NEUTRINOS

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Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Neutrino Oscillations

III. The Data and Its Interpretation

IV. Some Missing Pieces and The Meaning of All This

Plan of Lecture I

Standard Neutrino Properties and Mass Terms (Beyond Standard)

Introduction

Neutrinos in the SM

Neutrino Properties:

Helicity versus Chirality, Majorana versus Dirac

Neutrino Mass Terms Beyond the SM:

Dirac, Majorana, the See-Saw Mechanism, Lepton Mixing

Direct Probes of Neutrino Mass Scale

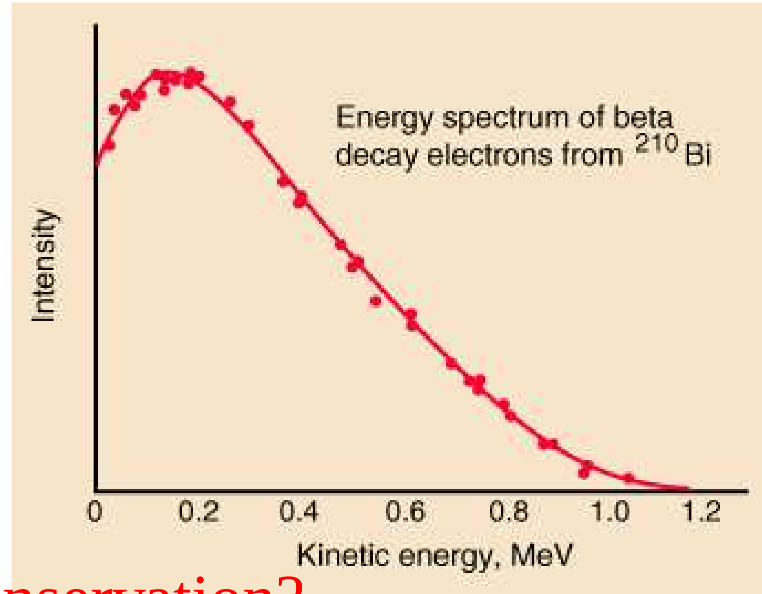
Discovery of ν's

- At end of 1800's radioactivity was discovered and three types identified: α, β, γ
  β : an electron comes out of the radioactive nucleus.

- Energy conservation $\Rightarrow$ e^- should have had a fixed energy

$$(A, Z) \to (A, Z+1) + e^- \;\Rightarrow\; E_e = M(A, Z+1) - M(A, Z)$$

But 1914 James Chadwick showed that the electron energy spectrum is continuous



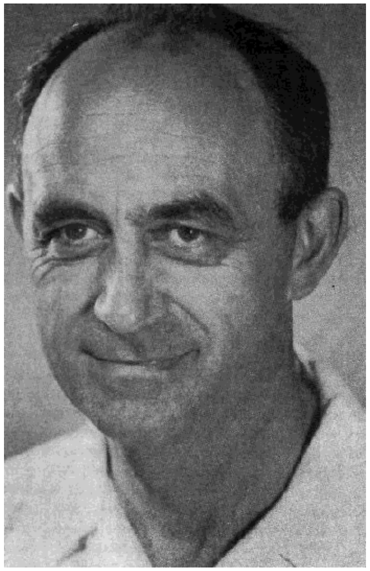
Do we throw away the energy conservation?

Discovery of ν's

• The idea of the neutrino came in 1930, when W. Pauli tried a desperate saving operation of "the energy conservation principle".

In his letter addressed to the "Liebe Radioaktive Damen und Herren" (Dear Radioactive Ladies and Gentlemen), the participants of a meeting in Tubingen. He put forward the hypothesis that a new particle exists as "constituent of nuclei", the "neutron" ν, able to explain the continuous spectrum of nuclear beta decay

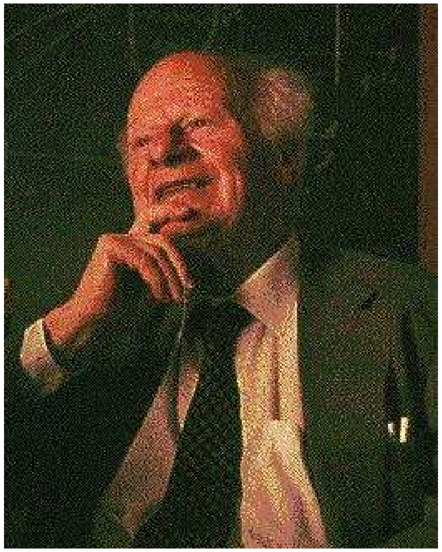
$$(A, Z) \to (A, Z+1) + e^- + \nu$$



• The ν is light (in Pauli's words: "the mass of the ν should be of the same order as the e mass"), neutral and has spin 1/2

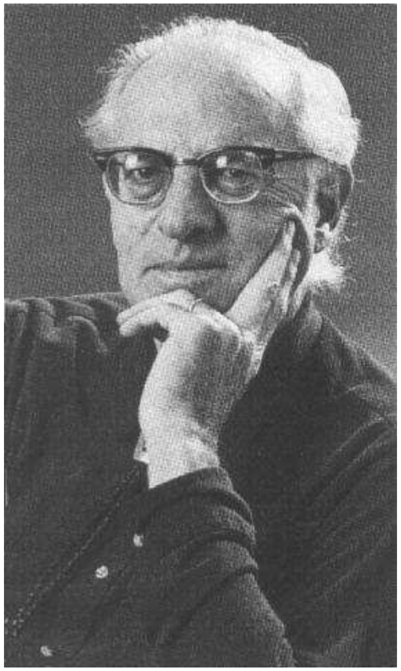
• In order to distinguish them from heavy neutrons, Fermi proposed to name them neutrinos.

