Baryogenesis via active neutrino oscillation

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Neutrino Magic!

1. Have a good look!
2. Neutrino oscillation!
The flavor content of neutrinos and that of anti-neutrinos are modified differently by the CP violation in the neutrino oscillation.
3. And hit Higgs bosons!
The numbers of the heavy neutrinos and the heavy anti-neutrinos are equalized by hitting the Higgs bosons.
4. Ta-da!
   There are more anti-neutrinos?!

More anti-neutrinos than neutrinos?
Starting with the same numbers of neutrinos and anti-neutrinos, some magic under the cloth created an imbalance between them. This CP violating phenomenon, if it has really happened in the early Universe, give the reason for the Universe being made of matter rather than anti-matter.

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comic by Yuki Akimoto, higgstan.com
1. Introduction

How to generate the baryon asymmetry?

*Sakharov’s conditions*

*Baryon/Lepton number violation*

*C and CP violation*

*Out of thermal equilibrium*

Unfortunately, the SM does not sufficiently satisfy...
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*A clear New Physics! Neutrino mass*

The SM (probably) is an effective theory with Majorana neutrino mass term

\[-\frac{\kappa_{ij}}{2}(\bar{l}_i^c P_L l_j)HH + \text{h.c.}\]
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*C and CP violation ✔

Neutrino oscillation can provide CP violation. Observed at 2sigma level.

*Out of thermal equilibrium*

A clear New Physics! Neutrino mass

The SM (probably) is an effective theory with Majorana neutrino mass term

$$- \frac{\kappa_{ij}}{2} (\bar{l}_i^c P_L l_j) H H + h.c.$$
Big bang is a one way process

Inflaton decay: \[ \phi \rightarrow \text{SM particles} \]

Number density of SM particles

Thermal distribution

@ last period of inflaton decay

\[ E \sim m_\phi / 2 \]

from direct decay

Number density of SM particles

\( 10^8 \) \( 10^9 \) \( 10^{10} \) \( 10^{11} \) \( 10^{12} \) \( 10^{13} \) \( 10^{14} \)

\( E \) [GeV]
Big bang is a one way process

Inflaton decay: \( \phi \rightarrow \text{SM particles} \)

Number density of SM particles

Thermal distribution

@ last period of inflaton decay

\( E \sim \frac{m_\phi}{2} \)
What I will show

Setup:

\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{\kappa_{ij}}{2} (\overline{\ell}_i^c P_L l_j) H H + \text{h.c.} \]

Baryogenesis due to active neutrino oscillation during the reheating/thermalization.

Leptogenesis from active neutrino oscillation with two higher dimensional terms.

Kitano, Hamada 1609.05028.

c.f. Leptogenesis with light enough right-handed neutrinos.

Fukugida, Yanagida, 86; Pilaftsis, 97; Akhmedov et al, 98;
2. Neutrino Oscillation at big bang

\[ \phi \rightarrow \nu_{\text{ini}} + X, \bar{\nu}_{\text{ini}} + \bar{X} \]

\[ \langle \nu_{\text{ini}} \rangle \]

\[ P_{\text{ini}\rightarrow I} \sim \left| \sum_{\alpha} \langle \nu_{\text{ini}} | \nu_{\alpha} \rangle e^{i t \text{MFP} (m^{\text{th}}_{\nu_{\alpha}})^2 / k} \langle \nu_{\alpha} | \nu_{I} \rangle \right|^2 \]

c.f. \[ P_{e\rightarrow \mu} \sim \left| \sum_{\alpha} \langle \nu_{e} | \nu_{\alpha} \rangle e^{i t m^{2}_{\nu_{\alpha}} / k} \langle \nu_{\alpha} | \nu_{\mu} \rangle \right|^2 \] @ vacuum
2. Neutrino Oscillation at big bang

\[ \phi \rightarrow \nu_{ini} + X, \bar{\nu}_{ini} + \bar{X} \]

\[
\begin{align*}
P_{ini \rightarrow I} & \approx | \sum_{\alpha} \langle \nu_{ini} | \nu_{\alpha} \rangle e^{i t MFP (m_{\nu_{\alpha}}^{th})^2 / k} \langle \nu_{\alpha} | \nu_I \rangle |^2 \\
& \text{c.f. } P_{e \rightarrow \mu} \approx | \sum_{\alpha} \langle \nu_e | \nu_{\alpha} \rangle e^{i t m_{\nu_{\alpha}}^2 / k} \langle \nu_{\alpha} | \nu_{\mu} \rangle |^2 \quad @ \text{vacuum}
\end{align*}
\]
2. Neutrino Oscillation at big bang

