Why neutrinos?

LMU Neutrino Course

Spring 2021

13/4/2021

• cool - about;

Sun $\rightarrow$ $10^{10}/\mathrm{cm}^2\,\mathrm{sec}$ neutrinos

mean free path:

$\lambda_{air} \sim 1\,m$

$\lambda_e \simeq cm$ (electron)

$\lambda_\nu \simeq 10^{20}\,cm$ $\qquad E_\nu \simeq MeV$

$(m_e \simeq 0.5\,MeV)$

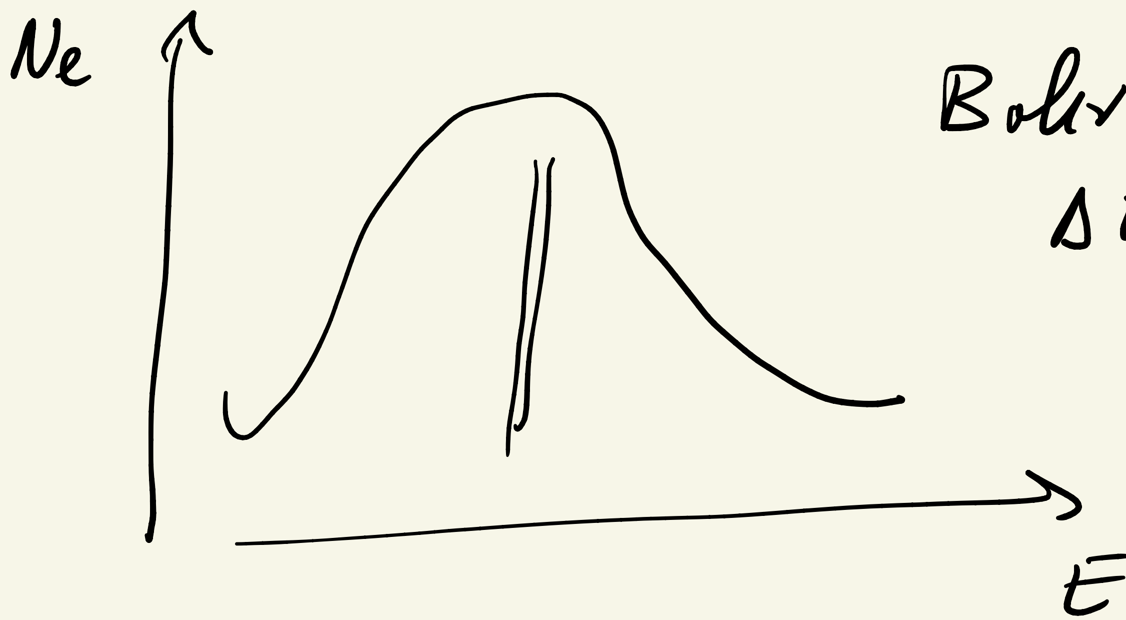
open the door to

new physics

• $n \to p + e$ 1920's

missing energy

E_e = fixed



Bohr

$\Delta E \neq 0$!?

Pauli 1930

Postcard !

$\exists \, \nu_e \quad (Q_\nu = 0)$

neutral "light" particle

Fermi Theory 1934

"effective" theory of weak interaction

$$\boxed{\sigma_W \simeq 10^{-44}\,cm^2}$$

$E = 1\,MeV$

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

(β decay)

e = beta

anti-neutrino

$$\boxed{e = \text{lepton}}$$

(lepton = thin)

p, n = hadrons (hadron = stout, heavy)

$$\boxed{\text{Lepton (L) \# = conserved}}$$

$$\boxed{(\text{def.})\quad L(\nu) = 1}$$

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

$$\Delta B \neq 0 \qquad \Delta L \neq 0$$

n, p = baryons (fermions) $s = 1/2$

π, K = mesons (bosons) $s = 0$

- QED $\quad e + e \to e + e$

$$\sigma_{QED} \simeq 10^{-22}\,\mathrm{cm}^2 \qquad E \simeq \mathrm{MeV}$$

Pauli: forgive me, I have sinned!

