Neutrino BBSM Course

Lecture III

LMU

Spring 2020

It's neutrino, stupid!

$$\boxed{\gamma, \mu, e \leftarrow \nu}$$

$$\left.\begin{array}{l} \theta^+ \to \pi^+ \pi^0 \\ \tau^+ \to \pi^+ \pi^0 \pi^0 \end{array}\right\}$$ pions are pseudo-scal

$$P(3\pi) = - P(2\pi)$$

$\underline{P \text{ is good}} \Rightarrow \boxed{\theta^+ \neq \tau^+}$

$$\left\{\begin{array}{l} m_{\theta^+} \simeq m_{\tau^+} \simeq 490\ \text{MeV} \\ \tau_+ \simeq \tau_- \simeq 100\ \text{cm} \simeq 10^{-8}\ \text{sec} \end{array}\right.$$

$$\boxed{K^+ \equiv \theta^+ = \tau^+}$$

$\boxed{\cancel{P} \text{ maximally}} \Longleftarrow \text{'56}$

$$\boxed{\begin{gathered} J^\mu_w = \bar{u}_L \gamma^\mu d_L + \bar{\nu}_L \gamma^\mu e_L \\ d \to u + e + \bar{\nu}_e \end{gathered}}$$

$$\boxed{\cancel{P} \Longleftrightarrow \cancel{C}}$$

$$\boxed{\begin{gathered} u_L \xleftrightarrow{P} u_R \\ u_L \xleftrightarrow[C]{} i\sigma_2 u_R^* \end{gathered}}$$

$\boxed{CP}$

$\to$ '64 $\cancel{CP}$ in Kaon physics

Symmetries that help formulate theories

- equivalence principle $\Rightarrow$ Einstein
- gauge symmetry in S.M.
- Lorentz inv.

B = baryon number

L = lepton —"—

$\Delta B = 0 \leftarrow$ proton $\Delta B \neq 0$

P = parity

$\Uparrow$ play an important role

'70s $\boxed{m_\nu = 0}$ prejudice

$$\mathcal{L}_D = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$

$$\psi \to e^{i\alpha}\psi \Rightarrow \psi_{L,R} \to e^{i\alpha}\psi_{L,R}$$

$$\psi = \psi_L + \psi_R$$

$\underline{m=0}$

$$\hookrightarrow \quad \bar{\psi}\gamma^\mu\partial_\mu\psi_L = \bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + h.c.$$

$$\psi_{L,R} \to e^{i\alpha}\psi_{L,R}$$

$$\boxed{\psi_L \to e^{i\alpha}\psi_L, \quad \psi_R \to e^{i\beta}\psi_R}$$

$$\underbrace{\psi \to e^{i\beta\gamma_5}\psi}_{\boxed{\text{chiral symmetry}}} \quad \text{axial}$$

<u>isospin</u> $m_n \simeq m_p$

$\Longleftrightarrow SU(2)_I$ <u>almost</u> good

$m_\nu \leq 1\,eV$ | direct limit from KATRIN exp

endpoint of neutron spectrum

$$T_e \simeq Q = M_i - M_f - m_e$$

PDG

$$m_n \simeq m_{\bar{n}} \qquad \frac{\Delta m_n}{m_n} \leq 10^{-18}$$

$$\underset{n}{\uparrow} \qquad \underset{\bar{n}}{\uparrow}$$

$$\mathcal{L}_D = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi - m\bar{\Psi}\Psi \qquad \text{'28}$$

