Majoron as the QCD axion in a radiative seesaw model

Takahiro Ohata (Kyoto University)

Based on [1] Phys. Rev. D 96, 075039
with Ernest Ma (UC Riverside)
and Koji Tsumura (Kyoto U.)
Our research’s purpose

- Strong CP problem
- Dark matter
- (small) Neutrino mass
- Baryon number asymmetry
How to explain small neutrino mass

SM+ heavy particle:

\[ \frac{c_{\alpha\beta}}{\Lambda} (\bar{L}_\alpha H) (\bar{H}^\dagger L_\beta) + \text{H.c.} \quad [4] \]

ex) Type I Seesaw [5]

- Heavy right-hand neutrino \( N_{iR}, (i = 1, \cdots, n_N) \) is added.
- After integrating out \( N_{iR} \), neutrino Majorana mass is created.

\[ \langle H \rangle \bigg| N_i \bigg| \langle H \rangle \]

\[ L^c \quad N_i \quad L \]

\[ M_{\nu ij} = \sum_k \frac{h_{ik} h_{jk} v^2}{2 M_{Mk}} \]

Heavier than weak scale!
Leptogenesis

Seesaw model can generate baryon number asymmetry.

- $N_R$ is far from equilibrium at reheating scale.
- The decay process: $N_R \rightarrow LH$ (or $\bar{L}H^\dagger$) breaks B-L and CP.

\[ Y_B = \frac{12}{37} Y_B - \frac{n_B}{s} \sim 10^{-10} \]
Dark Matter

• There are many evidence of Dark matter (DM):
  • The flatness of galaxy rotation curve
  • The mass distribution among bullet cluster measured by gravitational lensing
  • The formation of large-scale structure
  • Cosmic microwave background (CMB) observation
  • etc…

$$\Omega_{\text{DM}} h^2 \sim 0.12$$ \[8,9\]

• In the standard model of particle physics (SM), there are no candidate of DM, naively.

DM may be New particle.

• WIMP dark matter [10] (Symmetry stabilizes dark matter)
• invisible QCD axion [11,12] (the coupling to SM is very small)
• etc…
Strong CP problem

• QCD $\theta$ term is allowed in SM:

• This $\theta$’s range is $-\pi$ to $\pi$. Naively, $\theta$ has a random value in the range.

• However $\theta$ is very small. (the measurement of neutron electric dipole moment)

• What mechanism makes $\theta$ small?

\[ \mathcal{L}_\theta = + \frac{\theta g_3^2}{32\pi^2} \tilde{G}^A_{\mu\nu} G^{A\mu\nu} \quad ( -\pi < \theta < \pi ) \]

\[ \theta \lesssim 10^{-11} \quad [13] \]
Strong CP problem (2)

QCD axion model \[11,12,14,15]\n
ex) KSVZ axion model
- colored fermion $\Psi$
- complex scalar $S$ with wine bottle potential
- Additional Chiral symmetry (Peccei Quinn (PQ) symmetry)
- PQ symmetry is broken by $S$, and its pseudo NG-boson is axion $\alpha$.

QCD $\theta$ term becomes small by axion dynamical effect:

$$\mathcal{L}_\theta = + \frac{g_3^2}{32\pi^2} \left( \theta - \frac{n_\Psi a(x)}{\nu_a} \right) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$$

$\rightarrow 0$

solution of the strong CP problem
Our research
Our research is

The unification of Seesaw model and Axion model:

• mediator in seesaw = colored fermion in axion model

• Lepton symmetry breaking = PQ (spontaneous) symmetry breaking

\[
\frac{M_i}{2} N_{iR}^c N_{iR} + \text{H.c.} - y'_{\Psi} \langle S \rangle \overline{\Psi}_{iL} \Psi_{iR} + \text{H.c.}
\]

Majoron = Axion

→ It explains Dark matter, neutrino mass, the baryon number asymmetry and strong CP problem.

I explain it below…
Additional fields & their representation

- $S$: Complex scalar with wine bottle potential.
- $\Psi_{iR}^A$: **Color octet** right-handed fermion ($i = 1, \ldots, n_{\Psi}$).
- $\Phi^A$: Complex scalar field in $(8, 2)_{1/2}$.