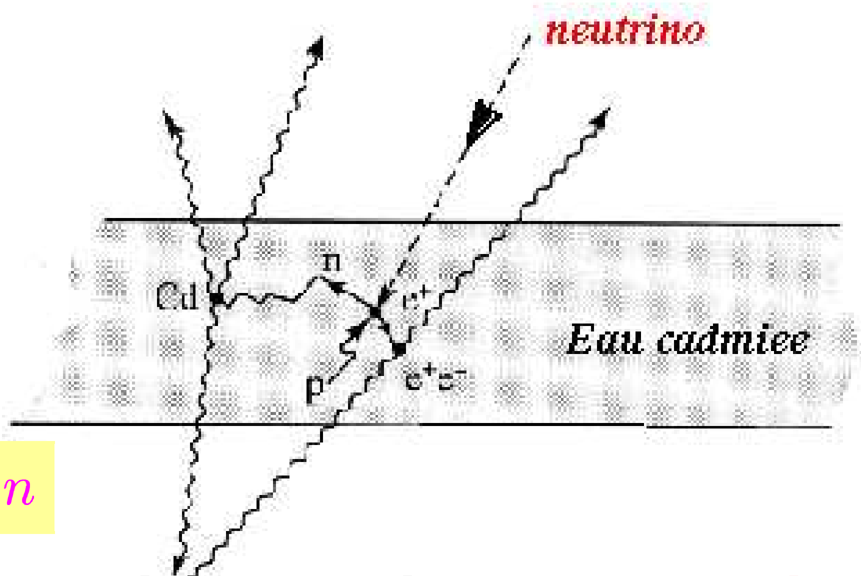
First Detection of ν's



In 1934, Hans Bethe and Rudolf Peierls showed that the cross section between ν and matter should be so small that a ν go through the Earth without deviation

In 1953 Frederick Reines and Clyde Cowan place a neutrino detector near a nuclear plant





400 litters of water and cadmium chloride.

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

e^+ annihilates e^- of the surrounding material giving two simultaneous γ's.
neutron captured by a cadmium nucleus with emission of γ's some 15 msec after

The neutrino was there. Its tag was clearly visible

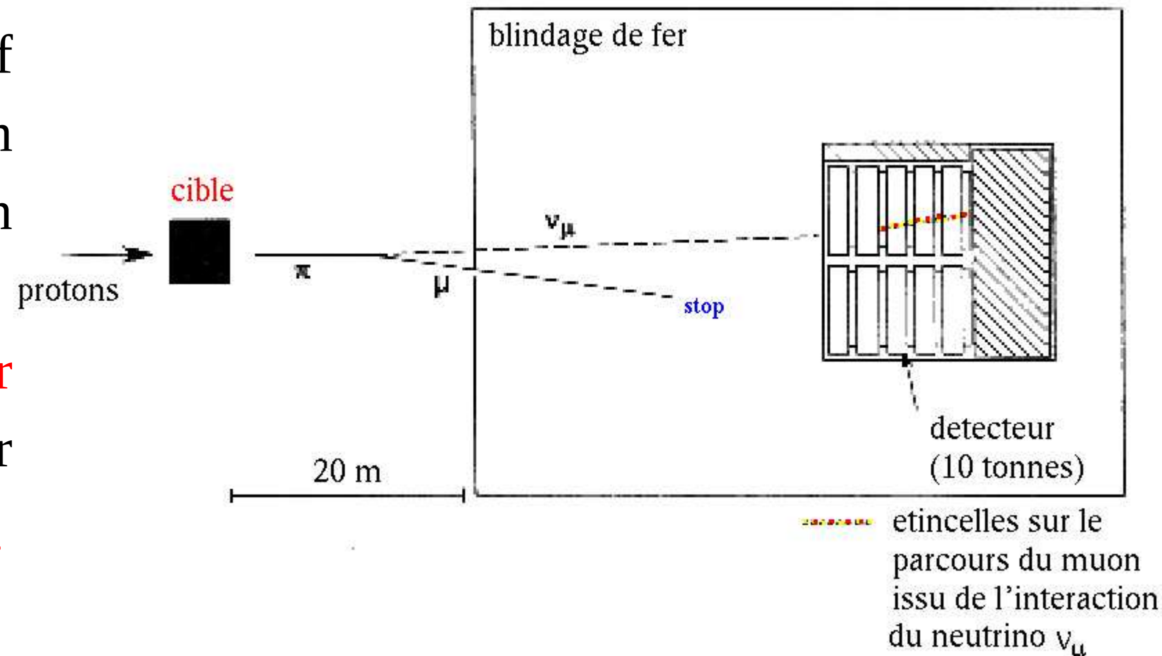
The Other Flavours

ν coming out of a nuclear reactor is $\overline{\nu}_e$ because it is emitted together with an e^-

Question: Is it different from the muon type neutrino ν_μ that could be associated to the muon? Or is this difference a theoretical arbitrary convention?

In 1959 M. Schwartz thought of producing an intense ν beam from π's decay (produced when a proton beam of GeV energy hits matter)

Schwartz, Lederman, Steinberger and Gaillard built a spark chamber (a 10 tons of neon gas) to detect ν_μ



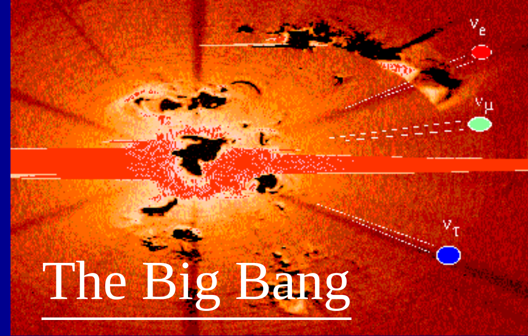
They observe 40 ν interactions: in 6 an e^- comes out and in 34 a μ^- comes out.

If $\nu_\mu \equiv \nu_e \Rightarrow$ equal numbers of μ^- and $e-$ $\Rightarrow$ Conclusion: ν_μ is a different particle

In 1977 Martin Perl discovers the particle tau $\equiv$ the third lepton family.