Modern particle physics

$$e \Longrightarrow \bar{e} = \text{positron} \qquad \text{'31}$$

$$(\Psi \longleftrightarrow \Psi^c \equiv C\bar{\Psi}^T)$$

'32 Anderson

Cosmic rays $\bar{e}$

particle $p \longrightarrow \bar{p}$ anti-particle

$$\boxed{m_p = m_n}$$

neutrino — anti neutrino

dipole moment

$$\boxed{\text{Majorana '37}}$$

$$\psi_L \xrightarrow[C]{} (\psi^c)_R \equiv C\bar{\psi}_L^T$$

same particle
Neutral particle

Majorana particle

$$\boxed{\psi_M = \psi_L + C\bar{\psi}_L^T}$$

$$\psi_D = \psi_L + \psi_R = \begin{pmatrix} 0 \\ u_R \end{pmatrix}$$

$$\psi_L = \begin{pmatrix} u_L \\ 0 \end{pmatrix}$$

independent

$$\boxed{\psi_M = \begin{pmatrix} \boxed{u_L} \\ -i\sigma_2 u_L^* \end{pmatrix}}$$

$$C = i\gamma_2 \gamma_0$$

$$\psi^c = i\gamma_2 \psi^*$$

$\frac{1}{2}$ of Dirac $=$ 2 d.o.f.

- $m_D \bar{\psi}\psi = m_D(\bar{\psi}_L \psi_R + \text{h.c.}) = m_D \underbrace{u_L^\dagger u_R}_{\text{Boost}} + \text{h.c.}$

- $\frac{m_M}{2} u_L^T i\sigma_2 u_L + \text{h.c.} = \frac{m_M}{2} u_L^T \epsilon\, u_L + \text{h.c.}$

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$u_1^T \epsilon\, u_2 = \underbrace{|\uparrow\downarrow - \downarrow\uparrow\rangle}_{s=0} = \text{inv.}$$

$\underline{\text{ROT}}$ $\quad i\vec{\sigma}/2 \qquad$ BOOST $\vec{\sigma}/2$

$$m_M\, \psi_L^T C\, \psi_L = m_M\, u_L^T i\sigma_2 u_L$$

$$\psi_L = \begin{pmatrix} u_L \\ 0 \end{pmatrix}$$

$$\mathcal{L}_M = i\, u_L^\dagger \underline{\sigma}^\mu \partial_\mu u_L - \left(\frac{m_M}{2} u_L^T i\sigma_2 u_L + h.c. \right)$$

$$= i\,\bar{\psi}_L \gamma^\mu \partial_\mu \psi_L - \left(\frac{m_M}{2} \psi_L^T C \psi + h.c. \right)$$

$$\cancel{=\tfrac{1}{2}} \underbrace{\left[i\,\bar{\psi}_M \gamma^\nu \partial_\nu \psi_M - m\,\bar{\psi}_M \psi_M \right]}$$

$\Longleftrightarrow$ Dirac

$$\psi_M = \begin{pmatrix} \nu_L \\ -i\sigma_2 \nu_L^* \end{pmatrix} \begin{array}{l} \rightarrow L=1 \\ \rightarrow L=-1 \end{array}$$

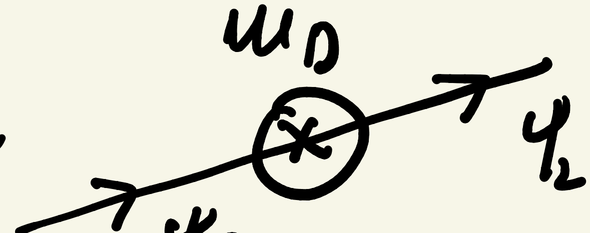
$\nu_M \Longleftrightarrow$ breaks $U(1)_{\text{lepton}}$
$= L$

$$\begin{array}{l} n \longrightarrow p \\ d \longrightarrow u \end{array} \; \underbrace{+\, e + \bar{\nu}_e}$$

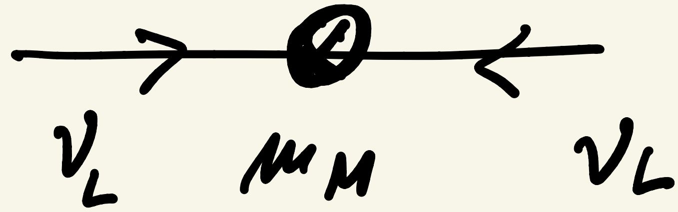
$$\boxed{\Delta L = 0}$$

$$-m_M \underset{L=1}{\nu_L^T} C \underset{L=1}{\nu_L} \qquad \boxed{\Delta L = 2}$$