## Additional Symmetry: $U(1)_{PQ} = U(1)_{\text{Lepton} \#}$

- $S$, $\Psi_{iR}^A$, and $\Phi^A$ behave as (radiative) seesaw model.
- $S$ and $\Psi_{iR}^A$ behave as invisible axion model.
- After PQ breaking, $\Psi_{iR}^A$'s Majorana mass is generated: $-\frac{1}{2} \bar{\psi}_i \langle S \rangle (\psi_{iR}^A)^c \psi_{iR}^A + \text{H.c.}$

I assumed that $\mathcal{O}(10^4) \text{TeV} \lesssim M_\Phi \ll M_{\Psi_1} \lesssim 10^{12} \text{GeV}$ in my analysis.
neutrino mass

Neutrinos gain mass through radiative correction:

\[
(M_\nu)_{ij} \approx \frac{1}{4\pi^2} \lambda_5 v^2 \sum_k h_{\Psi k} h_{\bar{\Psi} k} M_{\Psi k} \frac{M_{\Psi k}^2 \ln \frac{M_{\Psi k}^2}{m_0^2} - M_{\Psi k}^2 + m_0^2}{(M_{\Psi k}^2 - m_0^2)^2}.
\]

\[
\langle H \rangle \xrightarrow{\lambda_5} \langle H \rangle
\]

heavy !

\[
\Phi \xrightarrow{\Phi} \langle S \rangle
\]

Lepton #

\[
\nu \xrightarrow{\Psi} \langle S \rangle
\]

\[
\Psi \xrightarrow{\bar{\Psi}} \langle S \rangle
\]

Lepton #

Lepton number’s breaking is occurred by $S$, the mediator $\Psi^A_{iR}$’s mass comes from PQ scale.
As axion model

The fields which work as axion model:

- Colored fermion $\Psi^A_{iR}$
- Complex scalar $S$
- PQ number = Lepton number $\mathbb{L}(\Psi^A_R) = 1$, $\mathbb{L}(S) = -2$

Strong CP problem is solved.

Axion behaves as DM.

$$\mathcal{L}_\theta = + \frac{g_3^2}{32\pi^2} \left( \theta - \frac{a(x)}{v_a/(3n_\Psi)} \right) \tilde{G}^{A}_{\mu\nu} G^{A}_{\mu\nu}$$

$$\Omega_a h^2 \sim 0.18 \theta_a^2 \left( \frac{v_a/(3n_\Psi)}{10^{12} \text{ GeV}} \right)^{1.19}$$

[17,18]
Leptogenesis
(preliminary)
the picture of Leptogenesis in our model

- $\Psi_{iR}^A$ is far from equilibrium at the reheating scale.

- After reheating, the process $\Psi_1^A \rightarrow \Phi^{A(t)} L^{(t)}$ creates Lepton number asymmetry.

- $\Psi_{iR}^A$ is colored particle. $\Psi_{iR}^A$'s thermalization in our model is faster than the one of right-handed neutrino $N_{iR}$ in the type I Seesaw model.
Parameter setting from DM and neutrino data

- PQ scale $\nu_a \leftarrow$ determined by DM relic density

$$\Omega_{DM} h^2 \approx 0.18 \theta_i^2 \left( \frac{\nu_a/(3n_\Psi)}{10^{12} \text{ GeV}} \right)^{1.19} , \ n_\Psi = 3, \ \theta_i = \mathcal{O}(1)$$

$$\rightarrow \nu_a \approx 7.1 \times 10^{11} \text{ GeV}$$

- coupling $h_{\Psi}^{ik} \leftarrow$ determined by Neutrino Mass Matrix

$$(M_\nu)_{ij} \approx \frac{\lambda_5 v^2}{4\pi} \sum_k \frac{h_{\Psi}^{ik} h_{\Psi}^{jk}}{M_{\Psi_k}} \quad (M_\Phi \ll M_\Psi)$$

$$\mathcal{L}_{L\Phi\Psi_R} = h_{\Psi}^{ij} \tilde{\Phi}^A_{ji} \tilde{\Psi}^A_{jR} L_i + \text{H.c.}$$

$$h_{\Psi}^{ik} \rightarrow \frac{2\pi}{\sqrt{\lambda_5} v} U^*_{\text{PMNS}} \sqrt{m_{\nu}^{\text{diag}}} R^T \sqrt{M_{\Psi}^{\text{diag}}}$$

(R: complex orthogonal matrix)

(I assumed Normal Hierarchy in my analysis.)

$\lambda_5 : (H^T \Phi^A)^2$'s coupling
numerical solution of Boltzmann equation

- After reheating, $\Psi_{iR}^A$ is thermalized quickly. During it, Lepton number asymmetry is created.

- After generating and washout of Lepton asymmetry are balanced, Lepton asymmetry becomes stabilized.