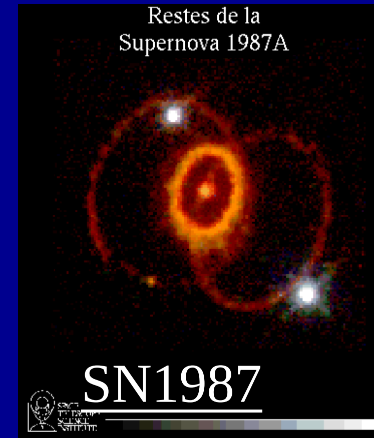
The ν_τ was observed by DONUT experiment at FNAL in 1998 (*officially* in Dec. 2000).

Sources of ν's



$\rho_\nu = 330/\mathrm{cm}^3$

E_ν =0.0004 eV



$E_\nu \sim$ MeV

The Sun

ν_e

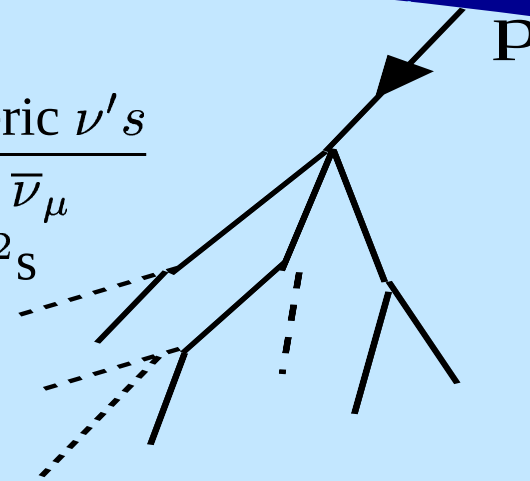
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\mathrm{cm}^2\mathrm{s}$

$E_\nu \sim$ 0.1–20 MeV

Atmospheric $\nu' s$

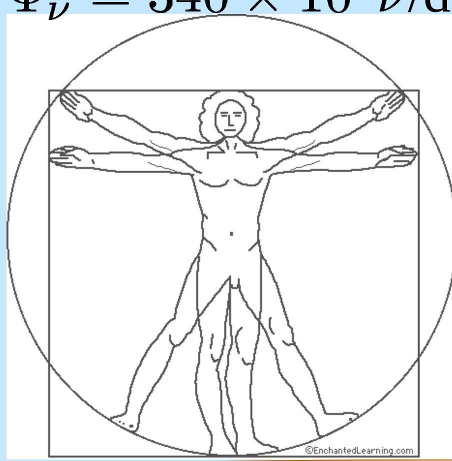
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1 \nu/\mathrm{cm}^2\mathrm{s}$



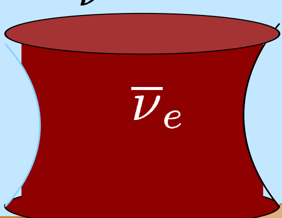
Human Body

$\Phi_\nu = 340 \times 10^6 \nu/\mathrm{day}$



Nuclear Reactors

$E_\nu \sim$ few MeV



Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^6 \nu/\mathrm{cm}^2\mathrm{s}$

Accelerators

$E_\nu \simeq$ 0.3–30 GeV

Fermilab

Discovering the Nature of Nature

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ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- LEP tested this symmetry to 1% precission and the missing particles t, ν_τ

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	n^i_R

Notice there is no ν_R

$\Rightarrow$ Accidental global symmetry:

$B \times L_e \times L_\mu \times L_\tau$

- When SM was invented upper bounds on m_ν

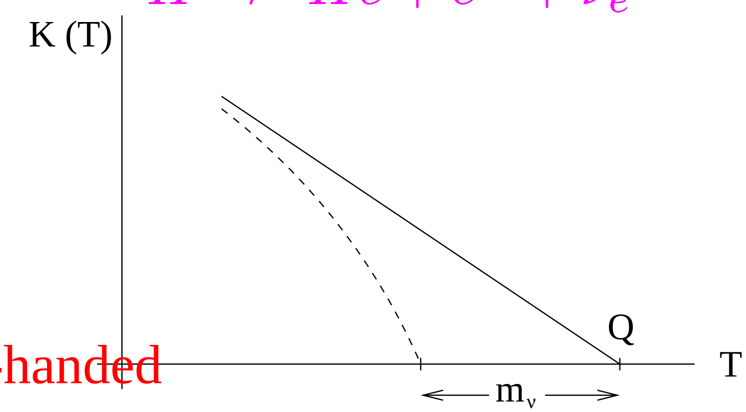
$m_{\nu_e} < 2.2$ eV

$m_{\nu_\mu} < 190$ KeV $\quad (\pi \to \mu \nu_\mu)$

$m_{\nu_\tau} < 18.2$ MeV $\quad (\tau \to n \pi \nu_\tau)$

- Neutrinos are conjured to be massless and left-handed

$${}^3H \to {}^3He + e^- + \bar{\nu}_e$$



Neutrino Helicity

- The neutrino helicity was measured in 1957 in a experiment by Goldhaber et al.

- Using the electron capture reaction
$$e^- + \,^{152}Eu \to \nu + \,^{152}Sm^* \to \,^{152}Sm + \gamma$$
with $J(^{152}Eu) = J(^{152}Sm) = 0$ and $L(e^-) = 0$

- Angular momentum conservation $\Rightarrow$
$$\left\{ \begin{array}{ccl} J_z(e^-) & = & J_z(\nu) + J_z(Sm^*) \\ & = & J_z(\nu) + J_z(\gamma) \\ \pm\frac{1}{2} & = & \pm\frac{1}{2} \quad \pm 1 \;\Rightarrow\; \boxed{J_z(\nu) = -\frac{1}{2} J_z(\gamma)} \end{array} \right.$$

- Nuclei are heavy $\Rightarrow \vec{p}(^{152}Eu) \simeq \vec{p}(^{152}Sm) \simeq \vec{p}(^{152}Sm^*) = 0$

  So momentum conservation $\Rightarrow \vec{p}(\nu) = -\vec{p}(\gamma) \Rightarrow$ ν helicity= γ helicity

- Goldhaber et al found γ had negative helicity $\Rightarrow$ ν has helicity -1

Thus so far ν was a particle with $m_\nu = 0$ and left handed.