<u>DIRAC</u> $\bar{\Psi}\Psi$
$= \bar{\Psi}_L \psi_R + h.c.$



Majorana $\quad \nu_L^T \, C \, \nu_L$



$$\boxed{\Delta L = 2}$$

'Furry '38

- Neutrino-less double beta decay ($0\nu 2\beta$)

Digression $\quad e \; (^4 e) \quad \boxed{\nu \to \nu}$

$U(1)_{em} \quad e \to e^{i\alpha} e \Rightarrow \alpha = \alpha(x)$

$\Rightarrow$ messenger | photon

U(1) Lepton

$$\boxed{\begin{aligned} e &\to e^{i\beta} e \\ \nu &\to e^{i\beta} \nu \end{aligned}}$$

Lepton # (L)

U(1)

$\boxed{0\nu 2\beta}$

$^1/_{35}$ Maj

$$\cancel{{}^{76}_{34}\mathrm{Ge} \to {}^{76}_{35}\mathrm{Ar} + e + \bar{\nu}_e}$$

? ?

$$\boxed{m_{Ar} > m_{Ge}}$$

$\boxed{2\beta}$

$$ {}^{76}_{34}\mathrm{Ge} \to {}^{76}_{36}\mathrm{Se} + e + \bar{\nu}_e + e + \bar{\nu}_e $$

? ?

