RECENT PROGRESS IN NEUTRINO PHYSICS

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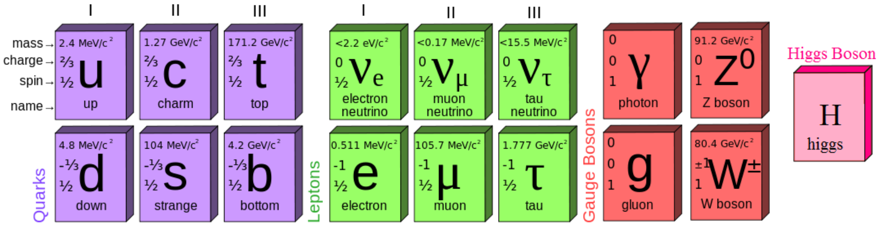
Standard Model



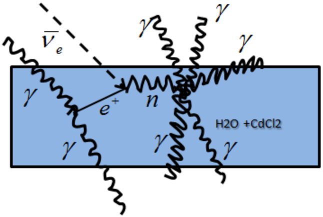
- Massless $m_\nu = 0$
- Neutrinos are left-handed (the antineutrinos are right-handed)
- Chargeless
- Electroweak and gravitational interactions

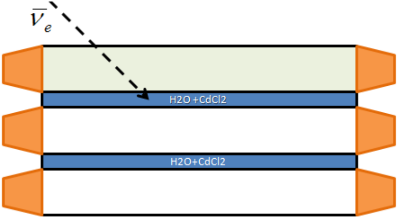
Neutrino History

- Pauli 1930 $C_6^{14} \rightarrow N_7^{14} + e+?$
- Discovery of electron neutrino 1956

β decay: $n \rightarrow p + e^- + \bar{\nu_e}$

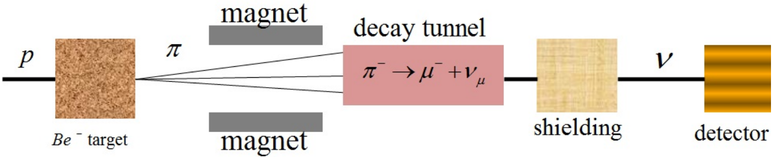
Inverse β decay: $\bar{\nu_e} + p \rightarrow n + e^+$





Neutrino History

- Discovery of muon neutrino 1962



- Discovery of tau neutrino 2000

$$D_s \to \tau \nu_\tau$$

$$\tau \to e\nu\nu, \qquad \tau \to \nu_\tau + hadrons$$

Neutrino Sources

Weak interactions (like β decay) :

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- Natural sources
- Artificial sources

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  1. Solar neutrinos
  2. Relic neutrinos
  3. Supernova neutrinos
  4. Atmospheric neutrinos
  5. Cosmogenic neutrinos
  6. Geo neutrinos
- Artificial sources

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- Artificial sources
  1. Accelerator neutrinos
  2. Reactor neutrinos
  3. Future techniqes
     1. Beta beams
     2. Neutrino factories

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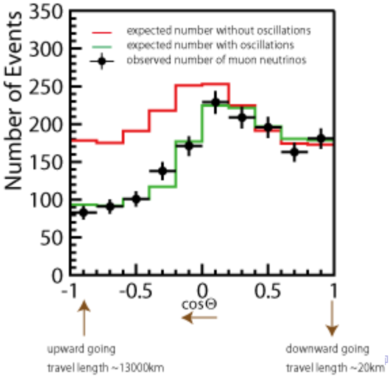
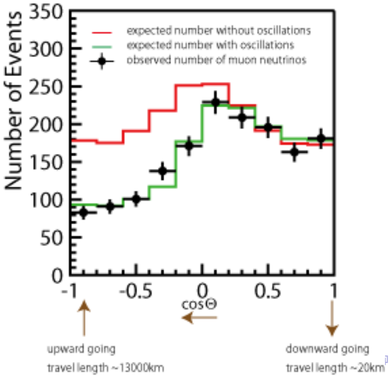


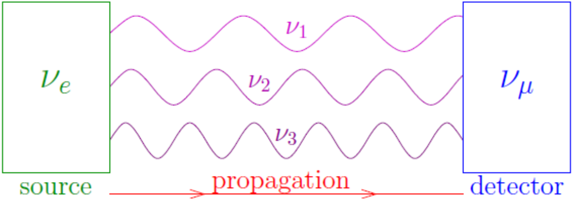
Solar and Atmospheric Neutrino Problems

- Solar neutrino problem
  1. Flux of ν_e arriving on the Earth is about 1/3 of that produced in core of the Sun
  2. The SNO experiment 2002: flux of ν_e , ν_μ and ν_τ arriving on Earth is the same as the flux of ν_e produced in the core of the Sun
- The atmospheric neutrino anomaly, $\frac{F(\nu_\mu)}{F(\nu_e)} \approx 1, \quad 2:1$



