Neutrino Physics

Steve Elliott
LANL

Nuclear Physics Summer School 2005

Lecture Outline

- Neutrinos and the weak interaction
- Neutrino oscillations
- Experimental results on neutrinos
  - Solar-Atmospheric experiments
  - Reactor-Accelerator experiments
- Double beta decay
- "Direct" neutrino mass studies

Outline
for this lecture

- Neutrinos in the “standard model”
- Sources of neutrinos
- Neutrino detection
- Connections to other physics

The Standard Model Particles

Quarks	**u** up	**c** charm	**t** top	**γ** gamma	Force Carriers
	d down	**s** strange	**b** bottom	**g** gluon	
Leptons	**ν_3**	**ν_1**	**ν_2**	**W** W boson	
	e electron	**μ** muon	**τ** tau	**Z** Z boson	

The Neutrinos

Neutrinos mix, therefore:

- Neutrinos have mass
  - Might have non-zero magnetic moments
  - Heavier neutrinos might decay
  - Might be Majorana or Dirac
- What are the implications for
  - unification, supersymmetry, and extra dimensions?
  - possible existence of additional species?
  - the possibility that neutrinos have something to do with the matter-antimatter asymmetry?

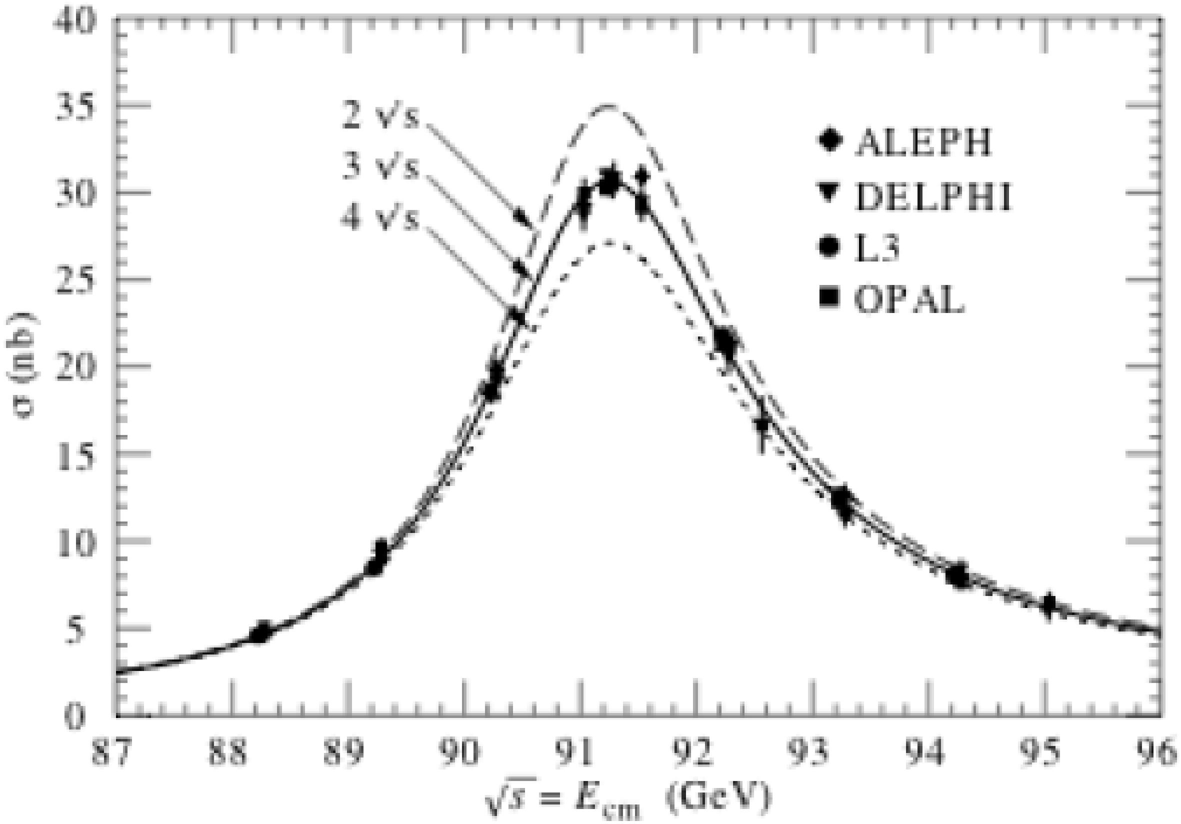
Why neutrinos are unusual

- **Neutrinos might be the ultimate neutral particle**
  - **They would not be distinct from their antiparticles.**
  - **If so they would be Majorana particles**
- **They might also be Dirac particles**
  - **Like the charged quarks and leptons**