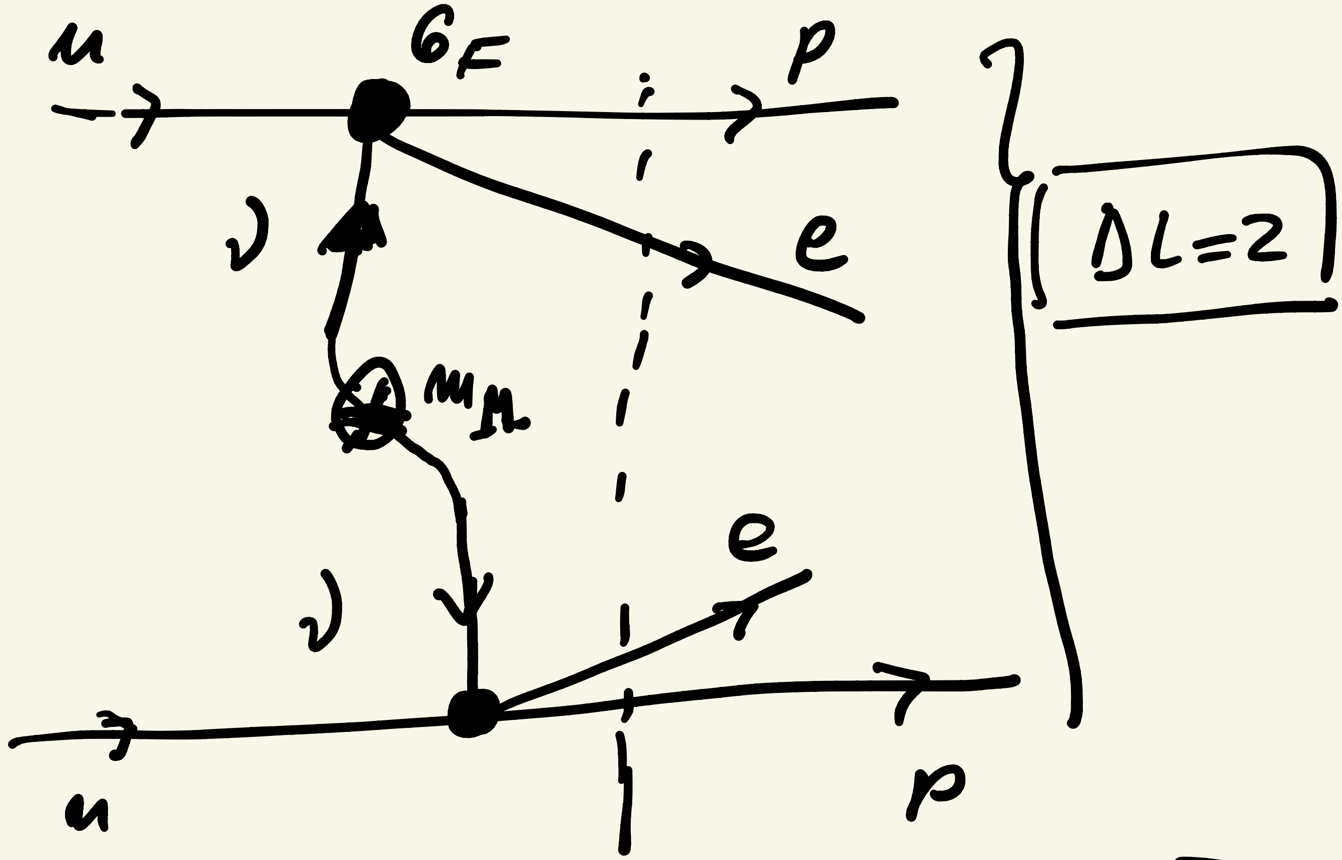
$$m_{Ge} > m_{Se}$$

$$\boxed{\tau_M \simeq 10\,\mathrm{min}}$$ weak

$\tau_K \simeq 10^{-8}$ sec weak

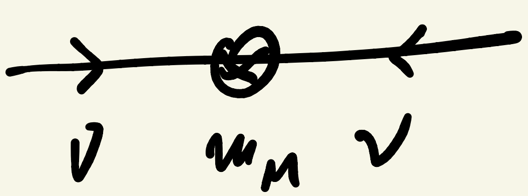
$\underbrace{\tau_n \gg \tau_h}_{\text{small phase space}}$

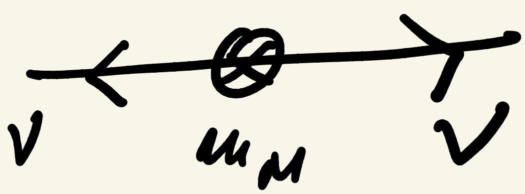
$$\boxed{\tau_{2n} \simeq 10^{21}\,\text{yr}}$$



$$n + n \to p + p + e + e + \bar{\nu}_e + \bar{\nu}_e$$

$$m_M \, \nu_L^T C \, \nu_L \qquad + \qquad m_M \, \nu_L^\dagger C^\dagger \nu_L^*$$





$\beta: \; n \to p + e + \bar{\nu}$

$E_e = \text{continuous}$

$0\nu 2\beta: \quad \boxed{E_e + E_e = Q}$

$$\boxed{A_{0\nu 2\beta} \propto m_\nu^M}$$

$$\boxed{\Rightarrow \; m_\nu^M \leq 1\,\text{eV}}$$

$0\nu 2\beta \neq$ seen

$\tau_{0\nu 2\beta} \geq 10^{25}\,\text{yr}$

Heat powered meter $0\nu 2\beta$

CUORE = heart in Italian

Gran Sasso

MAJORANA

NEMO, GERDA

$0\nu 2\beta$ is a probe of neutrino mass (Majorana)

WRONG

1958

Feinberg, Goldhaber

New Physics???

$SM \Rightarrow m_\nu = 0$

$m_\nu^M \Longleftrightarrow$ New Physics

DIRAC $\nu \Longleftrightarrow 0\nu 2\beta$

$0\nu 2\beta \longleftrightarrow$ LHC

deep connection

probe of NP and m_ν

- $\cancel{L}$ = LNV
- $\cancel{P} \Leftrightarrow$ SM structure

$SU(2) \times U(1)$

$W \; \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R \Rightarrow \boxed{m_\nu = 0}$

$\boxed{\bar{e}_L e_R \Phi}$

Weinberg '67

ν_R

seesaw

Theories of natural phenomena

Deep principle
Minimality ✓

SM = minimal gauge theory of ew phenomena (weak)

only observed (necessary) states

NO ν_R phantom

1961 Glashow $\underbrace{SO(2) \times U(1)}_{ew}$