?
Are Neutrinos their own antiparticle?
Are there more than three neutrinos?
What new Physics can we find?

References

Cleveland, Bruce T. et al. Measurement of the Solar Electron Neutrino Flux with the Homestake Chlorine Detector". In: The Astrophysical Journal 496.1 (1998), pp. 505{526. doi: 10.1086/305343. url: https://doi.org/10.1086%2F305343.

Fantini, Guido et al. The Formalism of Neutrino Oscillations: An Introduction. 2018. arXiv: 1802.05781 [hep-ph].

Griffiths, David. Introduction to Elementary Particles. WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim, 2004.

Moaz, Dan. Astrophysics in a Nutshell (aka Basic Astrophysics). Princeton University Press, 2007.

Perkins, Donald H. Introduction to High Energy Physics. Addison Wesley,1987.

Seiden, Abraham. Particle Physics: A Comprehensive Introduction. Addison Wesley, 2005.

Walter, Christopher W. \The Super-Kamiokande Experiment". In: Neutrino Oscillations (2008), 19-43. doi: 10.1142/9789812771971_0002. url:http://dx.doi.org/10.1142/9789812771971_0002.