Cowan Reines 1956

Pauli: "Everything comes to him who knows how to wait."

reactor

Pontecorvo

'40s

Φ (flux) $\simeq 10^{13}/\mathrm{cm}^2\,\mathrm{sec}$

1956

bombshell $\leftarrow$ Lee, Yang (theory)

Wu et al (exp)

$\boxed{P : L \leftrightarrow R}$

$\cancel{P}$ maximally

Lederman,

Garwin

$\Downarrow$

- only ν_L exist

weak int. : only LH fermions

$\psi(e)$: ψ_L, ψ_R

$$\psi_{L,R} \equiv L\,(R)\,\psi$$

$$\underset{(R)}{L} \equiv \frac{1 \pm \gamma_5}{2}$$

QED

$$e\,A_\mu \left[\overline{e_L}\,\gamma^\mu e_L + \overline{e_R}\,\gamma^\mu e_R \right] \quad (P)$$

weak

$$g\,W_\mu^+ \left[\bar{\nu}_L\,\gamma^\mu e_L + \bar{p}_L\,\gamma^\mu u_L \right] \quad (\cancel{P})$$

1983
CERN

V − A

Marshak, Sudarshan
1957

- W boson = messenger of weak int
  photon = 〃 em int.

SU(2) × U(1) = ew S.M

Glashow 1961

Standard Model 1967

Higgs ⇐ Weinberg

$\Downarrow$

$$\boxed{m_\nu = 0}$$

blessing

$\Downarrow$

"curse"

$\Downarrow$

SM is incomplete

(only incompleteness)

$\Downarrow$

(the) door to New Physics (NP)

gauge theory $\Longleftrightarrow$ gauge bosons

as messengers of forces

$U(1)_{em} = QED$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{f} \gamma^\mu D_\mu f$$

$$- m \bar{f} f \qquad (1)$$

$(f \equiv \psi_f)$

∂_μ

$$\boxed{D_\mu = \partial_\mu - ie A_\mu} \qquad (2)$$

$$\boxed{f \to e^{i \alpha(x) Q_{em}} f} \qquad (3)$$

$$Q_{em} f = q_f f$$

em charge

$$q_e = -1, \quad q_p = +1, \quad q_n = 0$$

$$q_\nu = 0$$

$$q_e + q_p = 0 \quad (\leq 10^{-40})$$

(neutrality of universe)

$$\boxed{A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \alpha(x)} \quad (4)$$

$$\boxed{F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (5)}$$

$$F_{0i} \equiv E_i$$

$$F_{ij} = \varepsilon_{ijk} B_k$$

$$\Downarrow$$

$$\boxed{e A_\mu \bar{f} \gamma^\mu Q_{em} f} \qquad \alpha = \alpha(x)$$

$$\Uparrow$$

$$\mathcal{L}_{Dirac} = i\bar{f}\gamma^\mu\partial_\mu f - m\bar{f}f$$

$$f \to e^{i\alpha Q} f \qquad \alpha = \text{const.}$$

$\Downarrow$ generalization

$$G_{SM}(ew) = SU(2)_L \times U(1)_Y$$

$\Downarrow$ (to be done)

$$W_\mu \circlearrowleft \begin{pmatrix} \nu \\ e \end{pmatrix}_L \to U \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$\boxed{\text{flavor} = \nu, e}$ $\therefore$ $\boxed{U^+ U = 1, \ \det U = 1}$

$$\mathcal{L}_{SM} = i \bar{f} \gamma^\mu D_\mu f - \cdots$$

$$D_\mu = \partial_\mu - i g T_a A_\mu^a \cdots$$

$$U = e^{i \theta_a(x) T_a}$$

Euler

$$[T_a, T_b] = i \varepsilon_{abc} T_c$$

$$T_a \equiv \frac{\sigma_a}{2} \qquad a = 1, 2, 3$$

$$A_\mu^1, \; A_\mu^2, \; A_\mu^3$$

$$W_\mu^{\pm} = \frac{A_\mu^1 \mp i A_\mu^2}{\sqrt{2}}$$

$$\boxed{\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}}$$

$$\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\boxed{\text{SM}}$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \cancel{\nu_R}$$

$$e_R$$

A_μ (QED) $\qquad \bar{f} \equiv f^\dagger \gamma^0$

$$\boxed{\text{mass} \quad m\bar{f}f = m f^\dagger \gamma_0 f = m(\bar{f}_L f_R + \bar{f}_R f_L)}$$

