PHYS 5396 – Lecture #2

Wednesday, Jan. 15, 2003
Dr. Jae Yu

1. What is a neutrino?
2. History of neutrinos
3. Neutrino cross section
4. Neutrino experiments

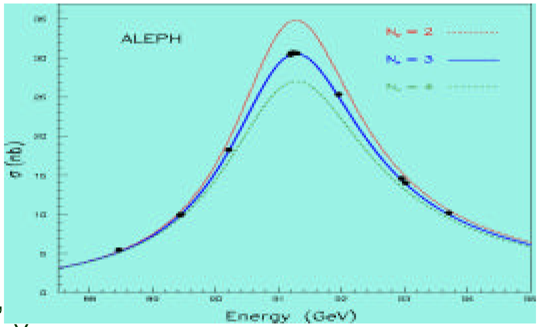
Reading Assignments

- S. Weinberg on Electroweak theory
  - S. Weinberg, PRL **19**, 1264 (1967)
- S. Weinberg paper on Standard Model:
  - S. Weinberg, Rev. Mod. Phys. **52**, 515 (1980)

What are neutrinos?

- Lepton species without electrical charge
- Only affected by weak interactions, no EM
- Have one helicity
  - we have observed only left-handed neutrinos and right-handed anti-neutrinos
  - This property led Yang & Lee to parity violation and eventually theory of weak interactions
- No mass prescription in the SM ➔ Atmospheric and solar neutrino experiments seem to have provided direct evidence that challenges this hypothesis

•Measurements show three species only



Properties of Neutrinos

Flavor	Spin	Masses	Magnetic Spin(MeV/T)	X-sec (cm^2)
ν_e	½	<2.8 ev	$<5.8\times10^{-20}$	$\sim10^{-38}$
ν_μ	½	<16~70KeV	$<4.3\times10^{-20}$	$\sim10^{-38}$
ν_τ	½	18.2 MeV	$<3.1\times10^{-17}$	$\sim10^{-38}$

History of neutrinos

- It was noticed at the end of 19th century by nuclear physicists that beta decays do not seem to conserve momentum and energy ➔ BIG problem!!!

$$\boxed{n \longrightarrow p + \bar{n}_e + e^-}$$

- 1931: W. Pauli postulates that the missing energy may be carried by a neutral particle, as a "desperate remedy".
- 1934: Fermi develops a theory of beta decay in which the inclusion of a neutral particle (neutrino) explains many experimentally observed results.

Neutrino history, cnt'd

- 1956: Cowen and Reines detects electron neutrinos from a reactor experiment by detecting photons (a few from neutron capture by Cd nucleus and the other from positron annihilation with an electron) emitted as a result of an inverse beta decay, with a several μs time separation

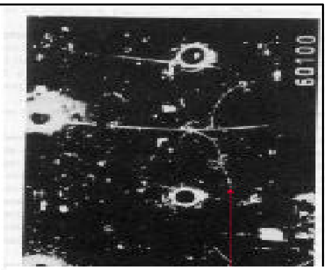
$$\boxed{\bar{n}_e + p \rightarrow n + e^+}$$

- 1956: Yang and Lee develops theory of parity violation of weak interactions ➔ Existence of different types from lack of experimental observation of reactions like

$$\boxed{m^- \rightarrow e^- + g}$$

Neutrino history, cnt'd

- 1962: BNL accelerator experiment proves the existence of muon neutrinos, by producing neutrinos from pion decays and determining the product of interaction to be muons → No electrons above the background observed
- Late 60': Proposal of Electroweak theory based on SU(2)xU(1) by Weinberg, Salam and Glashow (Weinberg, PRL **19**, 1264 (1967))
- 1970:GIM model (Glashow, PR **D2**, 1285 (1970)) of second quark family, confirmed experimentally in 1974

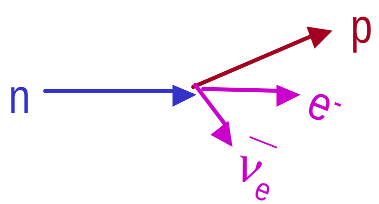


•1973: Experimental observation of neutral current interaction at the Gargamelle experiment (bubble chamber neutrino experiment)→ Confirmation of electroweak theory

