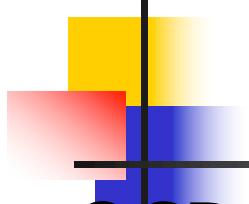


Parity Solution to Strong CP problem and leptogenesis

R. N. Mohapatra

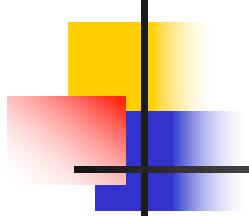


Mitchell Conference, May, 2023
College Station, Texas



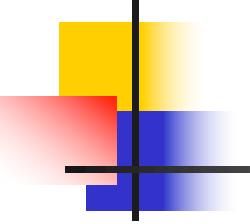
Strong CP problem

- QCD $\rightarrow \mathcal{L}_{QCD} = \mathcal{L}_{QCD}^0 + \frac{\alpha_s}{8\pi} \theta G \tilde{G}$
- Theory with flavor: $\bar{\theta} = \theta_0 + \text{Arg Det } M_u M_d$
- Current nedm limit $\rightarrow \bar{\theta} < 10^{-10}$
- No anthropic reasons for it to be small; so why is it so small?



Axion Solution

- $\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^0 + \frac{\alpha_s}{8\pi} (\bar{\theta} + \frac{a}{f_a}) G \tilde{G}$ (Peccei-Quinn'78)
- Ground state $\rightarrow (\frac{a}{f_a} + \bar{\theta}) = 0$; no strong CP violation
- Model realization: Postulate a global axial $U(1)_{\text{PQ}}$ symmetry: axion Goldstone boson. (Weinberg; Wilczek)
- Cosmology and SN
 $10^9 \text{ GeV} \leq f \leq 10^{12} \text{ GeV} \quad m_a \sim 10^{-6} \text{ eV}$



Many experiments searching for axion

- EXPTS: ADMX, ADMX-HF, CARRACK, CASPER , CAST, IAXO, CAPP, HAYSTAC, LSW, ALPS II, MADMAX, QUAX, ABRACASDABRA, SHAFT, ARIDANE,
- No sign of axion yet.
- Also axion has a gravity problem !!!

Gravity problem of the axion

- Lore: All global symmetries are broken by Planck scale effects and they induce Planck suppressed ~~PQ~~ terms into theory e.g. $\beta\sigma^5/M_{Pl}$

$$\rightarrow V(a) = V_0 \left(\frac{a}{f_a} + \bar{\theta} \right) + \frac{Im\beta f_a^5}{M_P} \sin \frac{a}{f_a}$$

- They generate large $\bar{\theta}$ unless the coefficient $\beta < 10^{-44}$. (Kamionkowski et al'92, Holman et al'92; Barr, Seckel'92;)

Alternative solutions to strong CP without axion

- If parity is a short distance symmetry of the theory, strong CP problem can be solved without an axion: (Beg, Tsao'78; RNM, Senjanovic'78)
- For low scale (multi-TeV) Parity restoration, no gravity problem: (Berezhiani, RNM, Senjanovic'92)
- Should be testable in colliders

Parity solution: Minimal fermion Left-Right Model

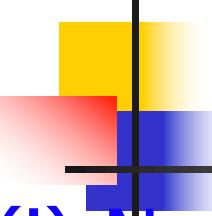
- LR basics: Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- Fermions
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \xrightleftharpoons{P} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \xrightleftharpoons{P} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$
- $g_L = g_R \rightarrow L = \frac{g}{2} [\vec{J}_L^\mu \cdot \vec{W}_{\mu L} + \vec{J}_R^\mu \cdot \vec{W}_{\mu R}]$
- Parity a spontaneously broken symmetry $M_{W_R} \gg M_{W_L}$

