Neutrino Theory

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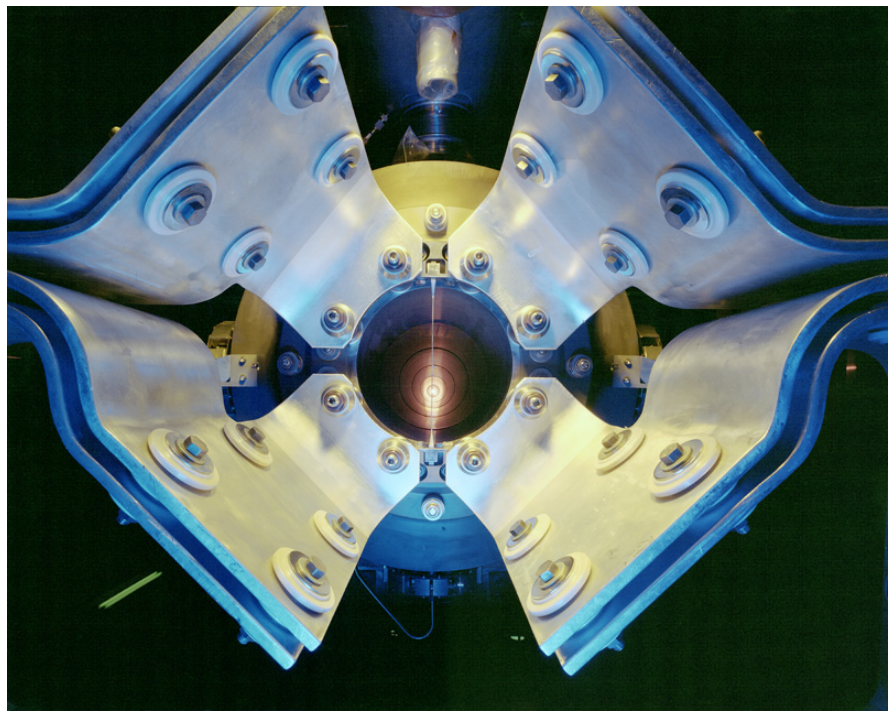
Physics 135c

May 8th, 2007



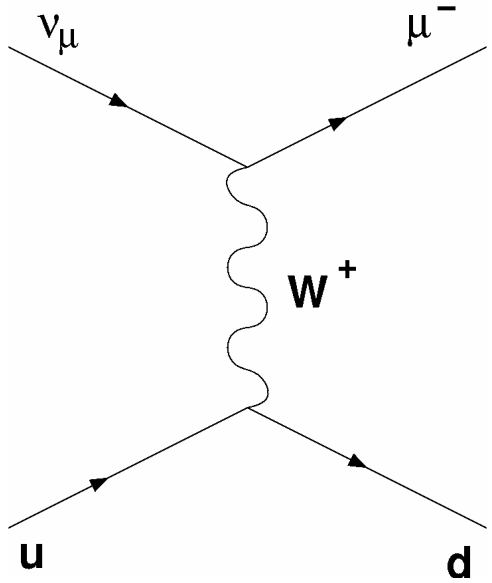
Outline

- Neutrion Basics
- A History of Neutrinos – In Pictures
- Oscillations and Mass
- Matter Effects
  - Solar Oscillations
  - Mass Hierarchy
- Dirac vs. Majorana
  - Magnetic Moment
  - See-Saw Mechanism

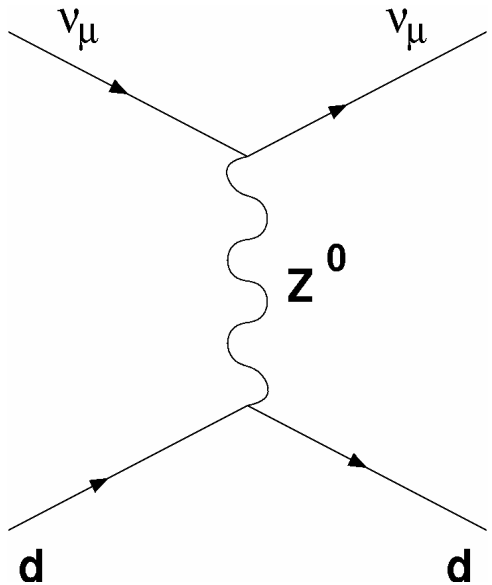
Neutrino Basics

- Electrically Neutral
- Fermion (Spin ½)
- Very small mass
- Three Flavors: e, μ, τ