(because for massless fermions helicity$\equiv$ chirality...)

Helicity versus Chirality

- The Lagrangian of a massive free fermion ψ is $\mathcal{L} = \overline{\psi}(x)(i\gamma\cdot\partial - m)\psi(x)$

- The Equation of Motion is: $i\frac{\partial}{\partial t}\psi = H\psi = \gamma^0\left(\vec{\gamma}.\vec{p} + m\right)\psi$

- In momentum space this equation has 4 possible solutions

$$(\gamma\cdot p - m)u_s(\vec{p}) = 0 \qquad\qquad (\gamma\cdot p + m)v_s(\vec{p}) = 0$$

$s = \pm\frac{1}{2}$ and $u_s(\vec{p})$ and $v_s(\vec{p})$ are the four component Dirac spinors.

- For this free fermion $[H,\vec{J}]$=0 and $[\vec{p},\vec{J}.\vec{p}]$=0 with $\vec{J} = \vec{L} + \frac{\vec{\sigma}}{2}$ $\qquad (\sigma^i = -\gamma^0\gamma^5\gamma^i)$

$\Rightarrow$ we can chose $u_s(\vec{p})$ and $v_s(\vec{p})$ to be eigenstates also of the helicity projector

$$P_\pm = \frac{1 \pm 2\vec{J}\frac{\vec{p}}{|p|}}{2} = \frac{1 \pm \vec{\sigma}\frac{\vec{p}}{|p|}}{2}$$

So the helicity states can be chosen as physical states for free fermions

Helicity versus Chirality

- We define the chiral projections $P_{R,L} = \frac{1 \pm \gamma_5}{2}$

$$\psi = \psi_L + \psi_R \qquad \psi_L = \frac{1-\gamma_5}{2}\psi \qquad \psi_R = \frac{1+\gamma_5}{2}\psi$$

- In the SM the neutrino interaction terms

$$\mathcal{L}_{int} = \frac{i\,g}{\sqrt{2}}[j^+_\mu W^-_\mu + j^-_\mu W^+_\mu] + \frac{i\,g}{\sqrt{2}\cos\theta_W} j^Z_\mu Z_\mu$$

$$j^-_\mu = \bar{l}_\alpha \gamma_\mu P_L \nu_\alpha \quad \alpha = e, \mu, \tau \quad j^+_\mu = j^{-\,\dagger}_\mu \quad j^Z_\mu = \bar{\nu}_\alpha \gamma_\mu P_L \nu_\alpha$$

$\Rightarrow$ ν_L interact and ν_R do not interact

$\Rightarrow$ chirality states are physical states for weak interactions

- For massless fermions the Dirac equation can be written

$$\vec{\sigma}\,\vec{p}\,\psi = -\gamma^0\gamma^5\vec{\gamma}\,\vec{p}\,\psi = -\gamma^0\gamma^5\gamma^0 E\,\psi = \gamma^5 E\psi \Rightarrow$$ For $m = 0$ $P_\pm = P_{R,L}$

$\Rightarrow$ Helicity and chirality states are the same for massless fermions.

Helicity versus Chirality

- For massive fermions the chiral states are a combination of both helicity states.

$$P_{R,L} = P_{\pm} + \mathcal{O}(\frac{m}{p})$$

- Let's do the following *gdanken* experiment:

– Set a ν state with its spin looking down

(1st) Let's assume it moves up (it has helicity -1) till it hits a target

(2nd) Let's assume it moves down (it has helicity +1) till it hits a target

- If $m_\nu = 0$: (1) the upgoing $\nu \equiv \nu_L$ produces e^-

(2) down we see nothing

- If $m_\nu \neq 0$: (1) the upgoing ν $\equiv$ mostly ν_L produces e^-

(2) the downgoing ν n$\equiv$ small ν_L component produces few e^-

Dirac versus Majorana Neutrinos

- In the SM neutral bosons can be of two type:
  - Their own antiparticle such as γ, π^0 ...
  - Different from their antiparticle such as K^0, $\bar{K}^0$...
- In the SM ν are the only *neutral fermions*

$\Rightarrow$ OPEN QUESTION: are neutrino and antineutrino the same or different particles?

$*$ ANSWER 1: ν different from anti-ν $\Rightarrow$ ν is a *Dirac* particle (like e)

$\Rightarrow$ It is described by a *Dirac* field $\nu(x) = \sum_{s,\vec{p}} \left[a_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + b_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right]$

$\Rightarrow$ And the charged conjugate neutrino field $\equiv$ the antineutrino field

$$\nu^C = \mathcal{C}\,\nu\,\mathcal{C}^{-1} = \eta_C^\star \sum_{s,\vec{p}} \left[b_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right] = -\eta_C^* \, C \, \overline{\nu}^T$$

$(C = i\gamma^2\gamma^0)$

which contain two sets of creation–annihilation operators

$\Rightarrow$ These two fields can rewritten in terms of 4 chiral fields

ν_L , ν_R , $(\nu_L)^C$, $(\nu_R)^C$ with $\nu = \nu_L + \nu_R$ and $\nu^C = (\nu_L)^C + (\nu_R)^C$