- $\{\gamma^\mu, \gamma^\nu\} = 2 g^{\mu\nu}$

$$g^{\mu\nu} \equiv \eta^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$$

$$\gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}, \quad \gamma^0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\Sigma_{\mu\nu} = \frac{1}{4i} [\gamma_\mu, \gamma_\nu]$$

$$[\Sigma_{\mu\nu}, \Sigma_{\alpha\beta}] = g_{\mu\alpha} \Sigma_{\nu\beta} \; - - \cdots$$

(Lorentz)

$$\boxed{d=4: \quad \psi\ (\text{spinor}) \to \Lambda\,\psi}$$

$$\Lambda \equiv \exp\left(i\, \theta_{\mu\nu} \Sigma^{\mu\nu}\right)$$

6   6

(AS)

$$\gamma_5 \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\{\gamma_5, \gamma_\mu\} = 0, \quad \boxed{\gamma_5^2 = 1}$$

$$\Downarrow$$

$$[\gamma_5, \Sigma_{\mu\nu}] = 0$$

$$\left(\gamma_5 \overset{?}{=} \pm i\, \gamma_0 \gamma_1 \gamma_2 \gamma_3\right)$$

$$\Downarrow$$

$$\boxed{\begin{gathered} L(R) = \frac{1 \pm \gamma_5}{2} \\ [L(R), \Sigma_{\mu\nu}] = 0 \\ L^2 = L, \; R^2 = R, \; LR = 0 \end{gathered}}$$

$$L \equiv \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad R \equiv \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

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

(electron)

(D = Dirac)

u_L, u_R = fundamental entities

$$\mathcal{L}_{kin} = i\,\bar{\psi}_D \gamma^\mu \partial_\mu \psi_D =$$

$$= i\,\bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + i\,\bar{\psi}_R \gamma^\mu \partial_\mu \psi_R$$

L stays L

R stays R

$\boxed{1928}$

$$\mathcal{L}_D = \mathcal{L}_{kin} - m\,\bar{\psi}\psi =$$

$$= i\,\bar{\psi}\gamma^\mu \partial_\mu \psi - m\,\bar{\psi}\psi$$

$$\Downarrow$$

$$\boxed{i\gamma^\mu \partial_\mu \psi = m\psi}$$

(Dirac equation)

$$\Downarrow$$

$$\Psi(x) = e^{ip\cdot x}\,\tilde{\Psi}(p)$$

$$p\cdot x = px = p^{\mu}x_{\mu}$$

$$\Rightarrow \quad p^{\mu}\gamma_{\mu}\,\tilde{\Psi}(p) = m\,\tilde{\Psi}(p) \Big/$$

Jgue

$$p^{\mu}p^{\nu}\,\gamma_{\mu}\gamma_{\nu}\,\tilde{\Psi}(p) = m^{2}\,\tilde{\Psi}(p)$$

$$\parallel$$

$$\frac{1}{2}\{\gamma^{\mu},\gamma^{\nu}\}$$

$$\Downarrow$$

$$p^{\mu}p_{\mu} \equiv p^{2} = m^{2}$$

$$\boxed{E^{2} = \vec{p}^{\,2} + m^{2}} \quad (\text{def.})$$

$$\cdot\ m\bar{f}f = m(f_L^{\dagger} + f_R^{\dagger})\gamma^0(f_L + f_R)$$

$$= m\Big(f_L^{\dagger}\gamma^0 f_L + L\leftrightarrow R \quad +$$

$$+ f_L^{\dagger}\gamma^0 f_R + L\leftrightarrow R\Big)$$

$$= m\left(f^{\dagger} L\gamma^0 L f + L\leftrightarrow R\right) \quad (1)$$

$$+ m\left(f^{\dagger} L\gamma^0 R f + L\leftrightarrow R\right) \quad (2)$$

$$= m\left(f^{\dagger}\gamma^0 \cancel{RL} f + L\leftrightarrow R\right) \quad (1)$$

$$+ m\left(f^{\dagger}\gamma^0 RRf + L\leftrightarrow R\right) \quad (2)$$

$$= m\, f^{\dagger}\gamma^0(R+L)f = m\bar{f}f$$

$$\boxed{m\bar{f}f = m(\bar{f}_R f_L + \bar{f}_L f_R)}$$

Dirac mass

$$\Downarrow$$

$$\cancel{\exists} \quad \nu_R \quad \text{in SM}$$

$$\Downarrow$$

$$\boxed{m_\nu = 0}$$

SM = a theory of ew processes and particles that undertake them

$$\underbrace{SU_L(2) \times U_Y(1)}_{\text{particles carry quantum numbers under } G_{SM}} \equiv G_{SM}$$