"Charged Current"



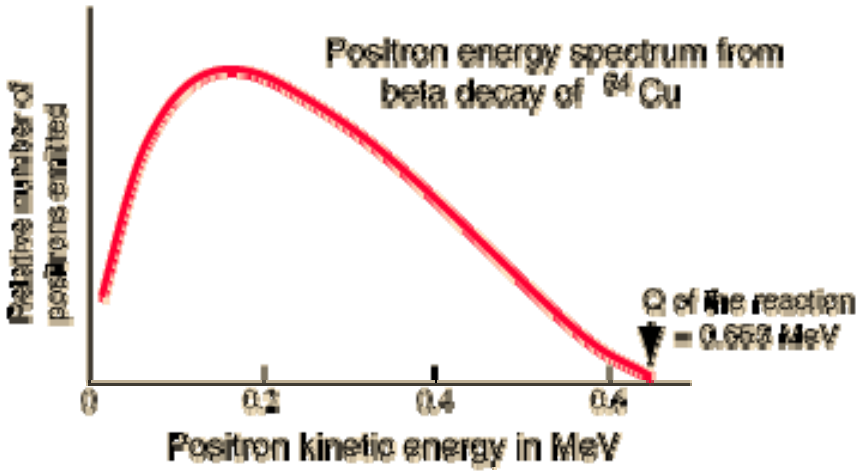
"Neutral Current"