Weak Interaction Formalism

$$\boxed{n \rightarrow p + \bar{n}_e + e^-}$$

- Fermi 4-fermion contact interaction to describe nuclear β-decay (E. Fermi, Z. Physik **88**, 161 (1934))



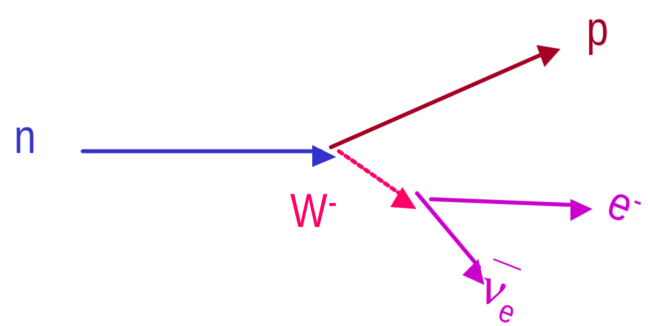
$$L_{Fermi} = -\frac{4G_F}{\sqrt{2}} J_a^{CC+} J_a^{CC-}$$

$$G_F = 1.16639 \times 10^{-5}\ \text{GeV}^2$$

- The theory begins to violate unitarity at about the momentum transfer scale 100GeV ➔ Cross section becomes larger than that from optical theorem

Introduction of IVB's and EW Unification

- Inspired by the failure of Fermi contact interaction and QED, Weinberg, Salam and Glashow introduced IVB's exchange to replace Fermi contact interactions

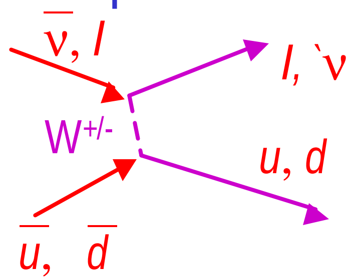


EW Formalism

- Lagrangian for EW interactions by GSW:

$$-L_{EW} = \underbrace{\frac{g}{2}\left(J_\alpha^{CC+}W_\alpha^{-} + J_\alpha^{CC-}W_\alpha^{+}\right)}_{\text{Charged Weak}} + \underbrace{\frac{g}{\cos\theta_W} J_\alpha^{NC} Z_\alpha^{0}}_{\text{Neutral Weak}} + \underbrace{g\cos\theta_W J_\alpha^{EM} A_\alpha}_{\text{EM}}$$

- Leptonic currents (J's) couple to vector bosons



$$J_\alpha^{CC+} = \bar{\nu}_i\gamma_\alpha \frac{1-\gamma_5}{2} l_i + \bar{u}_i\gamma_\alpha \frac{1-\gamma_5}{2} d_i$$

$$J_\alpha^{CC-} = \bar{l}_i\gamma_\alpha \frac{1-\gamma_5}{2} \nu_i + \bar{d}_i\gamma_\alpha \frac{1-\gamma_5}{2} u_i$$

EW Formalism cnt'd

- EM current $J_a^{EM} = q_j \overline{f}_i g_a f_j$
- Weak Neutral Current

$$J_a^{NC} = \overline{f}_j g_a \frac{V_j - A_j g_5}{2} f_j$$

- where Vector and axial-vector couplings are

$$V_j = I_j - 2Q_j \sin^2 q_W$$

$$A_j = I_j$$

- with propagator terms

$$\text{W or Z propagator} = \frac{-i\left(g_{mn} - q_m q_n / M^2\right)}{q^2 - M^2}$$

