

Neutron Physics

Lecture XVIII

LMV

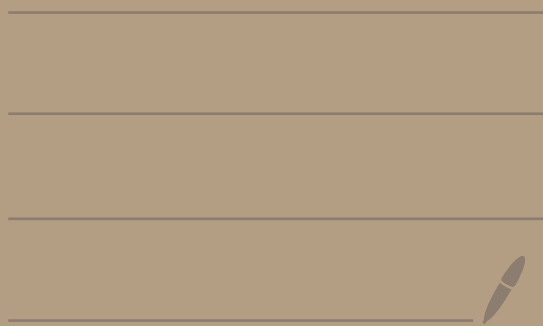
Summer 2021



Neutrino Physics Course

Lecture XVIII

11 / 16 / 20 21



LR symmetry

- $G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

A diagram showing two SU(2) groups, SU(2)_L and SU(2)_R, connected by a horizontal double-headed arrow. Below the arrow is the label P(c). Arrows also point from each SU(2) group towards the central arrow.

- (q, l)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$$



$$\begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

- Th'ggg (\$\$B)



$$G_{LR} \longrightarrow G_{SM} \longrightarrow U(1)_{em}$$

$$M_{WR} \simeq M_R$$

$$M_L \simeq M_{W_L}$$



$$\frac{Y}{2} = T_{3R} + \frac{B-L}{2} \iff Q_{em} = T_{3L} + \frac{Y}{2}$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\underbrace{\hspace{10em}}_{M_R} \longrightarrow U(1)_Y$$

• at $M_L \simeq M_W \equiv M_{W_L}$

$$Higgs = \phi \text{ (SM doublet)}$$



$$\bar{\Phi} = (\tilde{\phi}_1 \quad \phi_2)$$

$$\mathcal{L}_Y = \bar{f}_L \gamma_{\mu} \bar{\Phi} f_R + \text{h.c.}$$

$$+ \bar{f}_L \gamma_{\mu} \tilde{\Phi} f_R + \text{h.c.}$$

Q. what Higgs $\rightarrow M_R$?

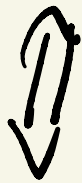
A?? Must be a doublet of $SU(2)_R$?
 (\Leftrightarrow SM sym. breaking)

SM: $\phi \therefore \phi_0 = \begin{pmatrix} 0 \\ v \end{pmatrix}$
 \Downarrow

$$\underbrace{\left(T_{3L} + \frac{Y}{2} \right)}_{Q_{em}} \phi_0 = 0$$

NO T true.

Any Higgs that leaves
 $\frac{Y}{2}$ is equally good!



any Higgs in SM that leaves
 Q_{em} is equally good

Glashow 1961

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



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

⇒ ∃ A ↔ coupled to Q_{em}



⇒ Z with the current

$$J_\mu^Z = \bar{f} \left(T_3 - Q_{em} \sin^2 \theta_w \right) f$$



Whatever Higgs ϕ \therefore

if $Q_{em} \phi_0 = 0$ (unbroken)

$$\Downarrow \quad Q_{em} \equiv T_3 + \frac{Y}{2}$$

$$A_\mu = \sin \theta_w A_\mu^3 + \cos \theta_w B_\mu$$

$$Z_\mu = + \cos \theta_w A_\mu^3 - \sin \theta_w B_\mu$$

- $D_\mu \phi = (\partial_\mu - ig T_a A_\mu^a - ig' \frac{Y}{2} B_\mu) \phi$

\Downarrow

$$D_\mu \phi_0 = \dots (-ig T_3 A_\mu^3 - ig' \frac{Y}{2} B_\mu) \phi_0$$

$$A_\mu^3 \propto \frac{1}{g} A_\mu, \quad B_\mu \propto \frac{1}{g'} A_\mu$$

$A_\mu = \text{massless photon}$

$$\Rightarrow D_\mu \phi_0 \propto -i \left(T_3 \frac{g}{g} A_\mu + \frac{Y}{2} \frac{g'}{g'} A_\mu \right) \phi_0$$

+ ...