Dirac versus Majorana Neutrinos

$*$ ANSWER 2: ν same as anti-ν $\Rightarrow$ ν is a *Majorana* particle : $\nu_M = \nu_M^C$

$$\Rightarrow \eta_C^\star \sum_{s,\vec{p}} \left[b_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right] = \sum_{s,\vec{p}} \left[a_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + b_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right]$$

$\Rightarrow$ So we can rewrite the field $\nu_M = \sum_{s,\vec{p}} \left[a_s(\vec{p}) u_s(\vec{p}) e^{-ipx} + \eta_C^\star a_s^\dagger(\vec{p}) v_s(\vec{p}) e^{ipx} \right]$

which contains only one set of creation–annihilation operators

$\Rightarrow$ A Majorana particle can be described with only 2 independent chiral fields:

ν_L and $(\nu_L)^C$ which verify $\nu_L = (\nu_R)^C$ $(\nu_L)^C = \nu_R$

- In the SM the interaction term for neutrinos

$$\mathcal{L}_{int} = \frac{i\,g}{\sqrt{2}} [(\bar{l}_\alpha \gamma_\mu P_L \nu_\alpha) W_\mu^- + (\bar{\nu}_\alpha \gamma_\mu P_L l_\alpha) W_\mu^+] + \frac{i\,g}{\sqrt{2}\cos\theta_W} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\alpha) Z_\mu$$

Only involves two chiral fields $P_L\,\nu = \nu_L$ and $\overline{\nu}\,P_R = \eta_C (\nu_L)^{C^T} C^\dagger$

$\Rightarrow$ Weak interaction cannot distinguish if neutrinos are Dirac or Majorana

The difference arises from *the mass term*

ν Mass Terms

• A fermion mass can be seen as at a Left-Right transition

$$m_f \overline{f_L} f_R + h.c. \quad \text{(this is not } SU(2)_L \text{ gauge invariant)}$$

• In the Standard Model mass comes from *spontaneous symmetry breaking* via Yukawa interaction of the left-handed doublet ψ_L with the right-handed singlet l_R:

$$\mathcal{L}_Y^{(\ell)} = -\frac{\sqrt{2}}{v}\overline{\psi_{l\,L}} M^{(\ell)} \ell_R \phi + \text{h.c.} \quad \phi = \text{the scalar doublet}$$

• After spontaneous symmetry breaking

$$\phi \stackrel{SSB}{\rightarrow} \left\{ \begin{array}{c} 0 \\ \frac{v+H}{\sqrt{2}} \end{array} \right\} \Rightarrow \mathcal{L}_{\text{mass}}^{(\ell)} = -\bar{\ell}_L M^{(\ell)} \ell_R + \text{h.c.}$$

$M^{(\ell)}$= Dirac mass matrix for charged leptons

• ν's do not participate in QED or QCD and only ν_L is relevant for weak interactions
$\Rightarrow$ there is no *dynamical* reason for introducing ν_R, so

How can we generate a mass for the neutrino?

ν Mass Terms: Dirac Mass

OPTION 1:

• One introduces ν_R which can couple to the lepton doublet by Yukawa interaction

$$\mathcal{L}_Y^{(\nu)} = -\frac{\sqrt{2}}{v}\overline{\psi_L} M^{(\nu)} \nu_R \tilde{\phi} + \text{h.c.} \qquad (\tilde{\phi} = i\tau_2 \phi^*)$$

• Under spontaneous symmetry-breaking,

$$\mathcal{L}_Y^{(\nu)} \Rightarrow \mathcal{L}_{\text{mass}}^{(\text{Dirac})} = -\overline{\nu_L} M_D^\nu \nu_R + \text{h.c.} \equiv -\frac{1}{2}(\overline{\nu}_L M_D^\nu \nu_R + \overline{(\nu_R)^c} M_D^{\nu\,T} (\nu_L)^c) + \text{h.c.}$$

M_D^ν =Dirac mass for neutrinos

• $\mathcal{L}_{\text{mass}}^{(\text{Dirac})}$ involves the four chiral fields ν_L , ν_R , $(\nu_L)^C$, $(\nu_R)^C$

$\Rightarrow$ The eigenstates of M_D^ν are Dirac particles (same as quarks and charged leptons)

$\Rightarrow$ Total Lepton number is conserved *by construction* (not *accidentally*):

$$U(1)_L\, \nu = e^{i\alpha}\, \nu \quad \text{and} \quad U(1)_L\, \overline{\nu} = e^{-i\alpha}\, \overline{\nu}$$
$$U(1)_L\, \nu^C = e^{-i\alpha}\, \nu^C \quad \text{and} \quad U(1)_L\, \overline{\nu^C} = e^{i\alpha}\, \overline{\nu^C}$$

ν Mass Terms: Majorana Mass

OPTION 2:

• One does not introduce ν_R but uses that the field $(\nu_L)^c$ is right-handed, so that one can write a Lorentz-invariant mass term

$$\mathcal{L}^{(\mathrm{Maj})}_{\mathrm{mass}} = -\frac{1}{2}\overline{\nu_L} M^{\nu}_{M} \nu^c_L + \mathrm{h.c.}$$

M^{ν}_{M} =Majorana mass for neutrinos

• But under any $U(1)$ symmetry

$$U(1)\,\nu^c = e^{-i\alpha}\,\nu^c \quad \text{and} \quad U(1)\,\overline{\nu} = e^{-i\alpha}\,\overline{\nu}$$

$\Rightarrow$ it can only appear for particles without electric charge

$\Rightarrow$ Total Lepton Number is not conserved

$\Rightarrow$ The eigenstates of M^{ν}_{M} are Majorana particles (verify $\nu^c_i = \nu_i$)

$\Rightarrow$ But $SU(2)_L$ gauge invariance is broken!!!