Neutrino Oscillations

- Neutrino oscillations ⇔ neutrinos are massive and mixed
- Flavor neutrinos: ν_e, ν_μ, ν_τ
- Massive neutrinos: ν_1, ν_2, ν_3



$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\nu(t>0)\rangle = U_{e1}e^{-iE_1 t}|\nu_1\rangle + U_{e2}e^{-iE_2 t}|\nu_2\rangle + U_{e3}e^{-iE_3 t}|\nu_3\rangle \neq |\nu_e\rangle$$

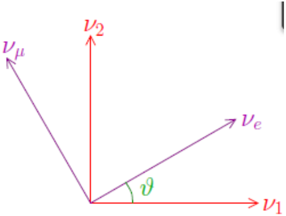
Where the $U_{\alpha\alpha}$'s are matrix elements of the mixing matrix U.

Two Neutrino Oscillation and Mixing

Transition probability:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$



$$|\nu_e\rangle = \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle$$

- Things we can measure:

  ν_e or ν_μ, E, L

- Parameters of nature:

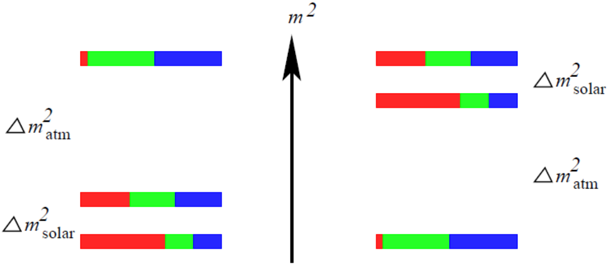
  1. Δm^2 (between the two ν flavors)

  2. $\sin^2 2\theta$ (mixing angle)

Mass spectrum of Neutrinos

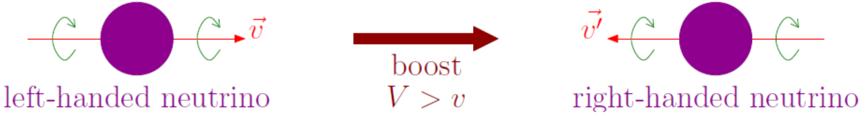
$$U_{MNS} = \begin{pmatrix} C_2 C_3 & S_3 C_2 & \sin \theta_{13} e^{-i\delta} \\ -S_3 C_1 - S_1 S_2 C_3 e^{i\delta} & C_1 C_3 - S_1 S_2 S_3 e^{i\delta} & S_1 C_2 \\ S_1 S_3 - S_2 C_1 C_3 e^{i\delta} & -S_1 C_3 - S_2 S_3 C_1 e^{i\delta} & C_1 C_2 \end{pmatrix}$$

- $\theta_{12} \equiv \theta_3$: The solar mixing angle
- $\theta_{13} \equiv \theta_2$: The reactor mixing angle
- $\theta_{23} \equiv \theta_1$: The atmospheric mixing angle



Massive Neutrino

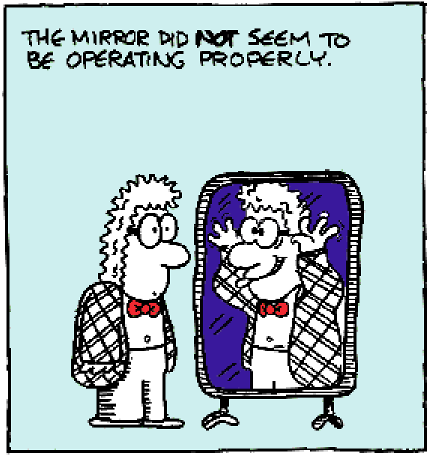
Neutrinos are massive:



- There are both left-handed (ν_L) and right-handed (ν_R) neutrinos
- Standard Model must be extended: add (ν_R) (Dirac neutrinos) or Majorana neutrinos

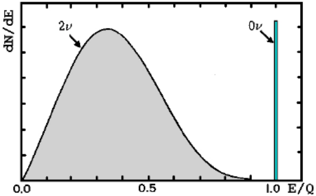
Dirac or Majorana Neutrinos

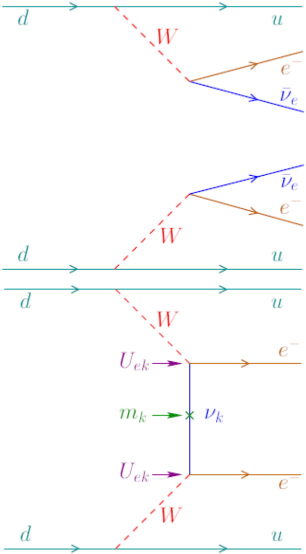
- Dirac particles: for each particle there is a corresponding antiparticle
- Charged particles: particle and antiparticle are different (Dirac)
- Neutral particles: particle and antiparticle can be different (Dirac) or equal (Majorana)
- A Majorana ν is its own antiparticle $\nu_M = \nu_M^C$