Some properties of GSW

- GSW model is SU(2)xU(1) gauge group theory with the specified relative coupling strength in the Lagrangian. EM coupling is $g\sin\theta_W = e$.
- GSW Prediction of IVB mass from spontaneous symmetry breaking mechanism, that gives masses to IVB and leptons, is

$$\sin^2\theta_W = 1 - \frac{M_W^2}{\rho M_Z^2}$$

- SM Predicts one Higgs boson, giving ρ=1

Linking Fermi to GSW

- Using the two Lagrangians of Fermi and GSW and CC propagator

$$L_{Fermi} = -\frac{4G_F}{\sqrt{2}} J_\alpha^{CC+} J_\alpha^{CC-}$$

$$-L_{EW} = \frac{g}{2}\left(J_\alpha^{CC+} W_\alpha^- + J_\alpha^{CC-} W_\alpha^+\right) + \frac{g}{\cos\theta_W} J_\alpha^{NC} Z_\alpha^0 + g\cos\theta_W J_\alpha^{EM} A_\alpha$$

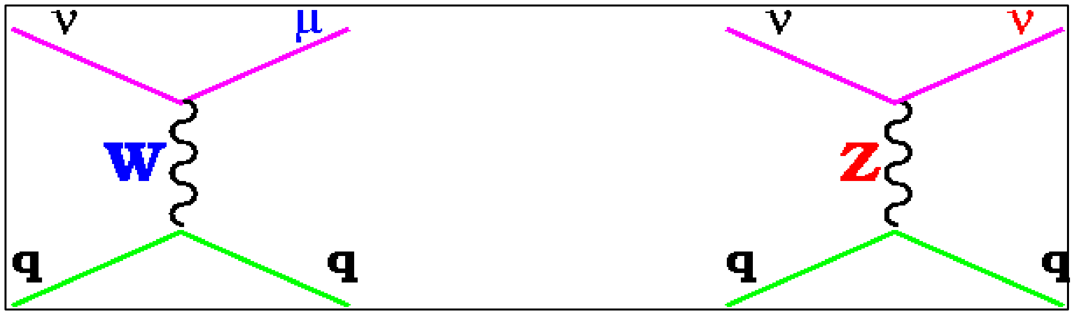
- The coupling *g* can be written ($q^2 << M^2$)

$$\text{W or Z propagator for } q^2 << M^2 = \frac{-ig_{\mu\nu}}{M^2}$$

- Effective coupling strengths can be related

$$\frac{4G_F}{\sqrt{2}} = \left(\frac{g}{\sqrt{2}}\right)\frac{1}{M_W^2}\left(\frac{g}{\sqrt{2}}\right) \qquad \boxed{G_F = \frac{g}{4\sqrt{2}M_W^2}}$$

Neutrino Cross Sections



$coupling \propto I_{weak}^{(3)}$

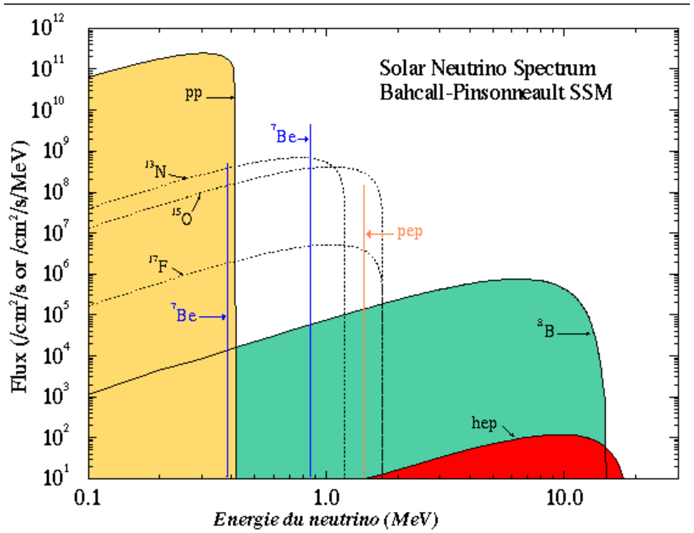
$coupling \propto I_{weak}^{(3)} - Q_{EM} \sin^2 q_W$

$$\frac{d^2 s}{dxdy} = \frac{2G_F ME}{p} \left[\begin{array}{l} \left(1 - y - \frac{Mxy}{2E}\right) F_2\left(x, Q^2\right) + \frac{y^2}{2} 2xF_1\left(x, Q^2\right) \\ \pm y\left(1 - \frac{y}{2}\right) xF_3\left(x, Q^2\right) \end{array} \right]$$

$$\boxed{\begin{array}{l} s_{nN} / E_n \approx 0.68 \times 10^{-38}\ \mathrm{cm}^2 / \mathrm{GeV} \\ s_{\bar{n}N} / E_n \approx 0.35 \times 10^{-38}\ \mathrm{cm}^2 / \mathrm{GeV} \end{array}}$$