\[ \phi \rightarrow \nu_{\text{ini}} + X, \bar{\nu}_{\text{ini}} + \bar{X} \]

\[ P_{\text{ini}\rightarrow I} \sim \left| \sum_{\alpha} \langle \nu_{\text{ini}} | \nu_{\alpha} \rangle e^{i t \text{MFP} (m_{\nu_{\alpha}}^\text{th})^2 / k} \langle \nu_{\alpha} | \nu_{I} \rangle \right|^2 \]

c.f. \[ P_{e\rightarrow \mu} \sim \left| \sum_{\alpha} \langle \nu_e | \nu_{\alpha} \rangle e^{i t m_{\nu_{\alpha}}^2 / k} \langle \nu_{\alpha} | \nu_{\mu} \rangle \right|^2 \] @ vacuum
**Neutrino Oscillation provides CP violation**

\[ P_{\text{ini} \rightarrow I} \approx \left| \sum_\alpha \langle \nu_{\text{ini}} | \nu_\alpha \rangle e^{it_{\text{MFP}}(m_{\nu,\alpha}^{\text{th}})^2/k} \langle \nu_\alpha | \nu_I \rangle \right|^2 \]

\[ t_{\text{MFP}} \approx \frac{1}{\alpha_2^2 T} \sqrt{\frac{k}{T}} \]

\((m_{\nu,\alpha}^{\text{th}})^2 = \text{eigen}[\frac{\eta_i^2 T^2}{16} \delta_{ij} + 0.046 (\kappa^* \kappa)_{ij} T^4] + C \delta_{ij}\)

\[ P_{\text{ini} \rightarrow I} - P_{\text{ini} \rightarrow \bar{I}} \propto \frac{\Delta (m_{\nu}^{\text{th}})^2}{k} t_{\text{MFP}} \sim 0.01 \sqrt{T/k} \]

c.f. \(P_{e \rightarrow \mu} - P_{e \rightarrow \mu} \propto \sin[t \Delta m_{\nu}^2 / k]\) @ vacuum

Oscillation phase is not too small at the reheating era.

(In fact it is even larger than the naive estimate by factor \(\sqrt{k/T}\) )
How to observe the “flavor”? 

\[ P_{\text{ini} \rightarrow I} \simeq \left| \sum_{\alpha} \langle \nu_{\text{ini}} | \nu_\alpha \rangle e^{it_{\text{MFP}} (m_{\nu_\alpha}^{\text{th}})^2 / k} \langle \nu_\alpha | \nu_I \rangle \right|^2 \]

Only flavor dependent process can identify the flavor.

“Observation” is made due to the following interaction process.

\[ | \nu_I \rangle \] is the state defined by the interaction.
**Lepton number violation happens through “observation”**.

\[ P_{\text{ini} \rightarrow I} \simeq \left| \sum_{\alpha} \langle \nu_{\text{ini}} | \nu_{\alpha} \rangle e^{i t_{\text{MFP}} \left( m_{\nu_{\alpha}}^{\text{th}} \right)^2 / k} \langle \nu_{\alpha} | \nu_I \rangle \right|^2 \]

Only flavor dependent process can identify the flavor.
“Observation” is made due to the following interaction process.

**Lepton asymmetry can be made!**
The (naive) estimation of lepton asymmetry

\[ m_\phi \sim T \ll 10^{12} \text{GeV} \quad \text{with certain CP phase} \]

\[
\frac{\Delta n^L_s}{s} \propto B r_{\phi \rightarrow \nu_{\text{ini}} + X/\bar{\nu}_{\text{ini}} + \bar{X}} \times t_{\text{MFP}} \frac{\Delta m^2_\nu}{T} \times \frac{\sigma^\text{th}_{llHH}}{\sigma^\text{th}_{\text{yukawa}}} 
\]

CP violation \hspace{3cm} \text{lepton # violation}

Flavor dependent asymmetry of order \( \frac{\Delta m^2_{\text{th}}}{T} \frac{1}{\Gamma_{\text{th}}} \sim 0.01 \)

How frequently the flavor is observed by the \( llHH \) interaction.