Neutrinoless Double Beta Decay

- Violation of lepton Number $\Delta L = 2$
- Signature of neutrinoless double beta decay:





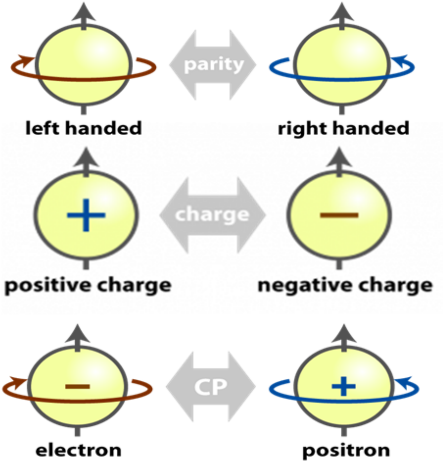
See Saw Mechanism

- Smallness of neutrino masses
- For $M_R \gg m_D$

$$M = \begin{pmatrix} m_L = 0 & m_D \\ m_D & M_R \end{pmatrix}$$

- There is a heavy neutrino $m_1 \approx M_R$
- And there is a light neutrino $m_2 = \frac{m_D^2}{M_R}$
- $m_1 m_2 = m_D^2$

CP Violation



CP Violation

- CP violation by neutrino oscillations

$$P(\overline{\nu_\mu} \to \overline{\nu_e}) \neq P(\nu_\mu \to \nu_e)$$

- Observation of CP violation:

  1. Sensitivity to the value of θ_{13}
  2. Sensitivity to oscillations due to Δm^2_{21} and Δm^2_{31}

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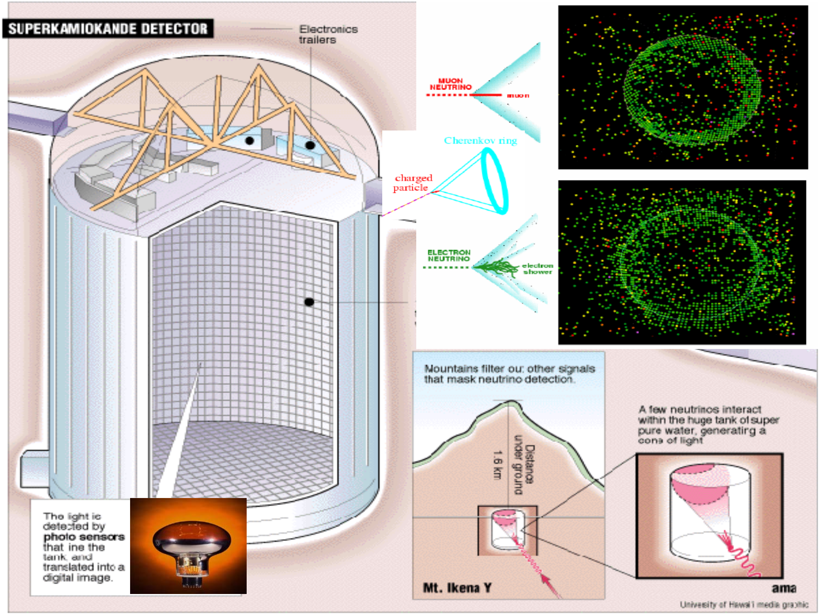
Neutrino Experiments Aims

- How large is the θ_{13} mixing angle?
- Is there CPV in the lepton sector and, if so, what is the value of δ?
- How are neutrino masses ordered: is $\Delta m^2_{31} > 0$ (NO) or $\Delta m^2_{31} < 0$ (IO)?
- Is the atmospheric neutrino mixing angle θ_{23} exactly equal to $\frac{\pi}{4}$?

Different Types of Experiments

- Solar experiments:
  Homestake, Kamiokande, Super-Kamiokande, SNO+, BOREXino
- Reactor experiments:
  KamLAND, Double Chooz France, RENO South Korea, Daya Bay China
- Accelerator experiments:
  (K2K, T2K Japan), NuMI US
- Atmospheric experiments:
  Kamiokande, IMB, Super-Kamiokande, Soudan, MACRO, MINOS
- Neutrino factories:
  Long baseline experiments that span the Earth
- Neutrino telescopes:
  Ice Cube, ANTARES, Baikal

Super Kamiokande



The light is detected by **photo sensors** that line the tank and translated into a digital image.