- In order to create sufficient baryon number: $Y_B = \frac{n_B}{s} \sim 10^{-10}$, the lightest $\Psi_{iR}^A$’s mass is:

\[ M_{\Psi_1} \gtrsim 2 \times 10^{10} \text{GeV} \]

$(\lambda_5 = 10^{-2}, M_{\Psi_1} \sim 10^{-2} M_{\Psi_{2,3}})$
The prediction of reheating temperature

In order to explain baryon number asymmetry, the reheating temperature is bounded:

\[ 2 \times 10^{10} \text{GeV} \lesssim M_{\Psi_1} \lesssim T_{\text{reheat}} \lesssim v_\alpha \ . \]

- The lower bound comes from the baryon number asymmetry.
- The upper bound comes from the Domain wall problem.
Summary

- Our model can explain DM, strong CP problem, neutrino mass and baryon number asymmetry.

- In our model, the mediator in seesaw model becomes colored fermion in axion model. This mediator’s mass comes from PQ scale.

- Based on the leptogenesis, our model can predict the reheating temperature: \( 2 \times 10^{10} \text{GeV} \lesssim M_{\psi_1} \lesssim T_{\text{reheat}} \lesssim v_a \).
Reference


Reference


Backup
Flavor Changing Neutral Current (FCNC)

\[ \mathcal{L}_{Q\Phi q_R} = g_u^{ij} \bar{Q}_i \Phi^A T^A u_{jR} + g_d^{ij} \bar{Q}_i \Phi^A T^A d_{jR} + \text{H.c.} \]

\( \Delta m_K \) is the mass difference in \( K^0 - \overline{K^0} \) mixing.

\[ \frac{\Delta m_{K}^{\Phi^A}}{\Delta m_{K}^{\text{exp}}} \sim \frac{g_{u,d}^2 \Lambda_{\text{QCD}}^3}{M_{\Phi}^2 \Delta m_K^{\text{exp}}} \]

\( \Delta m_{K}^{\text{exp}} = (3.484 \pm 0.006) \times 10^{-15}\text{GeV} \) [8]

Assuming that \( \Phi^A \)'s contribution to \( \Delta m_K \) is in the error and \( g_{u,d} \sim \mathcal{O}(1) \),

\[ M_{\Phi} \gtrsim \mathcal{O}(10^4)\text{TeV} \]
LFV process

Based on leptogenesis, $\Psi_{iR}^A$ is heavy.
So, LFV process in our model meets the experimental limit.

$$\text{Br}(\ell_i \rightarrow \ell_j \gamma) = \frac{3\alpha}{\pi M_{\Phi_+}^4 G_F^2} |h_{\Psi}^{ik} F_2(M_{\Psi_k}^2 / M_{\Phi_+}^2) h_{\Psi}^{kj}|^2$$

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1 - x)^4}$$

$$\text{Max} \left( \frac{\text{Br}(\mu \rightarrow e\gamma)}{(\text{Br}(\mu \rightarrow e\gamma))_{\text{limit}}} \right) \sim 10^{-27}$$

$10^7 \text{GeV} < M_{\Phi_1} < 10^{12} \text{GeV}$, $10^{-6} < \lambda_5 < 1$,
$10^8 \text{GeV} < M_{\Phi_\pm} < 10^7 \text{GeV}$, $M_{\Phi_\pm} < 10^{-2} M_{\Phi_1}$
New Yukawa coupling

\[ \mathcal{L}_{Q\Phi q_R} = g_u^{ij} \overline{Q}_i \tilde{\Phi}^A T^A u_{jR} + g_d^{ij} \overline{Q}_i \Phi^A T^A d_{jR} + \text{H.c.} \]

\[ \mathcal{L}_{L\Phi \Psi_R} = h^{ij}_{\Psi} \overline{L}_i \tilde{\Phi}^A \Psi^A_{jR} + \text{H.c.} \]

\[ \mathcal{L}_{S\Psi_R \Psi_R} = -\frac{1}{2} y^i_{\Psi} S \overline{(\Psi^A_{iR})^c} \Psi_{iR} + \text{H.c.} \]
Boltzmann equation

\[
\frac{dY_{\Delta L}}{dt} \simeq \frac{g_{\Psi_1} M_{\Psi_1}^3}{2\pi^2 z} K_1(z) \Gamma(\Psi_1^A \to 2) \left[ \frac{Y_{\Psi_1}^A - Y_{\Psi_1}^{eq}}{Y_{\Psi_1}^{eq}} - \frac{1}{6} \frac{Y_{\Delta L}}{Y_{\Psi_1}^{eq}} \right]
\]