Minimal fermion Left-right model and parity solution

- Higgs fields: ϕ (2, 2, 0); $\Delta_{L,R} = (3, 1, +2) + (1, 3, +2)$
- P: $\psi_L \leftrightarrow \psi_R$; $\phi \leftrightarrow \phi^\dagger$; $\Delta_L \leftrightarrow \Delta_R$

$$\mathcal{L}_Y = h_{ij} \bar{\psi}_L \phi \psi_R + h.c.$$

- P-invariance $\rightarrow h_{ij}^* = h_{ji}$ (hermitian h)
- Quark mass matrices: $M_q = h < \phi^0 >$
- If $< \phi^0 >$ real $\rightarrow M_q$ hermitian
 $\rightarrow \text{Arg Det } M_q = 0 \rightarrow \theta = 0$



Challenges for this solution

- (i) Need to have $\langle \phi^0 \rangle$ real naturally !
 - (ii) P-breaking will induce theta at Loop level.
How big is it ?
 - Minimal fermion LR model $\langle \phi^0 \rangle$ has phase;
 - Need something beyond parity e.g. SUSY
- (Mohapatra, Rasin, '96; Kuchimanchi'96; Babu, Dutta, RNM'2001)
- **Is there a parity only solution?**

A pure parity solution:

(Babu, Mohapatra, 1989)

- LR + singlet fermions $U_{L,R}, D_{L,R}, E_{L,R}$
- Higgs structure minimal: Doublets: χ_L, χ_R

$$\mathcal{L}_Y = h_{ij} \bar{Q}_{i,L} \chi_L U_R + h_{ij} \bar{Q}_{i,R} \chi_R U_L + D, E - terms$$

- $+ M_U \bar{U} U + \dots D, E$

$$V = -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R, \\ + \lambda_1 \left[(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2 \right] + \lambda_2 (\chi_L^\dagger \chi_L) (\chi_R^\dagger \chi_R)$$

- Vevs $v_{L,R}$ are naturally real; $P \rightarrow M_{U,D,E} = M_{U,D,E}^+$

Quark seesaw and tree level solution to strong CP

- Fermion masses in seesaw form

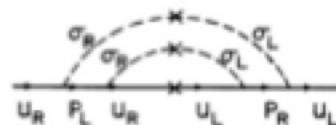
$$\rightarrow M_{Q,ij} = \begin{pmatrix} 0 & h_{ij}v_L \\ (h)_{ij}^\dagger v_R & M_q \end{pmatrix} \quad q = U, D$$

- Note now naturally $\bar{\theta}^{tree} = 0$
since Arg. Det $M_u M_d = 0$
- Solves strong CP without axion at tree level
- Check loop corrections:

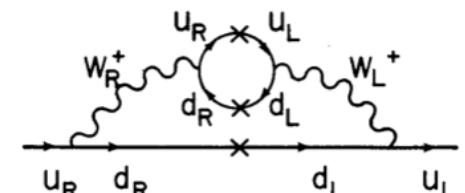
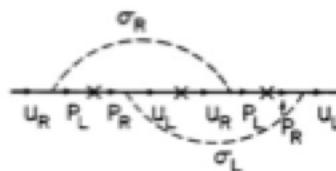
Estimating θ from loops

$$\delta\theta = \text{Im Tr} \left[m_u^{-1} \delta m_u + m_d^{-1} \delta m_d \right]$$

- 1-loop $\delta\theta = 0$



- As is 2-loop
 - (Babu, RNM'89)



- 3-loop small

$$\bar{\theta} < \left(\frac{1}{16\pi^2} \right)^3 \left(\frac{v_L}{v_R} \right)^2 f(h, g)$$

- Recent calculation (Hisano, Kitahara, Osamura, Yamada'23)

Planck scale corrections and Limit on WR scale

- Planck scale corrections: $\frac{\bar{Q}_L \chi_L \chi_R^\dagger Q_R}{M_{Pl}}$

$$\frac{v_L v_R}{M_{Pl}} \quad M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$$

- Arg Det M not zero and $\bar{\theta} < 10^{-10}$ (Berezhiani, RNM, Senjanovic'92)

$$\delta\theta = \frac{v_L v_R}{m_u M_{Pl}} \leq 10^{-10} \rightarrow v_R \leq 100 \text{ TeV}$$