Neutrinos and the weak interaction

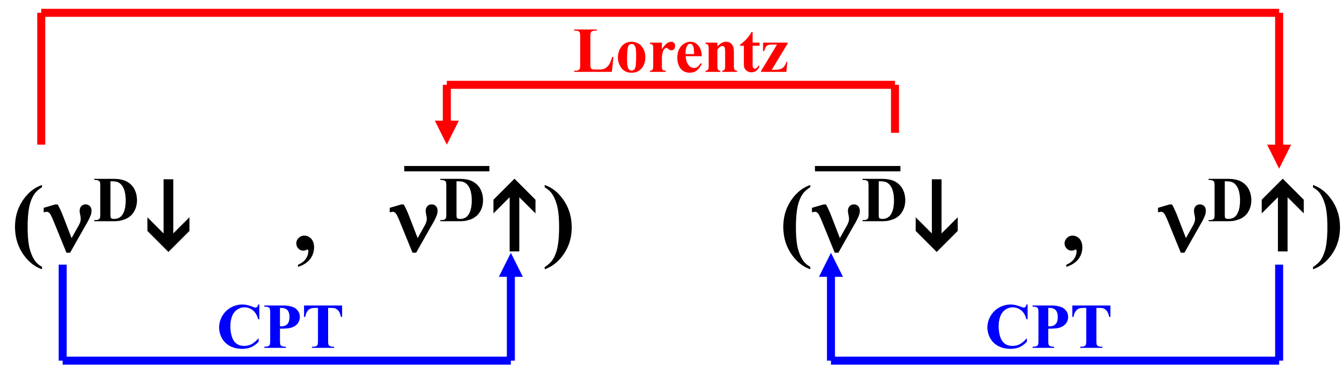
- The weak interaction violates parity.
- Hence there are no right handed current interactions
- This can be interpreted two ways.
  – There are no right handed neutrinos
  – There are RH neutrinos, they just don’t interact

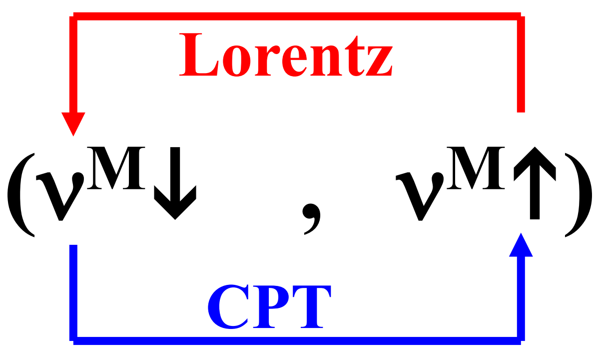
There are 3 active light neutrinos



The width of the Z decay depends on the number of channels available for the decay.

Dirac vs. Majorana

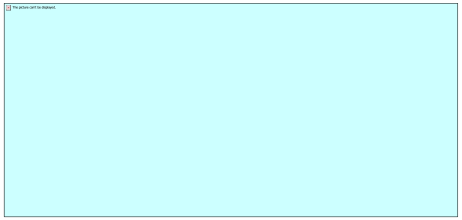




$\beta\beta(0\nu)$ addresses Dirac/Majorana nature of ν.

Typical Dirac mass term

Quarks and leptons get their mass by a coupling to the Higgs. Here is an example (the electron): a Dirac particle.



Mij doesn’t have to be diagonal, although it is for the charged leptons.

For neutrinos:

In the standard model, ν_{jR} (the RH neutrino) doesn't exist, therefore neutrinos are massless by construction.

Now that we know that neutrinos have mass, we need to learn how to incorporate that into the model. There are many possibilities.

We could simply put in ν_{jR}

The coupling f_{ij} doesn't have to be diagonal and in general it isn't. To find the physical fields, those of definite mass, we need to diagonalize M_{ij}.

Such a term leads to mixing

m_α is the α^{th} diagonal element of the mass matrix

The neutrinos mix.

Shortcomings

- f_{ij} is completely arbitrary
- Doesn't explain why neutrinos are so much lighter than their lepton partners.