$$\propto -i \underbrace{\left(T_3 + \frac{Y}{2} \right)}_{Q_{em}} A_\mu \phi_0 = 0$$

\Downarrow

$$\boxed{m_A = 0}$$

$$A_\mu^3 = \frac{c}{g}, \quad B_\mu = \frac{c}{g'}$$

$$\therefore \frac{c^2}{g^2} + \frac{c^2}{g'^2} = 1$$

$$\Rightarrow c = \frac{gg'}{\sqrt{g^2 + g'^2}}$$

• neutral currents \downarrow $D_\mu = \dots$

$$\bar{f} \gamma^\mu (g T_3 A_\mu^3 + g' \frac{Y}{2} B_\mu) f$$

$$= \bar{f} \gamma^\mu (T_3 \frac{c}{g} g + \frac{Y}{2} \frac{c}{g'} g') A_\mu f$$

$$= \bar{f} \gamma^\mu (T_3 + \frac{Y}{2}) f A_\mu \times \textcircled{c}$$

$$\equiv \bar{f} \gamma^\mu Q_{em} A_\mu \times \textcircled{e} \Rightarrow \boxed{c = e}$$

\Downarrow

$$e = \frac{g g'}{\sqrt{g^2 + g'^2}} = g \sin \theta w$$

$$= g' \cos \theta w$$

$$\tan \theta w = g' / g$$

$$A_\mu^3 = \sin \theta w A_\mu + \dots$$

$$B_\mu = \cos \theta w A_\mu + \dots$$



$$A_\mu = \sin \theta w A_\mu^3 + \cos \theta w A_\mu$$



but $Z \perp A \Rightarrow$

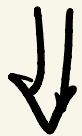
$M_z = ?$

$$Z_\mu = \cos\theta_w A_\mu^3 - \sin\theta_w B_\mu$$

Q. E. D.

$$e = \frac{g g'}{\sqrt{g^2 + g'^2}}$$

$$\Leftrightarrow \frac{1}{e^2} = \frac{1}{g^2} + \frac{1}{g'^2}$$



$$SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$$

any Higgs Δ_R will do,

$$a_1 \text{ long } \frac{y}{z} \Delta_R^0 = 0$$

$$Q_{em} \phi_0 = 0 \text{ in SM}$$

Gauge boson spectrum in LR theory

SM; $Q_{em} \phi_0 = 0 \Rightarrow$

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta_w & \cos\theta_w \\ \cos\theta_w & -\sin\theta_w \end{pmatrix} \begin{pmatrix} A_3 \\ B_\mu \end{pmatrix}$$

$$\tan\theta_w = g'/g$$

$$LR: \quad \frac{1}{2} \Delta_0^R = 0 \Rightarrow$$

$$\begin{pmatrix} B_\mu \\ Z'_\mu \end{pmatrix} = \begin{pmatrix} \sin \Theta_R & \cos \Theta_R \\ \cos \Theta_R & -\sin \Theta_R \end{pmatrix} \begin{pmatrix} A_{3R} \\ \bar{B}_\mu \end{pmatrix}$$

$$D_\mu^{LR} = \not{\partial}_\mu - ig (A_{3L} T_{3L} + A_{3R} T_{3R})_\mu - ig \bar{B}_\mu \frac{B-L}{2} + \dots$$

$$\left[\begin{array}{l} \tan \Theta_R = \bar{g}/g \\ (g_L = g_R \equiv g) \end{array} \right]$$



$$\frac{1}{g'^2} = \frac{1}{g^2} + \frac{1}{\bar{g}^2} \quad (\text{analogous with } 14)$$

$$g' = \frac{g\bar{g}}{\sqrt{g^2 + \bar{g}^2}}$$

$$\tan \theta_w = \frac{g'}{g} = \frac{\bar{g}}{\sqrt{g^2 + \bar{g}^2}}$$

$$(\tan \theta_R = \bar{g}/g)$$

\Rightarrow $\tan \theta_w = \sin \theta_R$

$\theta_w \approx 30^\circ$

$$B'_\mu = \sin \theta_R A_{\mu 3}^R + \cos \theta_R \bar{B}_\mu$$
$$Z_\mu = \cos \theta_R A_{\mu 3}^R - \sin \theta_R \bar{B}_\mu$$