- $m_{WR} < 50 \text{ TeV}$; of interest for future colliders

Alternative interpretation of the same model:

(Harigaya and Hall'2018)

- $\lambda_2 \rightarrow 2\lambda_1$ at 10^{12} GeV
- Higgs a pseudo-Goldstone boson
- W_R scale is 10^{12} GeV
- Grand unifies to SO(10)
- → Needs fine tuning to solve gravity problem;
→ WR beyond the reach of colliders

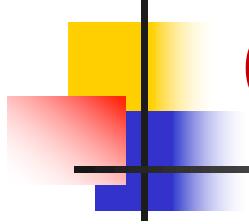


Implications of TeV scale universal seesaw

- Fermion masses are given by (Berezhiani'84; Davidson,Wali'87...)

$$m_q \simeq \frac{h^2 v_L v_R}{M_Q}$$

- Fundamental Yukawas don't have to be as small as in SM-
- Since hh^\dagger is an arbitrary hermitian matrix, it easily leads to right CKM mixing



Other implications

- (i) Vacuum stability
- (ii) Neutrino masses
- (iii) Origin of matter via Leptogenesis

(i) LR Quark seesaw cures the vacuum instability of SM

- Higgs potential of LR quark seesaw model

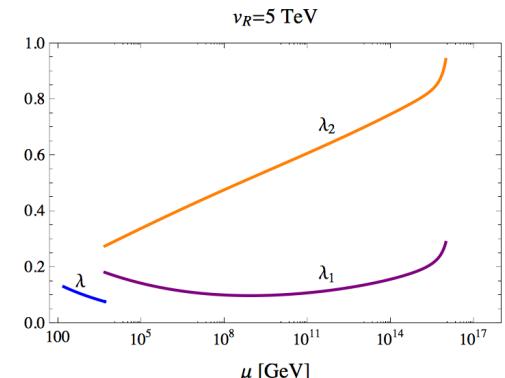
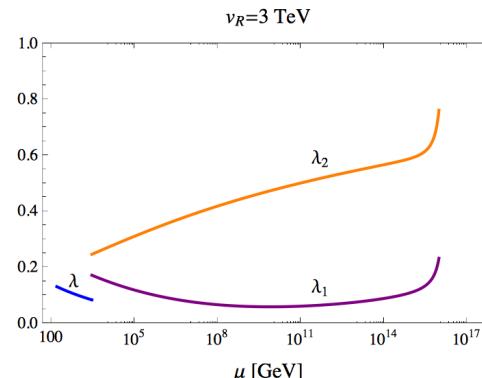
$$V = -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R, \\ + \lambda_1 [(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2] + \lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R)$$

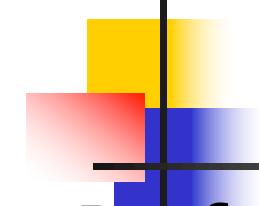
- Higgs masses

$$M_h^2 = 2\lambda_1 \left(1 - \frac{\lambda_2^2}{4\lambda_1^2} \right) v_L^2 \\ M_H^2 = 2\lambda_1 v_R^2.$$

$$\rightarrow \lambda_1(v_R) > \lambda_{\text{SM}}$$

(RNM, Zhang'14)

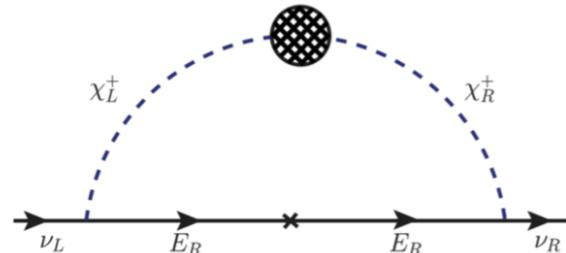
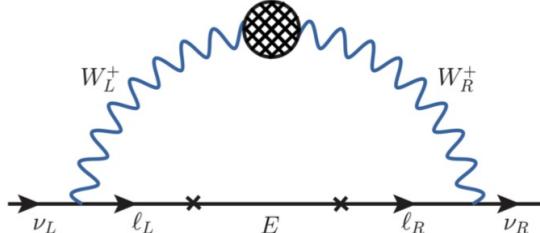