ν_R = phantom —

— knows nothing about $SU(2) \times U(1)$

$$\left.\begin{aligned} T_a \nu_R &= 0 \\ \text{(hyper charge)} \quad Y \nu_R &= 0 \end{aligned}\right\}$$

(ν_R does not interact with gauge bosons)

QED = theory of em processes

(not of ν — $Q_\nu = 0$)

theory of charged particles

$\boxed{\text{who is } \nu_R?}$

Sha | seesaw

$$\underbrace{\begin{pmatrix}\nu\\ e\end{pmatrix}_L + \begin{pmatrix}\nu\\ e\end{pmatrix}_R}_{\Downarrow} \quad \Big| \quad \underbrace{\begin{pmatrix}\nu\\ e\end{pmatrix}_L \quad \nu_R,\ e_R}$$

weak

G_{SM} = gauge group

G_{SM} = gauge group

$\Downarrow$

$$g\, W_\mu^+\, \bar{\nu}_R\, \gamma^\mu\, e_R = g\, W_\mu^+\, \bar{\nu}\, \gamma^\mu\, R\, e$$

$$\Downarrow$$

$\boxed{\text{we must change the gauge group !!}}$

$\boxed{\text{Task = theory of neutrino mass}}$

(Predictive, complete)

$$\Downarrow \quad \boxed{G_{SM} = \overset{g}{SU(2)_L} \times \overset{g'}{U(1)}}$$

$a = 1,2,3 \quad \Downarrow \quad A_\mu^a\, (T_a) \qquad B\, (Y)$

G_{SM} = gauge theory of weak

and em processes

$$\partial_\mu \to D_\mu = \partial_\mu - i g_1 T_a^1 A_\mu^{1a} -$$

$$- i g_2 T_\alpha^2 A_\mu^{2\alpha} - \cdots -$$

(repeated index =

= summed)

$$\Downarrow \qquad W_\mu^\pm = \frac{A_\mu^1 \pm i A_\mu^2}{\sqrt{2}}$$

$A_\mu \Rightarrow$ lives in G_{SM}

= linear combination of

$= f(A_\mu^a, B_\mu) =$

$$= f(A_\mu^3, B_\mu)$$

$$\Longleftrightarrow \quad Q_{em} = \text{linear comb. of}$$

$$T_a, Y$$

SU(2)

U(1)

$$\Downarrow$$

$$\boxed{Q_{em} = T_3 + \frac{Y}{2}}$$

neutral generators

$$\Downarrow$$

$$\boxed{Y = 2\left[Q_{em} - T_3\right]}$$

input

input of theory

leptons: $\begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\boxed{\begin{aligned} T_3\,\nu_L &= \tfrac{1}{2}\,\nu_L \\ T_3\,e_L &= -\tfrac{1}{2}\,e_L \end{aligned}}$

doublet

$$T_3 = \frac{1}{2}\sigma_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\boxed{[T_a, T_b] = i\,\varepsilon_{abc}\,T_c}$$

$\boxed{e_R}$ $\boxed{\begin{aligned} T_3\,e_R &= 0 \\ Y\,e_R &= -2\,e_R \\ e_R &= \text{particle} \end{aligned}}$

$$\boxed{\begin{aligned} Q\,e_R &= -1 \\ Q\,e_L &= -1 \end{aligned}}$$

ν_R : $Q\nu_R = 0$ neutral

(definition)

mass of neutral particles

(Majorana mass)

$W \circlearrowleft \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \Bigg\| \quad e_R \; \| \; \nu_R$

$Q\nu_R = 0, \; T_3 \nu_R = 0$

$\Downarrow$

$Y\nu_R = 0$

$\Downarrow$

$\boxed{\nu_R \neq \text{usual particles}}$