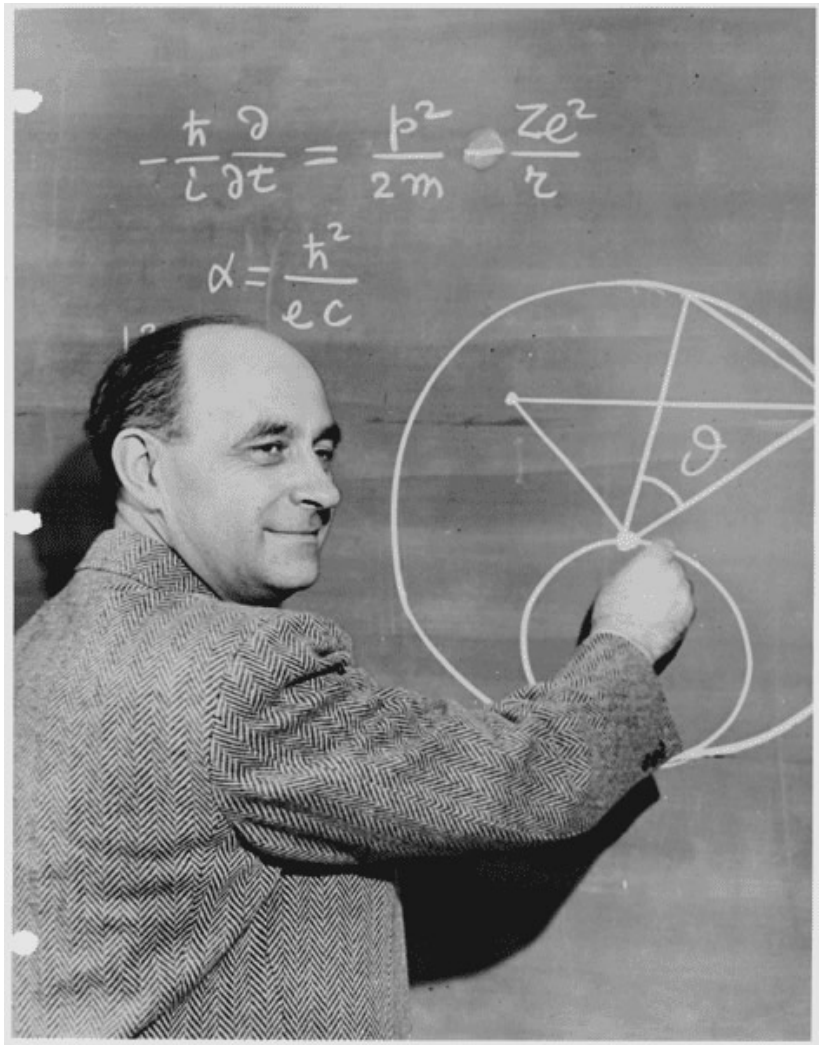
Neutrino History - 1930

$$^{6}He \rightarrow {}^{6}Li + e^{-}$$

$$^{60}Co \rightarrow {}^{60}Ni + e^{-}$$

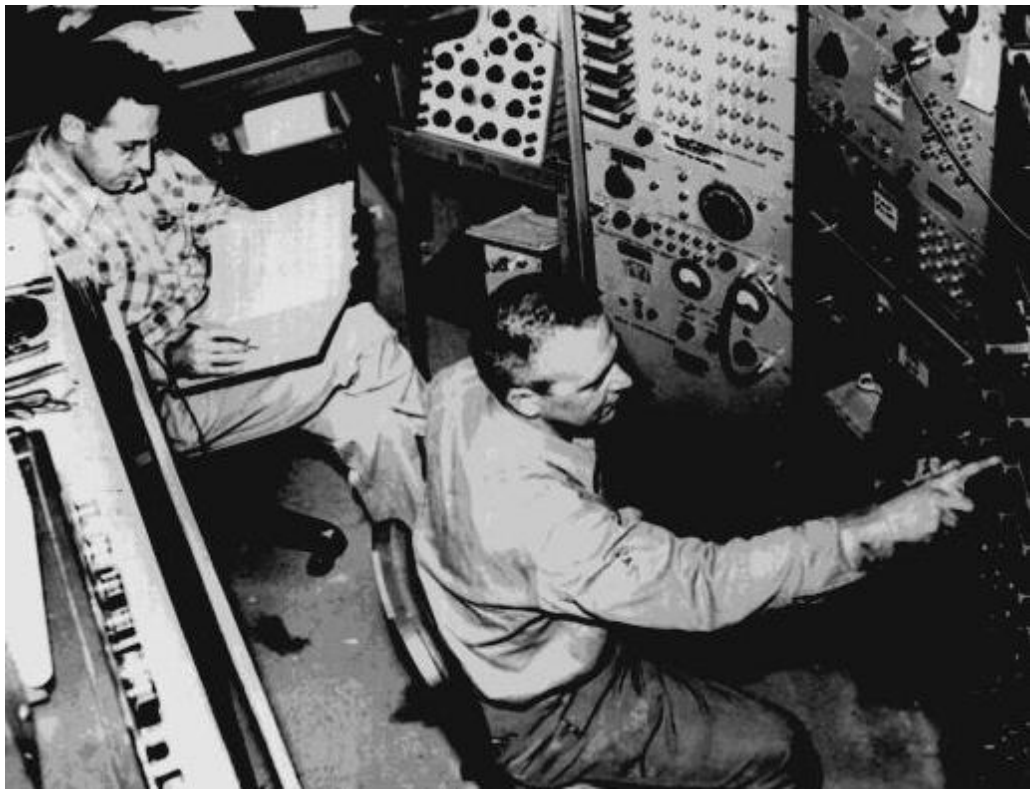


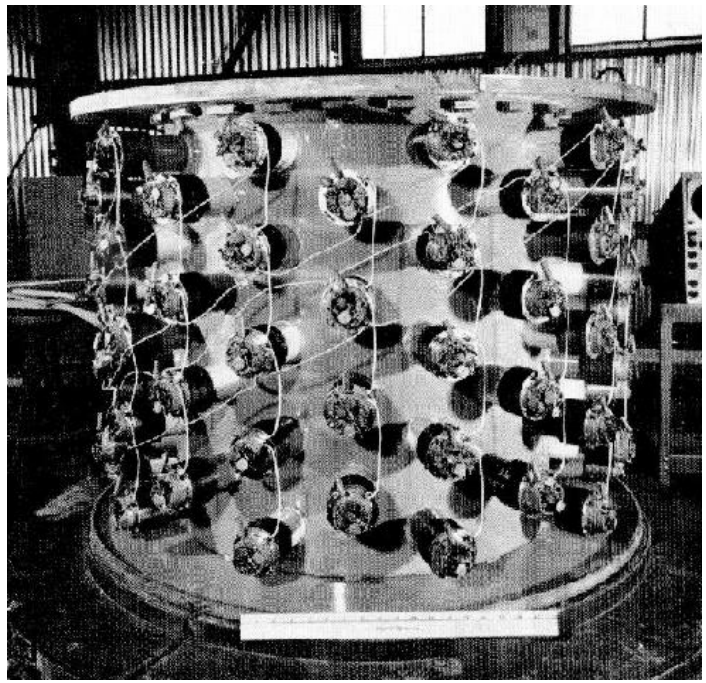
Neutrino History - 1933



"neutrino"

Neutrino History - 1956





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

Neutrino History - 1957

Neutrino History - 1968

Why do neutrino oscillations tell us that neutrinos are massive?