General $SU(2)_L$ invariant ν Mass Terms

OPTION 3:

- Introduce ν_{R_i} ($i=1,m$) and write all Lorentz and $SU(2)_L$ invariant mass term

$$\mathcal{L}_Y^{(\nu)} = -\frac{\sqrt{2}}{v}\overline{\psi_{L,j}} M^*_{D,ji}\nu_{R,i}\tilde{\phi} - \frac{1}{2}\overline{\nu_{R,j}} M_{N,ji}\nu^c_{R,i} + \text{h.c.}$$

- Under spontaneous symmetry-breaking

$$\begin{aligned}
\mathcal{L}^{(\nu)}_{\text{mass}} &= -\overline{\nu_{L,j}} M^*_{D,ji}\nu_{R,i} - \frac{1}{2}\overline{\nu_{R,j}} M_{N,ji}\nu^c_{R,i} + \text{h.c.} \\
&= -\frac{1}{2}(\overline{\nu_{R,j}} M^T_{D,ji}\nu_{L,i} + \overline{\nu^c_{L,j}} M_{D,ji}\nu^c_{R,i}) - \frac{1}{2}\overline{\nu_{R,j}} M_{N,ji}\nu^c_{R,i} + \text{h.c.} \\
&\equiv -\frac{1}{2}\overline{\vec{\nu}^c} M^\nu \vec{\nu} + \text{h.c.}
\end{aligned}$$

with $\vec{\nu} = \begin{pmatrix} \nu_{L,k} \\ \nu^c_{R,l} \end{pmatrix}$ and $M^\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$

- In general if $M_N \neq 0 \Rightarrow$ 3+m Majorana neutrino states (verify $\nu_i^c = \nu_i$)
  how many are light depends on hierarchy between M_D and M_N

$\Rightarrow$ Total Lepton Number is not conserved

The See-Saw Mechanism

- A particular realization of OPTION 3: Add 3 ν_{R_i} so

$$\begin{aligned}
\mathcal{L}^{(\nu)}_{\rm mass} &= -\overline{\nu_{L,j}} m_{D,ji} \nu_{R,i} - \frac{1}{2}\overline{\nu_{R,j}} M_{N,ji} \nu^c_{R,i} + \text{h.c.} \\
&= -\frac{1}{2}(\overline{\nu_{R,j}} m_{D,ji} \nu_{L,i} + \overline{\nu^c_{L,j}} m_{D,ij} \nu^c_{R,i}) - \frac{1}{2}\overline{\nu_{R,j}} M_{N,ji} \nu^c_{R,i} + \text{h.c.} \\
&\equiv -\frac{1}{2}\overline{\vec{\nu}^c} M^\nu \vec{\nu} + \text{h.c.}
\end{aligned}$$

with $\vec{\nu} = \begin{pmatrix} \nu_{L,k} \\ \nu^c_{R,l} \end{pmatrix}$ and $M^\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$

- Assume $M_N \gg m_D \Rightarrow$
  - 3 Heavy ν's of mass $m_{\nu_H} \sim M_N$
  - 3 light neutrinos ν's of mass $m_{\nu_l} = m_D^T M_N^{-1} m_D$
  - The heavier ν_H the lighter $\nu_l \Rightarrow$ See-Saw Mechanism
  - Arises in many extensions of the SM: SO(10) GUTS, Left-right...

Lepton Mixing

• Charged current and mass for 3 charged leptons ℓ_i and N neutrinos ν_j in weak basis

$$\mathcal{L}_{CC} + \mathcal{L}_M = -\frac{g}{\sqrt{2}}\overline{\ell_L^W}\gamma^\mu \nu^W W_\mu^+ - \overline{\ell_L^W} M_\ell \ell_R^W - \frac{1}{2}\overline{\nu^{cW}} M_\nu \nu^W + \text{h.c.}$$

• Changing to mass basis by rotations

$$\ell_L^W = V_L^\ell \ell_L \qquad \ell_R^W = V_R^\ell \ell_R \qquad \nu^W = V^\nu \nu$$

$$V_L^{\ell\,\dagger} M_\ell V_R^\ell = \text{diag}(m_e, m_\mu, m_\tau) \quad V^{\nu\,\dagger} M_\nu^\dagger M_\nu V^\nu = \text{diag}(m_1^2, m_2^2, m_3^2, \dots, m_N^2)$$

$V_{L,R}^\ell \equiv$ Unitary 3×3 matrices and $V^\nu \equiv$ Unitary $N \times N$ matrix.

• The charged current in the mass basis

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\overline{\ell_L^i}\,\gamma^\mu\, U_{\text{LEP}}^{ij}\, \nu_j\, W_\mu^+$$

$U_{\text{LEP}} \equiv 3 \times N$ matrix

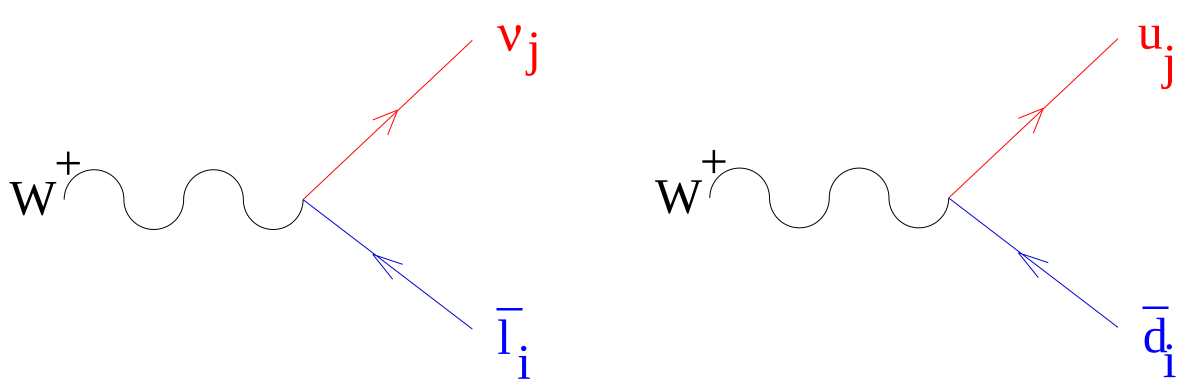
$$\boxed{U_{\text{LEP}}^{ij} = \sum_{k=1}^{3} V_L^{\ell\,\dagger\,ik}\, V^{\nu\,kj}}$$