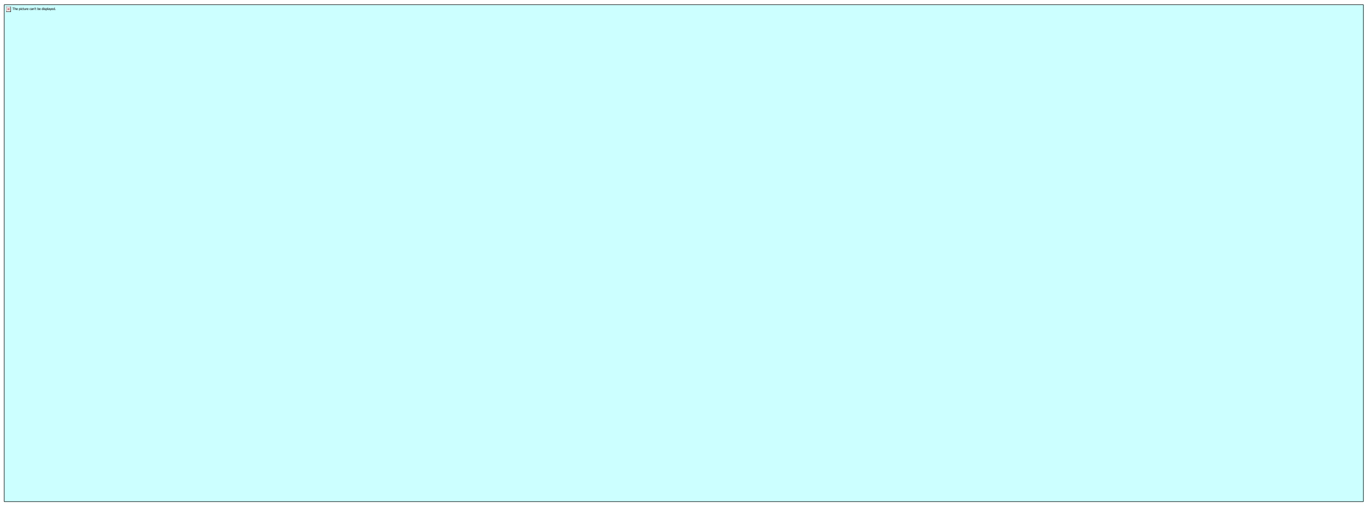
- We have not included additional possible mass terms…

Adding Majorana mass terms

- **Ms are nxn matrices for n generations.**
- **ν_R, ν_L are n element column vectors from n generations.**

From NC scattering,
We know M_L is small

Diagonalize M



Leads to two eigenvalues $m_1 \sim (M^D)^2/M^R$ and $m_2 \sim M^R$

Leads to the seesaw mechanism

- **If we take M^D to be order of lepton mass, and we know that M^R is large:**
- **We have two Majorana neutrinos**
  - **One with a mass much less than the leptons**
  - **One which is very heavy.**

Phases in the mixing matrix

For nxn unitary matrix (U):

$2n^2$ parameters in a complex matrix

$-n^2$ unitarity constraints

-(2n-1) unphysical phases: that can be absorbed into the fields, $\bar{\nu}$ and ν

$=(n-1)^2$ parameters (1/2)(n-1)n of these are rotation angles

Note however, that for Majorana fields, the phases of $\bar{\nu}$ and ν are related. Hence there are only n unphysical phases.

Sources of neutrinos

Big Bang
Radioactive decays
Stars
Supernovas
Cosmic rays
Reactors
Accelerators

Big Bang

- Relic neutrinos contribute at least as much mass to the Universe as all the stars.
- There are as many leftover neutrinos as photons.
  - N_γ ~420/cc
- Photon energy: 2.728 K
- Neutrino energy: 2 K
  - There are no viable ideas for detecting such low energy neutrinos.
  - Note that neutrinos are studied via their particle nature
  - The microwave background was discovered by the wave nature of photons.

Radioactive Decays

- **MCi sources have been made**
- **Mostly for use by solar neutrino radiochemical experiments for efficiency measurements.**
- **Electron capture isotopes provide a monoenergetic neutrino.**

^{51}Cr
^{37}Ar

Stars (our Sun)

Features

Very long baseline, ν_e disappearance, ν_x appearance

Low energy, spectral shape well known

L/E is large so sensitive to small δm^2

Large Flux

Matter enhancement

Data

Rates from several experiments

Energy dependence

Day vs. Night

Seasonal

Supernovas

Features

~ **Very long baseline**

~ ν_τ**'s**

~ **Complicated and poorly understood source**

~ **Target cross sections not all well understood**

Data

~ **Not a common phenomenon**

once ~30 years in our galaxy

~ **SN1987A provided little ν physics data**

~ **SN1987A did give hope for the future**

My personal prediction is that neutrinos will teach us a lot about supernovae, but the inverse will be much harder.