\[
\frac{\sigma^\text{th}_{llHH}}{\sigma^\text{th}_{\text{yukawa}}} \sim \frac{\Delta m^2_\nu / \nu^4 T^2}{y_T^2 y_t^2}
\]
The (naive) estimation of lepton asymmetry

\[ m_\phi \sim T \ll 10^{12} \text{GeV} \]

\[ \frac{\Delta n_L}{s} \propto Br_{\phi \rightarrow \nu_{\text{ini}} + X/\bar{\nu}_{\text{ini}} + \bar{X}} \times 10^{-9} \left( \frac{T_R}{10^9 \text{GeV}} \right)^2 \]

c.f. required asymmetry

\[ |\Delta n_L / s| \sim 10^{-10} \]

**Enough asymmetry can be made for sufficiently high reheat temperature.**

For a precise prediction or more complicated processes, we need a systematic approach.
3. Numerical result (Normal Hierarchy)

By solving kinetic equations, Sigl, Raffelt, 1993 we get

Dirac phase=-\pi/2, Majorana phase=0.3

\[ V \propto \{1,1,1\} \]

Assumption:
1. Flavor dependent coupling \( \phi \) to \( \nu \).
2. Preexisting thermal plasma of all SM particles.

\[ m_\phi / T_R = 1 \]
\[ m_\phi / T_R = 100 \]
3. Numerical result (Normal Hierarchy)

By solving kinetic equations, Sigl, Raffelt, 1993 we get

Dirac phase=–π/2, Majorana phase=0.3

V ∝ {1,1,1}

Assumption:
1. Flavor dependent coupling ϕ to ν.
2. Preexisting thermal plasma of all SM particles.

Baryogenesis can be successful for $T_R \gtrsim 10^8 \text{ GeV}$ due to active ν oscillation during thermalization.
Summary

Baryon asymmetry explained within SM with

\[- \frac{\kappa_{ij}}{2} (\bar{l}_i^c P_L l_j) H H + \text{h.c.}\]

- Required reheat temperature $> 10^8$ GeV.

- The scenario can be tested in future neutrino exps, such as neutrinoless double beta decay exps, especially for inflaton dominantly decays to Higgs. (given in our paper.)
Backups
**Mass basis** $\neq$ **interaction basis**!

Mass:

```
\begin{align*}
  \nu & \rightarrow y_i H e \\
  t & \rightarrow y_t H b
\end{align*}
```

Interaction:

```
\begin{align*}
  \nu & \rightarrow \bar{H} \nu \\
  \nu & \rightarrow \bar{H} \nu
\end{align*}
```

**CP violation can take place!**
Oscillating frequency during reheating.

\[ P_{\text{ini} \rightarrow I} \simeq | \sum_{\alpha} \langle \nu_{\text{ini}} | \nu_{\alpha} \rangle e^{it_{\text{MFP}} (m_{\nu,\alpha}^{\text{th}})^2 / k} \langle \nu_{\alpha} | \nu_I \rangle |^2 \]

\[(m_{\nu,\alpha}^{\text{th}})^2 = \text{eigen} \left[ \frac{y_i^2 T^2}{16} \delta_{ij} + 0.046 (\kappa^* \kappa)_{ij} T^4 \right] + C \delta_{ij} \]

\[ |\nu_{\alpha}\rangle \text{ is the mass eigen state.} \]
Kinetic Equation (Extended Boltzmann Eqs)

density matrix for left-handed leptons \( \rho(p) \equiv \rho_{ij}(p) \quad i, j = e, \mu, \tau \)

\[
\frac{d\rho(p)}{dt} = \left[ \Omega(p), \rho(p) \right] - \frac{i}{2} \{ \Gamma^d_p, \rho(p) \} + \frac{i}{2} \{ \Gamma^\rho_p, 1 - \rho(p) \},
\]

Oscillation term

Interaction terms (with CP phase)

\[
\left( \frac{d\bar{\rho}(p)}{dt} = - \left[ \Omega(p), \bar{\rho}(p) \right] - \frac{i}{2} \{ \Gamma^d_p, \bar{\rho}(p) \} + \frac{i}{2} \{ \Gamma^\rho_p, 1 - \bar{\rho}(p) \} \right)^* \]

Hamiltonian:

\( \Omega_{ij}(p) \approx \frac{y_i^2 T^2}{16|p|} \delta_{ij} + 0.046 (\kappa^* \kappa)^{ij} \frac{T^4}{|p|}, \) for \( |p| \gtrsim T. \)

This is absent in ordinary Boltzmann eqs.

\[
\text{tr} \left[ \Omega, \rho \right] = 0 \quad \text{tr} \left[ \rho - \bar{\rho} \right]
\]
Kinetic Equation (Extended Boltzmann Eqs)

density matrix for left-handed leptons \( \rho(p) \equiv \rho_{ij}(p) \quad i, j = e, \mu, \tau \)

\[
\frac{d\rho(p)}{dt} = \left[ \Omega(p), \rho(p) \right] - \frac{i}{2} \left\{ \Gamma^d_p, \rho(p) \right\} + \frac{i}{2} \left\{ \Gamma^p_p, 1 - \rho(p) \right\},
\]