Effects of ν Mass

- Neutrino masses can have kinematic effects

- Also if neutrinos have a mass the charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{LEP}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j + U^{ij}_{CKM}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) + h.c.$$



- SM gauge invariance *does not imply* $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$ symmetry

- Total lepton number $U(1)_L = U(1)_{Le+L_\mu+L_\tau}$ can be or cannot be still a symmetry depending on whether neutrinos are Dirac or Majorana

Neutrino Mass Scale: Tritium β Decay

• Fermi proposed a kinematic search of ν_e mass from beta spectra in ^3H beta decay

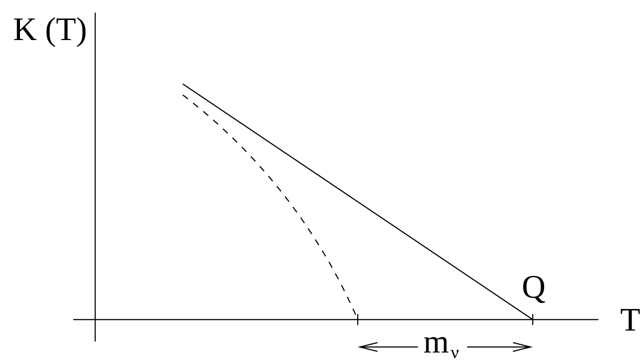
$^3H \to ^3He + e + \overline{\nu}_e$ • For "allowed" nuclear transitions, the electron spectrum is given by phase space alone

$$K(T) \equiv \sqrt{\frac{dN}{dT}\frac{1}{Cp\,E\,F(E)}} \propto \sqrt{(Q-T)\sqrt{(Q-T)^2 - m_\nu^2}}$$

$T = E_e - m_e$, Q= maximum kinetic energy, (for ^3H beta decay $Q = 18.6$ KeV)

• $m_\nu \neq 0 \Rightarrow$ distortion from the straight-line at the end point of the spectrum

$$m_\nu = 0 \;\Rightarrow\; T_{\max} = Q$$
$$m_\nu \neq 0 \;\Rightarrow\; T_{\max} = Q - m_\nu$$



– At present only a bound: $m_{\nu_e}^{eff} \equiv \sum m_j |U_{ej}|^2 < 2.2$ eV (at 95 % CL)
(Mainz & Troisk experiments)

– Katrin proposed to improve present sensitivity to $m_{eff}^{\beta} \sim 0.3\,\text{eV}$

Neutrino Mass Scale: Other Channels

Muon neutrino mass

- From the two body decay at rest

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$

- Energy momentum conservation:

$$m_\pi = \sqrt{p_\mu^2 + m_\mu^2} + \sqrt{p_\mu^2 + m_\nu^2}$$
$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2 + m_\mu \sqrt{p^2 + m_\pi^2}$$

- Measurement of p_μ plus the precise knowledge of m_π and $m_\mu \Rightarrow m_\nu$
- The present experimental result bound:

$$\boxed{m_{\nu_\mu}^{eff} \equiv \sum m_j |U_{\mu j}|^2 < 190 \text{ KeV}}$$

Tau neutrino mass

- The τ is much heavier $m_\tau = 1.776$ GeV

$\Rightarrow$ Large phase space $\Rightarrow$ difficult precision for m_ν

- The best precision is obtained from hadronic final states

$$\tau \to n\pi + \nu_\tau \quad \text{with } n \geq 3$$

- Lep I experiments obtain:

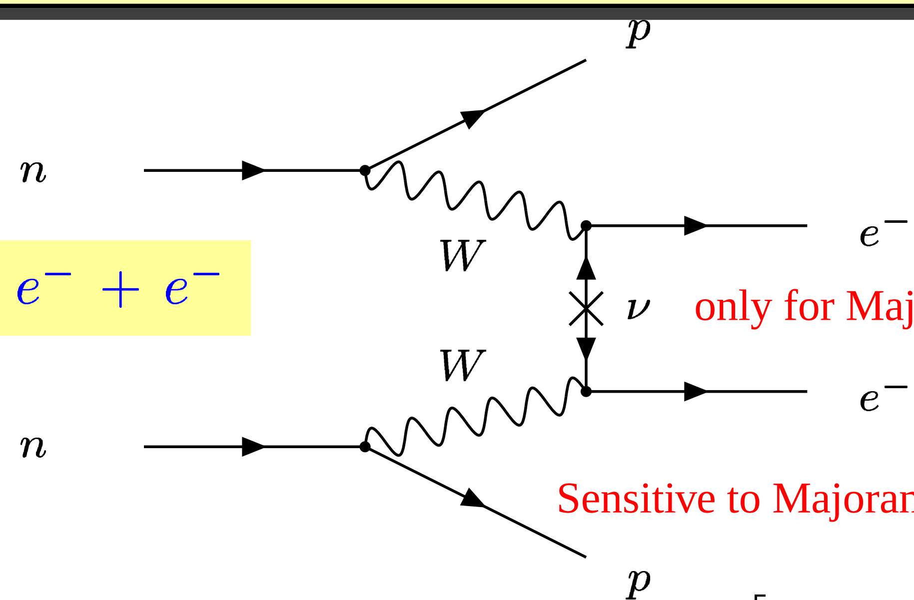
$$\boxed{m_{\nu_\tau}^{eff} \equiv \sum m_j |U_{\tau j}|^2 < 18.2 \text{ MeV}}$$