Supernovas

By using various targets with different energy- and flavor-dependent cross sections, one may be able to de-convolute the various fluxes.

Cosmic Rays

Reactors

<u>Features</u>

Complicated but well-understood source.

Low energy

Short, medium, long baselines

disappearance experiments

<u>Data</u>

Several at short baselines; 10-250 m

CHOOZ/Palo Verde at ~1 km

KamLAND at ~250 km

Accelerators

Features

Usually appearance

Various baselines and wide energy range

Controlled experimental conditions

Data

Oscillation limits for many species

Lots of experimental results

Neutrino detection

Targets

- H_2O
- D_2O
- Scintillator
- Ga
- Cl
- Emulsion
- Ice
- Iron
- Rock

ES on e^-:

$\nu_x + e^- \rightarrow \nu_x + e^-$

CC on Nucleus:

$\nu_l + A \rightarrow A' + l$

NC on Nucleus:

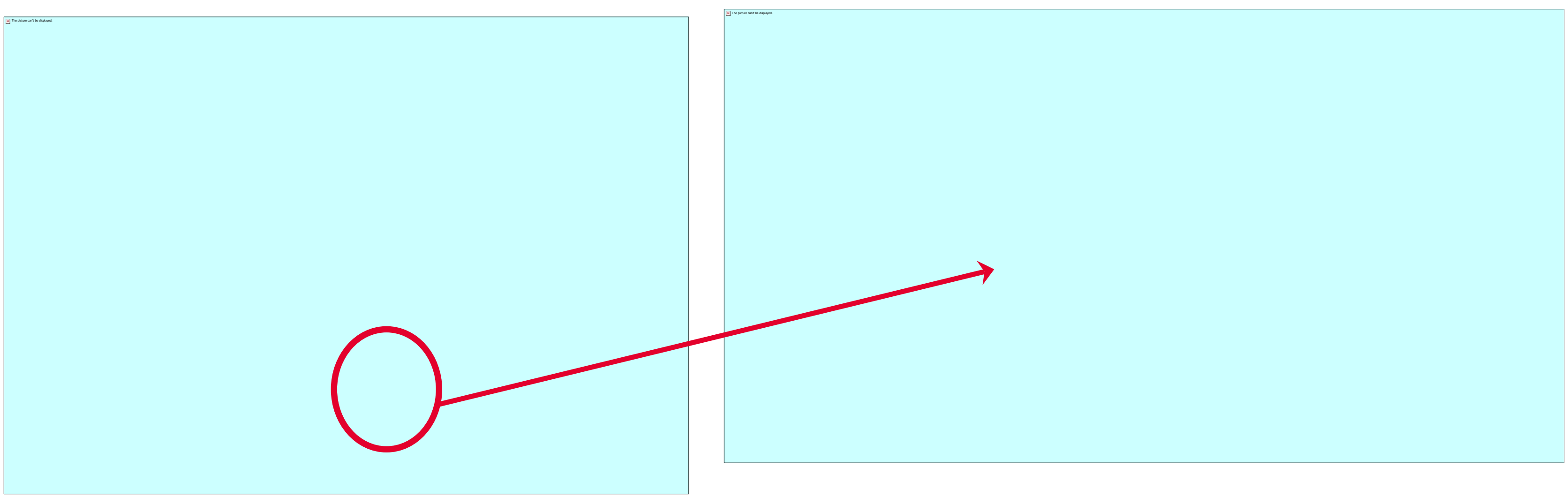
$\nu_x + A \rightarrow A' + \nu_x$

Cross sections

- **10,000 light years of Pb to stop half of solar neutrinos**
- **Beta decay provides estimate of strength**