Sources of Neutrinos: Solar Neutrinos

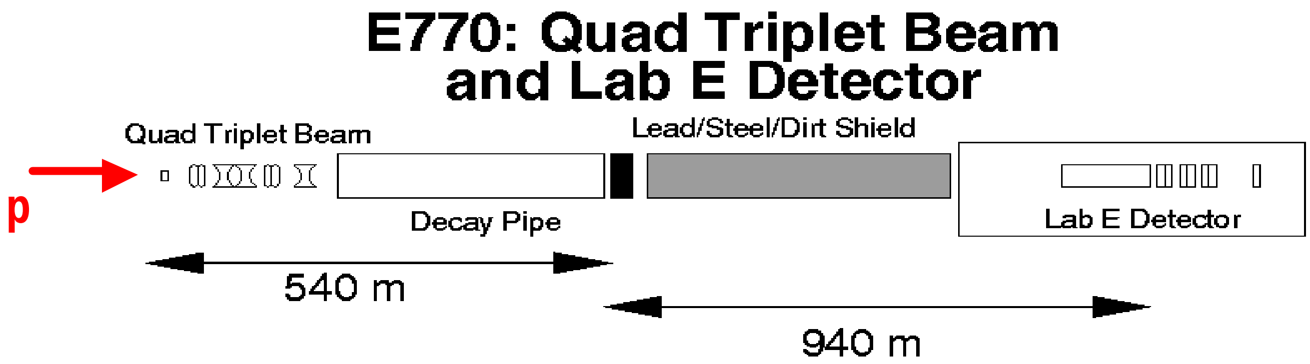
- Nuclear Fusion inside stars with the primary (85%) reaction $\boxed{p + p \rightarrow {}^{2}H + e^{+} + n_{e}}$
- Energy spectra

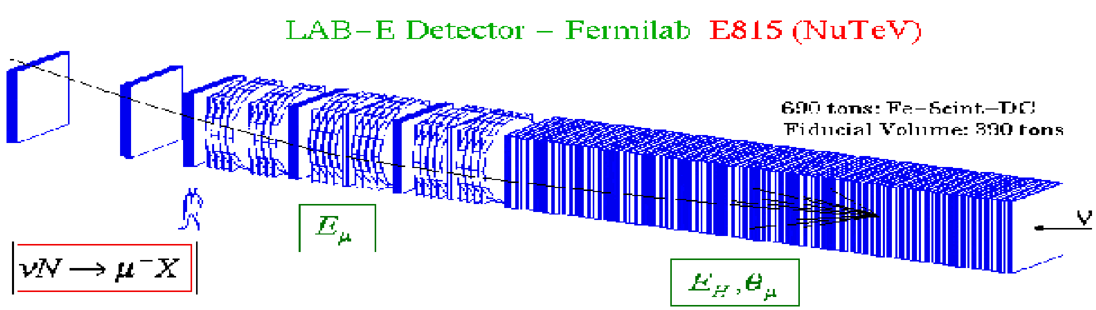


Sources of Neutrinos:Atm and other

- High energy cosmic-ray (He, p, n, etc) interactions in the atmosphere
  - Cosmic ray interacts with air molecules $He + p \rightarrow p, K$
  - Secondary mesons decay $p \rightarrow m + n_m + n_e$
  - Muons decay again in 2.6μs $m \rightarrow e + n_m + n_e$
- Neutrinos from Big Bang (relic neutrinos)
- Neutrinos from star explosion
- Neutrinos from natural background, resulting from radioactive decays of nucleus
- Neutrinos from nuclear reactors in power plants

Accelerator Based Neutrino Experiments





Homework Assignment

- Find a method of distinguishing neutrino signs (neutrinos from anti-neutrinos) in an accelerator based neutrino experiment.