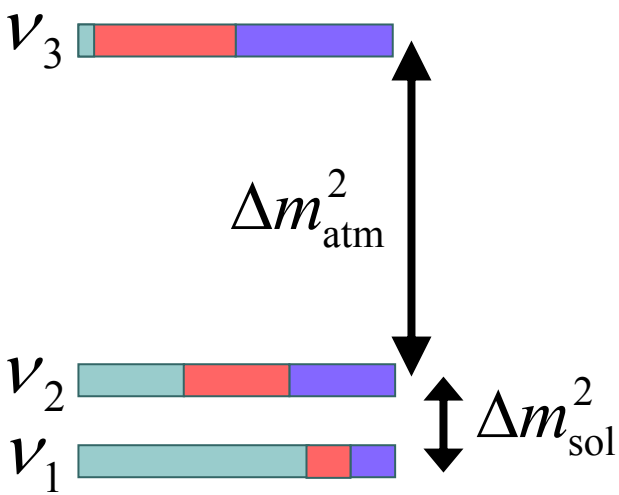
Full Mixing Matrix

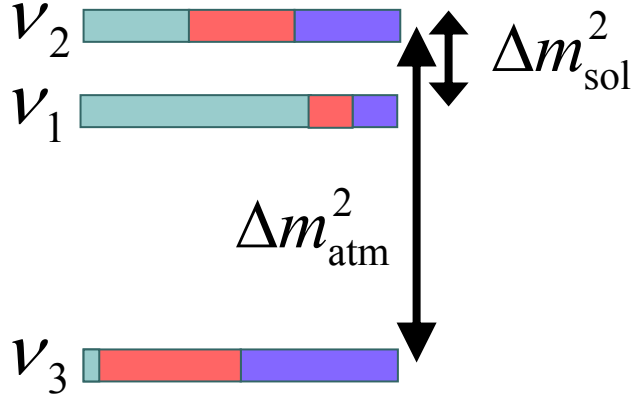
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar, Reactor}} \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{Atmospheric, Accelerator}}$$

$$\times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}, \; s_{ij} \equiv \sin\theta_{ij}, \{\delta, \alpha_1, \alpha_2\} \equiv \text{CP - Violating Phases}$$