Mountains filter out other signals that mask neutrino detection.

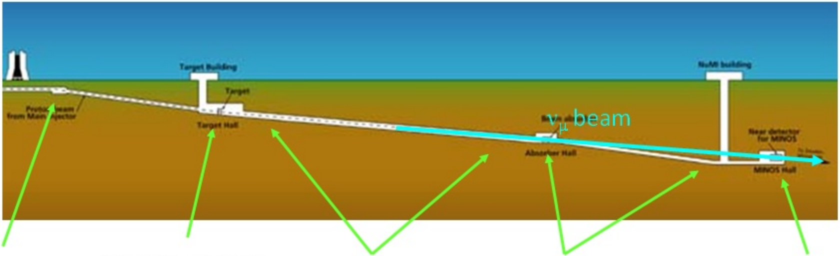
A few neutrinos interact within the huge tank of super pure water, generating a cone of light

University of Hawai'i media graphic

Accelerators: NuMI Fermilab

Make our own high energy protons

- Shoot them into a fixed target
- Focus the resulting πs into a beam
- Let the πs decay to νs
- Result a carefully controlled ν_μ beam!



120 GeV p^+

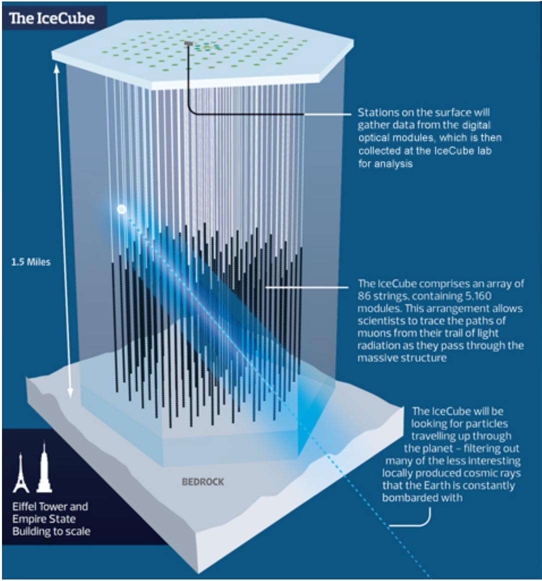
Graphite target,
Focusing “horn”

π decay pipe

π,μ absorber

“Near Detector”

Ice Cube Neutrino Telescope

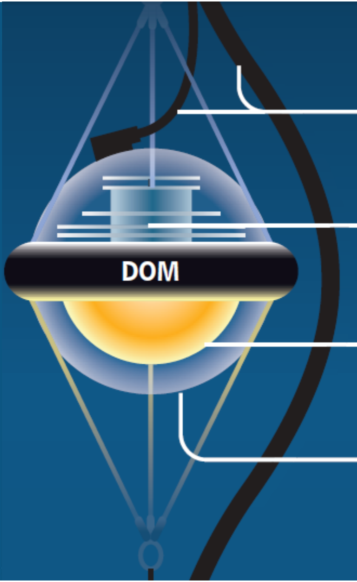


Stations on the surface will gather data from the digital optical modules, which is then collected at the IceCube lab for analysis

The IceCube comprises an array of 86 strings, containing 5,160 modules. This arrangement allows scientists to trace the paths of muons from their trail of light radiation as they pass through the massive structure

The IceCube will be looking for particles travelling up through the planet – filtering out many of the less interesting locally produced cosmic rays that the Earth is constantly bombarded with

Eiffel Tower and Empire State Building to scale



Black Hole Production by Neutrinos

- Cosmogenic neutrinos: $p \ \ \gamma \rightarrow \Delta \rightarrow n \ \ \pi \rightarrow \nu_\mu \overline{\nu_\mu} \nu_e ...$
    1. Large center of mass energies
    2. The signals of new physics could be detected in deeply penetrating air showers and neutrino telescopes.

- Depending on the fluxes of the ultrahigh energy cosmic neutrinos there is an opportunity to see the first sign or put constraints on black hole production parameters

- Black hole production can enhance the detection rate at cosmic ray facilities such as Auger and neutrino telescopes like IceCube significantly

Summary

- There are 3 active neutrino flavors.
- Neutrinos are massive and they oscillate between different flavors.
- If neutrinos are Majorana particles and if the See-Saw mechanism is the correct theory, the smallness of the neutrino mass has an explanation.
- Observing $0\nu\beta\beta$ would answer the questions about the absolute mass scale, the hierarchy and the nature of neutrinos.
- CP violation in quarks is not sufficient to explain the observed matter-antimatter asymmetry of the universe $\longrightarrow$ CP symmetry violation by leptons
- Different types of neutrino experiments: θ_{13} mixing angle, value of δ, order of neutrino masses...

THANK YOU !