Neutron beta decay

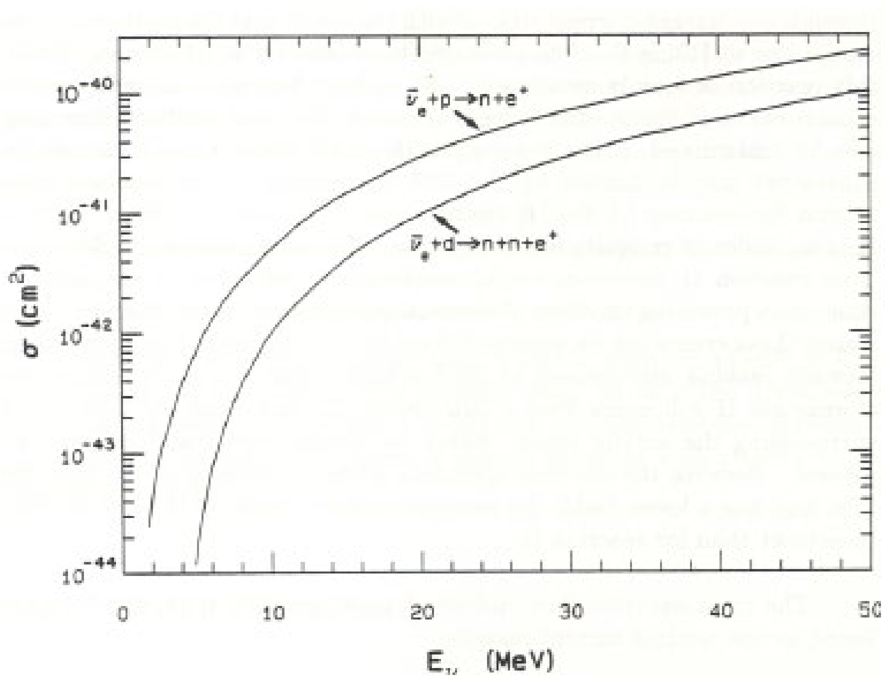
Anti-neutrino absorption

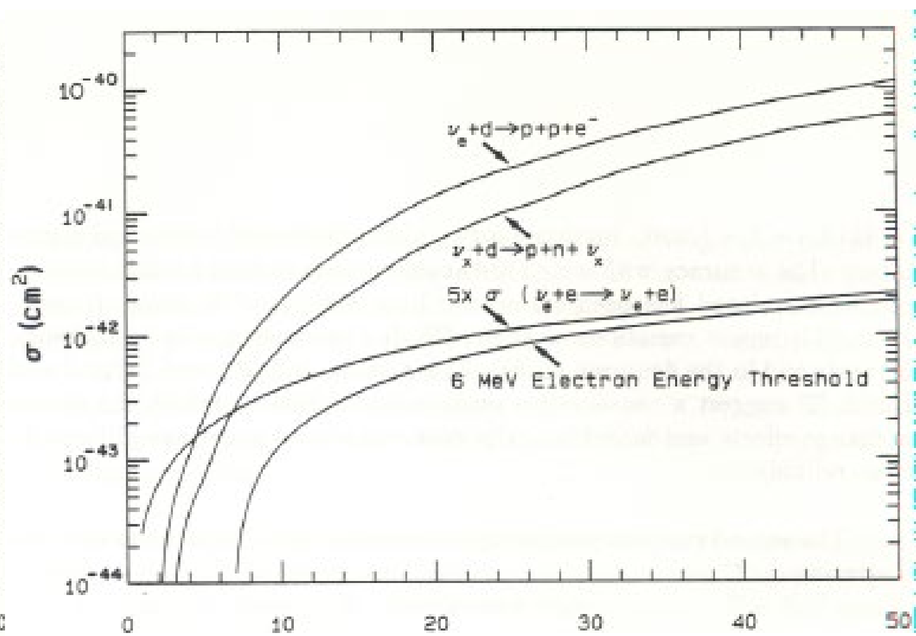


Los Alamos
NATIONAL LABORATORY

Cross Sections

The small size of these cross sections is what led early researchers to believe they had postulated an undetectable particle.





Hard experiments

- Rates are very low
  - Big detectors
- Background difficulties
  - Signal may not be very distinct
  - Other more common processes can mimic signal
  - Rare variations of common phenomena…

Los Alamos NATIONAL LABORATORY

Connections to other physics

- Cosmology
  - Large scale structure
  - Baryon asymmetry
- Nuclear and Particle physics
  - Incorporating mass into the standard model
- Astrophysics
  - Nucleosynthesis
  - Supernova dynamics

Neutrinos are very practical

A summary of the questions

- Are neutrinos Majorana or Dirac?
- What is the absolute mass scale?
- How small is θ_{13}?
- How maximal is θ_{23}?
- Is there CP violation in the neutrino sector?
- Is the mass hierarchy inverted or normal?
- Is the LSND evidence for oscillation true? Are there sterile neutrinos?

References

- **Mohapatra/Pal book**
- **Kayser book**
- **Bahcall book**
- **Boehm/Vogel book**