$$B_\mu = \tan \theta_w A_{\mu 3}^R + \sqrt{1 - \tan^2 \theta_w} \bar{B}_\mu \quad (*)$$

$$Z'_\mu = \sqrt{1 - \tan^2 \theta_w} A_{\mu 3}^R - \tan \theta_w \bar{B}_\mu$$

new (heavy) neutral gauge boson

$$Z' \equiv Z_R$$

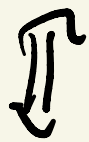
$$A_\mu = \sin \theta_w A_{\mu 3}^L + \cos \theta_w B_\mu \quad (*)$$

$$\rightarrow Z_\mu = \cos \theta_w A_{\mu 3}^L - \sin \theta_w B_\mu$$

- $Z \leftrightarrow Z'$ in LR
- $A \leftrightarrow Z$ in SM

$$J_\mu^A \neq J_\mu^Z$$

$$M_A \neq M_Z$$



$$J_\mu^Z \neq J_\mu^{Z'}$$

$$M_Z \neq M_{Z'}$$

$$M_{Z'} \gtrsim \text{TeV}$$

(LHC)

- example of "funny" world:

$$SU(2)_{L+R} \times U(1)_Y : \boxed{P \text{ good}}$$

\Rightarrow Adjoint Higgs \Rightarrow

$$\boxed{M_Z = 0, M_W \neq 0}$$

How to probe the Higgs?

SM; any Higgs \therefore Rem $\phi_0 = 0$

but; $M_Z / M_W \leftrightarrow$ depends on Higgs

e.g. $M_Z \cos \theta_w = M_W$

$\phi = \text{SM doublet}$

$$\rho \equiv \frac{M_Z^2 \cos^2 \theta_w}{M_W^2} = 1$$

SM: fermions chiral doublet

but BSM (say LR)

issue profound?



complete LR spectrum

$$A_{\mu} = \sin \theta_w A_{\mu 3}^L + \cos \theta_w \tan \theta_w A_{\mu 3}^R + \cos \theta_w \sqrt{1 - \tan^2 \theta_w} \overline{B}_{\mu}$$

$$\Downarrow \quad (\cos 2\theta_w = \cos^2 \theta_w - \sin^2 \theta_w)$$

$$A_{\mu} = \sin \theta_w (A_{\mu 3}^L + A_{\mu 3}^R) + \sqrt{\cos 2\theta_w} \overline{B}_{\mu}$$

$$\Leftrightarrow Q_{em} = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$\begin{aligned} "A_{\mu} \cdot A^{\mu}" &= \sin^2 \theta_w (1+1) + \cos^2 \theta_w - \sin^2 \theta_w \\ &= \sin^2 \theta_w + \cos^2 \theta_w = 1 \end{aligned}$$

$$Z_\mu = \cos \theta_w A_{\mu 3}^L - \sin \theta_w \tan \theta_w A_{\mu 3}^R \\ - \sin \theta_w \sqrt{1 - \tan^2 \theta_w} \bar{B}_\mu$$

$$Z_\mu = \cos \theta_w \left(A_{\mu 3}^L - \tan^2 \theta_w A_{\mu 3}^R \right) \\ - \tan \theta_w \sqrt{\cos 2\theta_w} \bar{B}_\mu$$

$$M_Z \cos \theta_w = M_W$$

b_i - doublet

$$M_Z' / M_W'$$

$$W \equiv W_L$$

$$W' \equiv W_R$$

$$J_\mu^A \equiv \bar{f} \gamma_\mu Q_{ew} f \quad (e A_\mu J_\mu^A)$$

$$J_\mu^Z = \bar{f} \gamma_\mu (T_{3L} - Q_{ew} \sin^2 \theta_w) f$$

($\frac{g}{\cos \theta_w} Z_\mu J_\mu^Z$)