\[
\frac{dY_{\Psi_1}^A}{dt} \simeq -\frac{Y_{\Psi_1}^A - Y_{\Psi_1}^{eq}}{Y_{\Psi_1}^{eq}} \frac{g_{\Psi_1} M_{\Psi_3}^3}{2\pi^2 z} K_1(z) \Gamma(\Psi_1^A \to 2)
\]

\[
+ 2 \gamma_{XX \Psi_1 \Psi_1} - 2 \left( \frac{Y_{\Psi_1}}{Y_{\Psi_1}^{eq}} \right)^2 \gamma_{\Psi_1 \Psi_1 XX}
\]

\[
\gamma_{\Psi_1 \Psi_1 XX} = \frac{1}{8\pi^4} \left( \frac{M_{\Psi_1}}{z} \right)^4 \left( \frac{3 \times 4}{\pi} + \frac{136}{2\pi} + \frac{6}{\pi} \right) \times \left\{ 4\pi \alpha_s(T = M_{\Psi_1}/z) \right\}^2
\]

\[
\gamma_{XX \Psi_1 \Psi_1} = \frac{1}{2} \frac{1}{8\pi^4} \left( \frac{M_{\Psi_1}}{z} \right)^4 \left( \frac{3 \times 4}{\pi} + \frac{36}{\pi} + \frac{12}{\pi} \right) \times \left\{ 4\pi \alpha_s(T = M_{\Psi_1}/z) \right\}^2
\]

\[
\Gamma(\Psi_1^A \to 2) = \frac{8 \times [h_{\Psi}^i h_{\Psi}^j]_{11} M_{\Psi_1}}{4\pi g_{\Psi_1}^A}
\]

\[
e = \frac{1}{8\pi} \sum_{k=2,3} \text{Im}(h_{\Psi}^i h_{\Psi}^{ik*} [h_{\Psi}^i h_{\Psi}]_{k1}) \left\{ f(\xi_k) + g(\xi_k) \right\}
\]

\[
f(\xi) = \sqrt{\xi} \left\{ 1 - (1 + \xi) \ln \frac{1 + \xi}{\xi} \right\}, \quad g(\xi) = \frac{\sqrt{\xi}}{1 - \xi}
\]

\[
\xi_k = \frac{M_{\Psi_k}^2}{M_{\Psi_1}^2}, \quad g_{\Psi_1}^A = 2 \times 8, \quad g_{\ell\alpha} = 2 \times 2
\]
The balance between $\Psi^A_{iR}$'s decay and lepton asymmetry's washout.

\[
\frac{dY_{\Delta L}}{dt} \sim \frac{g_{\Psi_1} M_{\Psi_1}^3}{2\pi^2 z} K_1(z) \Gamma(\Psi_1^A \to 2) \left[ \frac{Y_{\Psi_1^A} - Y_{\Psi_1^A}^{eq}}{Y_{\Psi_1^A}} - \frac{1}{6} \frac{Y_{\Delta L}}{Y_{\ell_{\alpha}}^{eq}} \right]
\]

The first term in RHS is $\Psi^A_{iR}$ decay term, and the second term is washout term.

$M_{\Psi_1}=10^{11}$ GeV, $\lambda_5=10^{-2}$

The terms become balanced at low redshifts.
Ψ1’s thermalization is fast due to its QCD process.

The analysis with Ψ1’s QCD process in our model.

\[ \Delta z \sim \mathcal{O}(10^{-5}) \]

The analysis without Ψ1’s QCD process in our model.

\[ \Delta z \sim \mathcal{O}(10^{-3}) \]
Axion coupling with SM particle

Axion (Majoron) in our model couples with Lepton. Especially, it couples with a charged lepton’s vector current.

However, when axion is on-shell, this coupling becomes zero.

\[
\frac{\partial_{\mu}a}{2v_a} (\bar{L}_L\gamma^\mu L_L + \bar{e}_R\gamma^\mu e_R)
\]

(Other coupling with SM particle is same as KSVZ-like axion.)

\[i\mathcal{M}_a = p_\mu \mathcal{M}^\mu = \]

\[i\mathcal{M}_A = -ie\epsilon^*_\mu(p)\mathcal{M}^\mu = \]

These \(\mathcal{M}^\mu\) are same, so \(i\mathcal{M}_a = 0\) due to Ward Takahashi identity.