(ii) Neutrino masses

- Preference for Dirac neutrinos: happens in several ways:
- (a) Minimal VLF sector (U,D,E): Lepton number good symmetry: Dirac nu from loop

(Babu, He, Su, Thapa'22)



(ii) Neutrino masses contd:

(b) Add neutral leptons $\mathcal{N}_{L,R}$ with $L=+1$; nu could be Majorana or Dirac

- Impose lepton number as a softly broken symmetry

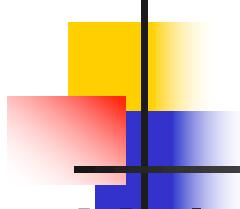
$$M_N \bar{N}_L N_R + h_\nu \bar{L} \chi_L N_R + L \rightarrow R + M'(N_L N_L + N_R N_R)$$

$$\begin{pmatrix} \nu_L & N_L & \nu_R & N_R \\ 0 & 0 & 0 & h\nu_L \\ 0 & M' & h\nu_R & M_N \\ 0 & h\nu_R & 0 & 0 \\ h\nu_L & M_N & 0 & M' \end{pmatrix}$$

$M'=0 \rightarrow$ Dirac nu

$$m_\nu \simeq \frac{h_\nu^2 v_L v_R}{M_N}$$

(useful for n_B and DM)



Leptogenesis

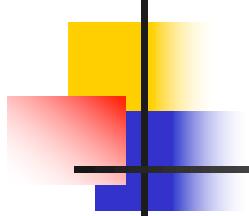
- Majorana neutrino possibility: $M' \neq 0$
- Standard resonant leptogenesis: fine tuning to keep two N's degenerate:

(Harigaya, Wang'22)

(iii) Leptogenesis with Dirac nu Outline of a possibility

- Add $L = -2$ gauge singlet Φ
- Φ couples to $N \bar{N}$ as $f\Phi (N_L N_L + L \rightarrow R) + h.c.$

(in progress with Babu and Okada)



Φ does inflation

- Φ , does inflation via non-minimal gravity coupling



$$\mathcal{S} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 f R + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(\Phi) \right]$$

$$V(\Phi) = m_\Phi^2 \Phi^\dagger \Phi - A(\Phi^2 + \Phi^{\dagger 2}) + \lambda (\Phi^\dagger \Phi)^2.$$

- $A = \epsilon M_\Phi^2$ breaks **L** weakly: $\epsilon \ll 1$ ($\Delta L = 4$)
- $V(\Phi)$ determines Φ evolution;