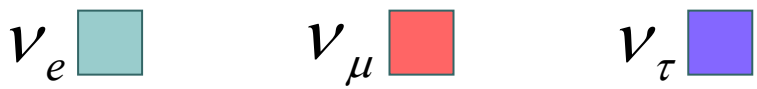
The Mass/Flavor Spectrum

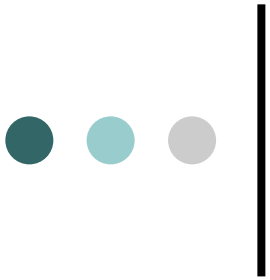




"Normal" Hierarchy

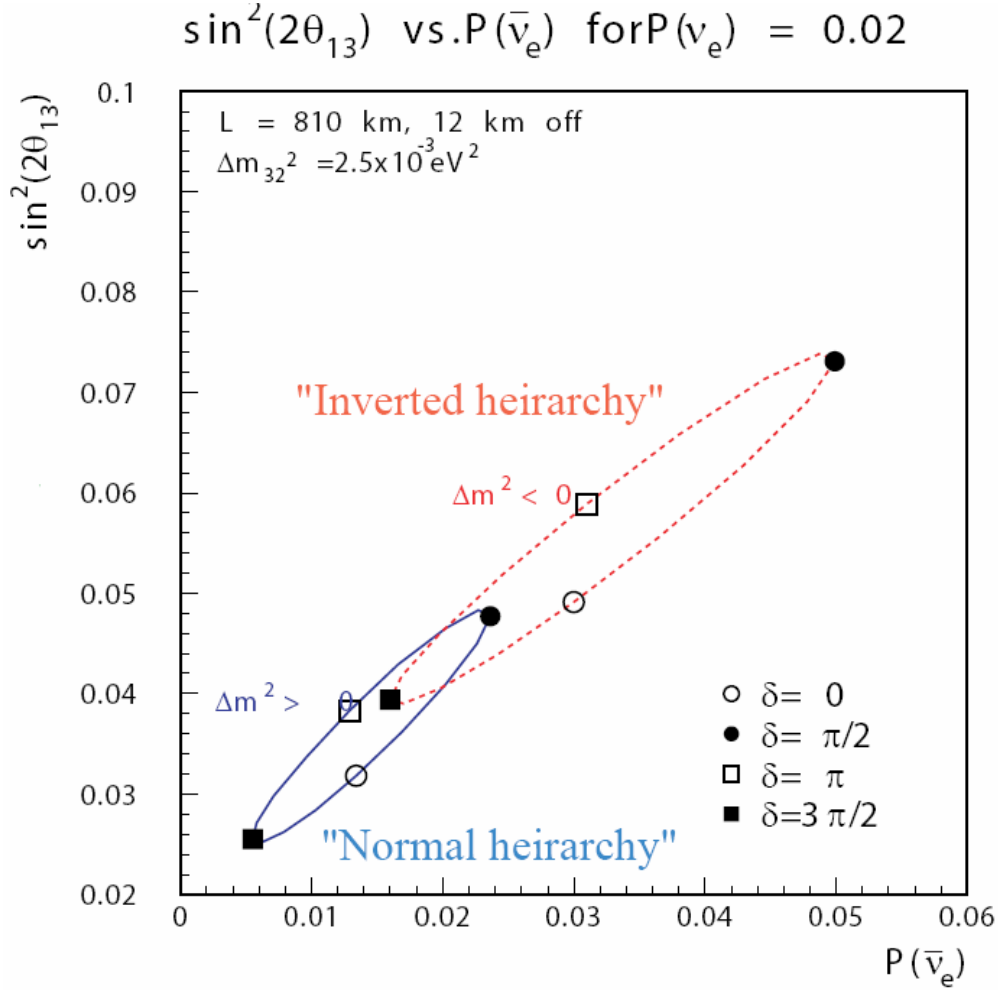
"Inverted" Hierarchy





Matter Effects

Matter Effects and the Mass Hierarchy



Dirac vs. Majorana:
What's the difference?

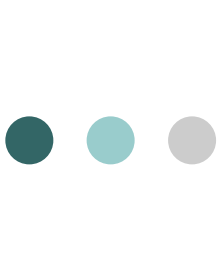
We Have	Dirac	Majorana
$\nu_i(\mathrm{L}),\ \bar{\nu}_i(\mathrm{R})$	$\nu_i(\mathrm{h}) \neq \bar{\nu}_i(\mathrm{h})$ $L(\nu_i) = -L(\bar{\nu}_i)$	$\nu_i(\mathrm{h}) = \bar{\nu}_i(\mathrm{h})$ $L(\nu_i) =$ undefined
Δm^2_{ij}	$\mathcal{L}_D = -m_D \bar{\nu}_L \nu_R + h.c.$	$\mathcal{L}_M = -M_h \bar{\nu}_h^C \nu_h + h.c.$
? magnetic moment **?** neutrino-less double beta decay	**Yes** magnetic moment **No** neutrino-less double beta decay	**No** magnetic moment **Yes** neutrino-less double beta decay

Dirac vs. Majorana:
What affect does it have?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$$\times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana Phases}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}, \; s_{ij} \equiv \sin\theta_{ij}, \{\delta, \alpha_1, \alpha_2\} \equiv \text{CP - Violating Phases}$$



Neutrino Magnetic Moment
&
The See-Saw Mechanism