$\Rightarrow$ If mixing angles U_{ej} are not negligible

Best kinematic limit on Neutrino Mass Scale comes from Tritium Beta Decay

Neutrino Mass Scale: ν-less Double-β Decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$



only for Majorana ν's

Sensitive to Majorana CP phases

- Amplitude involves the product of two leptonic currents: $\left[\overline{e}\gamma^\mu L \nu\right]\left[\overline{e}\gamma^\mu L \nu\right]$
  - If ν Dirac $\Rightarrow$ ν *annihilates* a *neutrino* and *creates* an *antineutrino*

    $\Rightarrow$ no same state $\Rightarrow$ Amplitude = 0
  - If ν Majorana $\Rightarrow$ $\nu = \nu^c$ *annihilates and creates* a *neutrino=antineutrino*

    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto$ $\nu\,(\nu^c)^T \neq 0$
- Amplitude of ν-less-$\beta\beta$ decay is proportional to $|\langle m_{ee}\rangle| = |\sum U_{ej}^2 m_j|$
  - Present bound: $|\langle m_{ee}\rangle| < 0.35$ eV +theor. uncert. < 1.05 eV (90% CL)
  - Several proposed experiments to reach $|\langle m_{ee}\rangle| \sim 10^{-2}$ eV

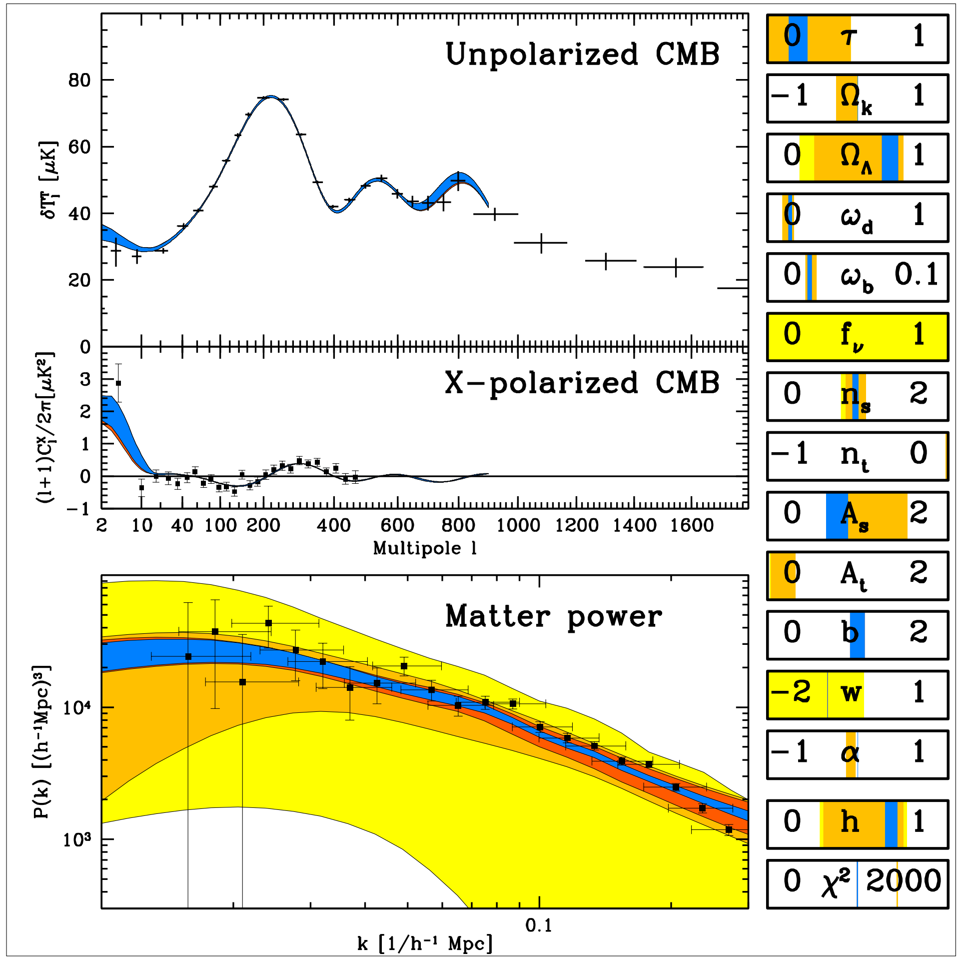
Neutrino Mass Scale in Cosmology

$\sum m_{\nu_i}$ has effects on:

Cosmic Microwave Background Temperature Fluctuations

Most recent from WMAP

Large scale structure:
– 2° Field Galaxy Redshift Survey (2dFGRS)
–Sloan Digital Sky Survey (SDSS)



Tegmark *et. al* astro-ph/0310723

Problem: 13 parameters to be determined!!

$\Rightarrow$ limit on $\sum m_{\nu_i}$ depends on
prior and data used to constraint
other 12 parameters

$\sum m_{\nu_i} \leq 0.7 - 2.1$ eV at 95 % CL

Summary I

- In the SM:
  - Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau \leftrightarrow m_\nu \equiv 0$
  - neutrinos are left-handed ($\equiv$ helicity -1): $m_\nu = 0 \Rightarrow$ chirality $\equiv$ helicity
  - No distinction between Majorana or Dirac Neutrinos
- If $m_\nu \neq 0 \rightarrow$ Need to extend SM

  $\rightarrow$ different ways of adding m_ν to the SM
  - *breaking* total lepton number ($L = L_e + L_\mu + L_\tau$) $\rightarrow$ Majorana ν: $\nu = \nu^C$
  - *conserving* total lepton number $\rightarrow$ Dirac ν: $\nu \neq \nu^C$

  $\rightarrow$ Lepton Mixing$\equiv$ breaking of $L_e \times L_\mu \times L_\tau$
- From direct searches of ν-mass: $m_\nu \leq \mathcal{O}(eV)$

  Question: How to search for $m_\nu \ll \mathcal{O}(eV)$?

  Answer: Tomorrow....