Different

Interaction terms (with CP phase)

\[
\left( \frac{d\rho(p)}{dt} = \left[ \Omega(p), \bar{\rho}(p) \right] - \frac{i}{2} \left\{ \Gamma^d_p, \bar{\rho}(p) \right\} + \frac{i}{2} \left\{ \Gamma^p_p, 1 - \bar{\rho}(p) \right\} \right)^* \]

strong phase

Hamiltonian:

\[
\Omega_{ij}(p) \simeq \frac{y_i^2 T^2}{16|p|} \delta_{ij} + 0.046(\kappa^* \kappa)_{ij} \frac{T^4}{|p|}, \quad \text{for} \ |p| \gtrsim T.
\]

This is absent in ordinary Boltzmann eqs.

Oscillation term generates flavor dependent lepton asymmetry, but \( \text{tr} [\Omega, \rho] = 0 \) means total asymmetry \( \text{tr} [\rho - \bar{\rho}] \) is not generated.
Two scales approximation

Two scales approximation, \( p \sim m_\phi, p \sim T \)

\[
(r_k)_{ij} = \int_{|p| \sim m_\phi} \frac{d^3p}{(2\pi)^3} \frac{\rho_{ij}(p, t)}{s},
\]

\[
(\delta \rho_T)_{ij} = \int_{|p| \sim T} \frac{d^3p}{(2\pi)^3} \left( \frac{\rho_{ij}(p)}{s} - \frac{\rho_{ij}^{eq}(p)}{s} \right),
\]

\[
i \frac{d\rho_k}{dt} = [\Omega_k, \rho_k] - \frac{i}{2} \{\Gamma^d_k, \rho_k\},
\]

\[
i \frac{d\delta \rho_T}{dt} = [\Omega_T, \delta \rho_T] - \frac{i}{2} \{\Gamma^d_T, \delta \rho_T\} + i\delta \Gamma^p_T,
\]
Equations to be solved

\[ i \frac{d \rho_k}{dt} = \{ \Omega_k, \rho_k \} - \frac{i}{2} \{ \Gamma_d^k, \rho_k \}, \]

\[ i \frac{d \delta \rho_T}{dt} = \{ \Omega_T, \delta \rho_T \} - \frac{i}{2} \{ \Gamma_d^T, \delta \rho_T \} + i \delta \Gamma_p^T, \]

\[ \Omega_k = \frac{y_i^2 T^2}{16 m_\phi} \delta_{ij} + 0.046(\kappa^* \kappa)_{ij} \frac{T^4}{m_\phi} \]

\[ \Omega_T = \frac{y_i^2 T}{16} \delta_{ij} + 0.046(\kappa^* \kappa)_{ij} T^3 \]

\[ \left( \Gamma_d^k \right)_{ij} \simeq C \alpha_2^2 T \sqrt{\frac{T}{|k|}} \delta_{ij} + \frac{9 y_i^2}{64 \pi^3 |k|} T^2 \left( \delta_{ir} \delta_{rj} y_{\tau}^2 + \delta_{ij} \delta \mu \nu y_{\mu}^2 \right) + \frac{21 \zeta(3)}{32 \pi^3} (\kappa^* \cdot \kappa)_{ij} T^3, \]

\[ \left( \Gamma_d^T \right)_{ij} \simeq C' \alpha_2^2 T \delta_{ij} + \frac{9 y_i^2}{64 \pi^3} T \left( \delta_{ir} \delta_{rj} y_{\tau}^2 + \delta_{ij} \delta \mu \nu y_{\mu}^2 \right) + \frac{21 \zeta(3)}{32 \pi^3} (\kappa^* \cdot \kappa)_{ij} T^3, \]

\[ (\delta \Gamma_p^T)_{ij} \simeq C \alpha_2^2 T \sqrt{\frac{T}{|k|}} (\rho_k)_{ij} - C' \alpha_2^2 T (\delta \rho_T)_{ij} \]

\[ + \frac{3 \zeta(3)}{8 \pi^3} (\kappa^* \cdot (\bar{\rho}_k - 3/4 \rho_k)^t \cdot \kappa)_{ij} T^3 + \frac{3 \zeta(3)}{8 \pi^3} (\kappa^* \cdot (\delta \rho_T - 3/4 \delta \rho_T)^t \cdot \kappa)_{ij} T^3. \]