Affleck-Dine leptogenesis

- Early universe: $\text{Re } \Phi$, $\text{Im } \Phi$ both non-zero

$$n_L = \text{Im}(\dot{\Phi}^\dagger \Phi)$$



Sphalerons $\rightarrow n_L$ to n_B

Calculating baryon asymmetry

- Analytic form for n_B for $1 \gg \epsilon \gg \frac{\Gamma_\Phi}{m_\Phi}$

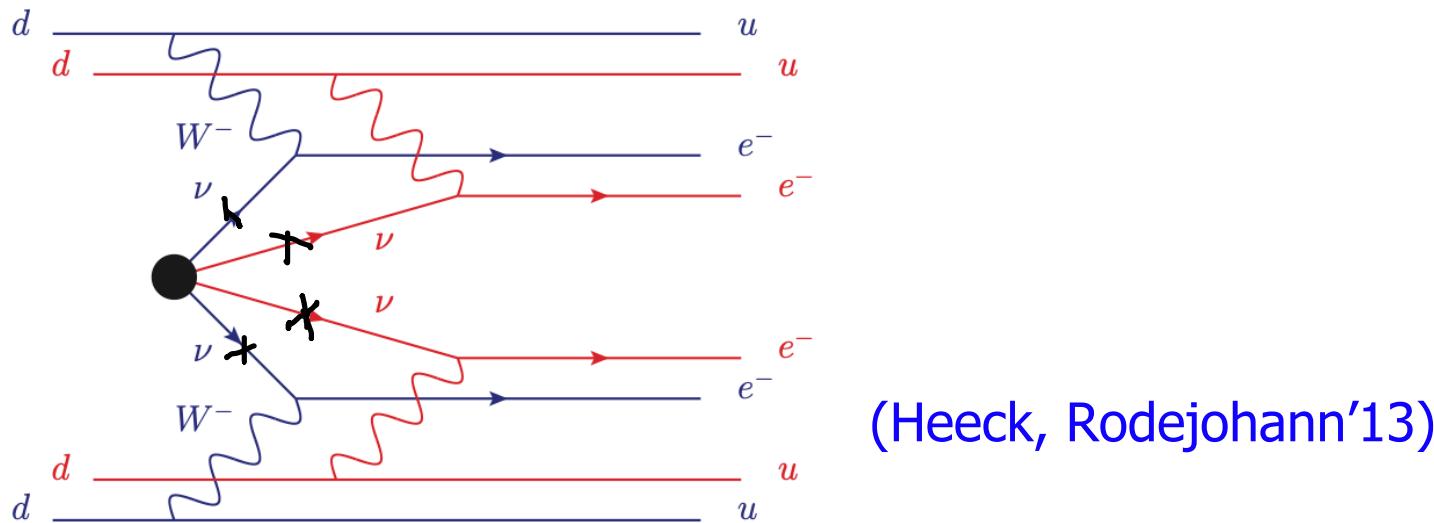
$$\frac{n_B}{s} \simeq \frac{3}{8} \sqrt{\frac{\pi^2}{90}} g_* \frac{Q_B}{\epsilon} \frac{T_R^3}{m_\Phi^2 M_P} \sin(2\theta)$$

- Reasonable choice of parameters makes it of right order:

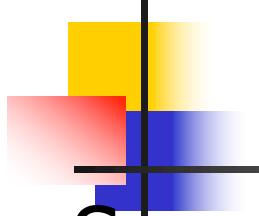
McDonald and Stubbs (2021); Babichev, Gorbunov, Ramazanov (2019); RNM, Okada (2021, 2022)

Exotic leptonic process implied by $A\Phi^2$ term

- Model has $\Delta L = 4$ but no $\Delta L = 2 \rightarrow \nu$ -Dirac
- $0\nu\beta\beta$ forbidden but $0\nu\beta\beta\beta\beta$ allowed i.e.
 $(A,Z) \rightarrow (A,Z+4) + 4e^-$ allowed (x is ν -N mixing)



- possible nuclei $Zr \rightarrow Ru$, $Nd \rightarrow Gd, \dots$

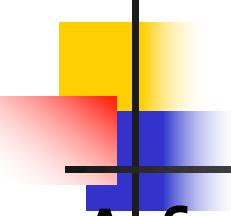


Other phenomenology

- Search for W_R, Z' at FCC: $W_R \rightarrow \ell_R \nu_R, t_R b_R$
- Second Higgs, tracks P-scale: $\frac{M_H}{M_h} \simeq \frac{v_R}{v_L}$
- Decays dominantly: $H \rightarrow WW, ZZ, hh$
- New fermions for colliders $pp \rightarrow T\bar{T}$: $T \rightarrow tZ, \dots$

Current LHC limits: $M_{T,B} > 1.2\text{-}1.4 \text{ TeV}$ (ATLAS, CMS)
(Craig, Garcia, Koszegi, McCune'21)

- Other advantages: W-anomaly and Cabibbo anomaly resolution (Babu, Dcruz'22; Belfatto, Trinilopoulos'23)



Summary

- A framework to solve strong CP problem without axion, explain baryogenesis, inflation, nu mass
- P-invariance is the key with \cancel{P} scale < 100 TeV
- New particles beyond SM:
 - Parity dictated: ν_R , a RH Higgs doublet, $W_R + Z'$
 - +four vector like fermions (U,D,E,N)
 - +complex L-carrying field Φ
- Can be tested in future colliders



Thank you for your attention !