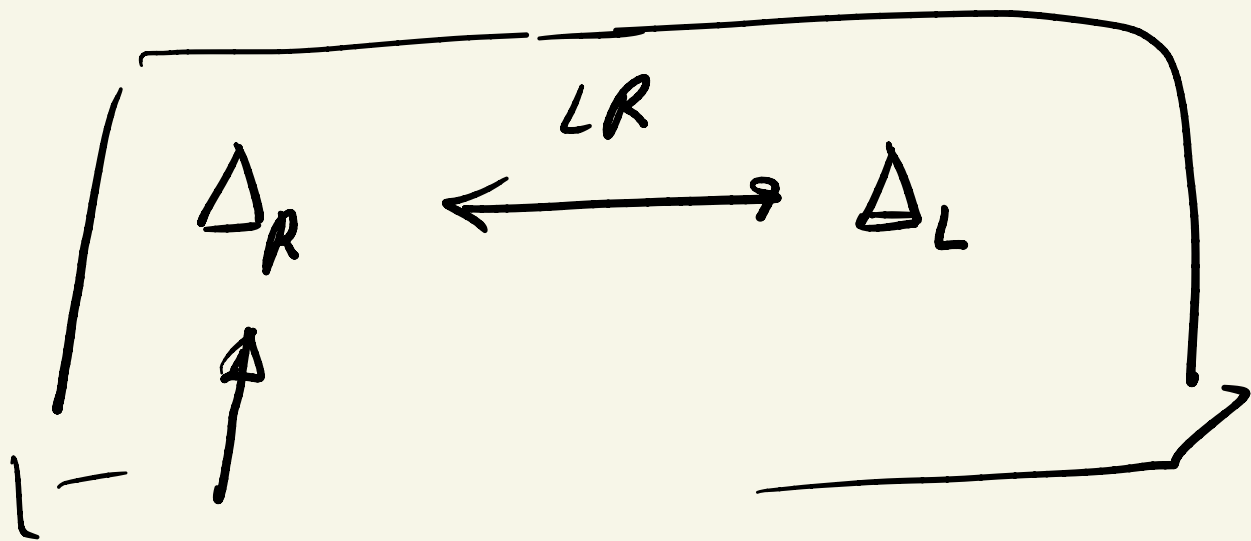
$$J_\mu^{Z'} = \bar{f} \gamma_\mu (? T_{3R} \pm Q \dots) f$$

???

to be completed

$$P' \equiv M_{Z'} / M_{W'} \equiv M_{Z_R} / M_{W_R}$$

depends on choice of Δ_R
 but $P' = ?$ (exp)



$$T_a^R \Delta_R \neq 0$$

$$T_a^L \Delta_R = 0 \quad \text{must}$$

$$(\Leftrightarrow M_{WL} \ll M_{WR})$$

↑ experiment

$$M_{WR} \gtrsim 5 \text{ TeV} \quad \text{LHC}$$

• what are Δ_L, Δ_R ?

• $\langle \Delta_L \rangle = 0, \langle \Delta_R \rangle \neq 0$?

~~Φ~~ s-p ant.



$\langle \Delta_R \rangle \gg \langle \bar{\Phi} \rangle$

SM = works great

$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R, d_R
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	e_R



$$\Delta_R \therefore \langle \Delta_R \rangle \neq 0$$

gives mass to all
non SM particles

\Leftrightarrow keep only SM states light:

$W_L^\pm, Z, \text{ charged fermions, } \nu_L,$
 h

\Leftrightarrow heavy states are:

$W_R^\pm, Z_R (Z'), \boxed{\nu_R \dots},$
new Higgs



$$M_{UR} \propto g \langle \Delta_R \rangle$$

$$-M_{ZR} \propto ? \langle \Delta_R \rangle$$

$$M_{VR} \propto Y_\Delta \langle \Delta_R \rangle$$



Δ_R couples to ν_R (Y_Δ)

\Leftrightarrow couples to $l_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

Q. What is the $SU(2)$ content of Δ ?

$\Delta =$ doublet, triplets,
quartets -- ?

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

$$m_\nu \simeq m_e$$

"natural"

Curse of LR in '70s!

why (how) $m_\nu \ll m_e$?