Some formula can be also found in Akhmedov, et al. 9803255; Abada, et al. 0601083.; Asaka, et al. 1112.5565. See Refs. [Landau and Pomeranchuk 1953; Migdal 1956] for LPM effect.
\[ \Delta_{33}/s/B \]

\[ -n_{L}/s/B \]

\[ \Delta_{33}/s \equiv (U_{PMNS}^{-1}(\rho - \bar{\rho})U_{PMNS})_{33} \]

\[ n_{L}/s \equiv \text{Tr}[\rho - \bar{\rho} + ...] \]
Flavor dependent asymmetry but

\[ n_L/s \approx \Delta_{33} + \Delta_{22} + \Delta_{11} \sim 0 \]

\[ \Delta_{33}/s/B \]

\[ -n_L/s/B \]

\[ t \times H(T_R) \]

\[ \Delta_{33}/s \equiv (U_{PMNS}^{-1}(\rho - \bar{\rho})U_{PMNS})_{33} \]

\[ n_L/s \equiv \text{Tr}[\rho - \bar{\rho} + ...] \]
\[(\Gamma_{\nu\nu})_{\alpha} \propto m_{\nu\alpha}^2\]

Normal hierarchy: \((\Gamma_{\nu\nu})_3\) is largest.

Flavor dependent asymmetry but

\[n_L/s \simeq \Delta_{33} + \Delta_{22} + \Delta_{11} \sim 0\]

\[\Delta_{33}/s/B\]

Washout

\[-n_L/s/B\]

Oscillation

\[\Delta_{33}/s/B\]

(net) Asymmetry Production

\[\Delta_{33}/s \equiv (U_{\nu_{PMNS}}^{-1}(\rho - \bar{\rho})U_{\nu_{PMNS}})_{33}\]

\[n_L/s \equiv \text{Tr}[\rho - \bar{\rho} + ...]\]
\[
(\Gamma_{w_0})_\alpha \propto m_{\nu_\alpha}^2
\]

Normal hierarchy: \((\Gamma_{w_0})_3\) is largest.

\[
\Delta_{33}/s/B
\]

Flavor dependent asymmetry but

\[
n_L/s \simeq \Delta_{33} + \Delta_{22} + \Delta_{11} \sim 0
\]

Washout

\[
-n_L/s/B
\]

Oscillation

\[
\Delta_{33}/s/B
\]

(\text{net}) Asymmetry Production

\[
\Delta_{33}/s/B
\]

“Observation” via Yukawa interaction

\[
\Delta_{33}/s \equiv (U_{\text{PMNS}}^{-1}(\rho - \bar{\rho})U_{\text{PMNS}})_{33}
\]

\[
n_L/s \equiv \text{Tr}[\rho - \bar{\rho} + ...]
\]
FIGURES FOR INFLATON->LEPTON
Inverted hierarchy one massless neutrino. Other parameters are same as the main part one.
normal order degenerate mass. $m_{\text{nu lightest}} = 0.07 \text{eV}$
Other parameters are same as the main part one.
inverted order degenerate mass. $m_{\nu\text{lightest}} = 0.07\text{eV}$
Other parameters are same as the main part one.
FIGURES FOR INFLATON->HIGGS
Solution (Normal Hierarchy)

$\phi \rightarrow $ Higgs

Solid: good sign.
Dashed: opposite sign

Majorana phase
- $\alpha_M=\pi/2$
- $\alpha_M=\pi/4$
- $\alpha_M=0$
- $\alpha_M=-\pi/4$
- $\alpha_M=-\pi/2$

Inflaton mass $=100$ $T_R$
Two massive neutrinos. Dirac Phase=$-\pi/2$
Inverted degenerate case.

\[ m_{\text{nulightest}} = 0.07 \text{eV} \]
Normal hierarchy one massless neutrino.

\[ \alpha_M = \frac{\pi}{2} \]
\[ \alpha_M = \frac{\pi}{4} \]
\[ \alpha_M = 0 \]
\[ \alpha_M = -\frac{\pi}{4} \]
\[ \alpha_M = -\frac{\pi}{2} \]
Normal hierarchy degenerate case.
mulightest = 0.07eV
Neutrinoless double beta decay

The CP phase and neutrino mass can be tested from neutrino exps.

\[ \delta = -\pi/2, T_R \geq 10^{15} \text{GeV} \]
\[ \delta = -3\pi/4, \quad T_R \leq 10^{13}\text{GeV} \]