Baryogenesis via Particle—Antiparticle Oscillations

Seyda Ipek
UC Irvine

There is more matter than antimatter

$\Omega_\Lambda \sim 0.69$
$\Omega_{DM} \sim 0.27$
$\Omega_B \sim 0.04$

number of baryons:

$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$
$\approx 6 \times 10^{-10}$
How the Universe would do

Need to produce 1 extra quark for every 10 billion antiquarks!

Sakharov Conditions

Three conditions must be satisfied:

1) Baryon number (B) must be violated ✔
   can’t have a baryon asymmetry w/o violating baryon number!

2) C and CP must be violated ❌
   a way to differentiate matter from antimatter

3) B and CP violating processes must happen out of equilibrium ❌
   equilibrium destroys the produced baryon number

Sakharov, JETP Lett. 5, 24 (1967)
We need New Physics

Couples to the SM

Extra CP violation

Some out-of-equilibrium process
We need New Physics

Couples to the SM

Let’s re-visit SM CP violation

Extra CP violation

Some out-of-equilibrium process
Particle—Antiparticle Oscillations

Take a Dirac fermion with an approximately broken $U(1)$ charge

$$-\mathcal{L}_{\text{mass}} = M \bar{\psi} \psi + \frac{m}{2} (\bar{\psi}^c \psi + \bar{\psi} \psi^c)$$

with interactions

$$-\mathcal{L}_{\text{int}} = g_1 \bar{\psi} \; X \; Y + g_2 \bar{\psi}^c \; X \; Y + \text{h.c.}$$

$\psi$ : pseudo-Dirac fermion

We will want the final state $XY$ to carry either baryon or lepton number
Particle—Antiparticle Oscillations

Hamiltonian: \[ H = M - \frac{i}{2} \Gamma \]

\[ M = \begin{pmatrix} M & m \\ m & M \end{pmatrix} \]

\[ \Gamma \approx \Gamma \begin{pmatrix} 1 & 2r e^{i\phi_\Gamma} \\ 2r e^{-i\phi_\Gamma} & 1 \end{pmatrix} \]

Eigenvectors: \[ |\psi_{H,L}\rangle = p |\psi\rangle \pm q |\psi^c\rangle \]

Mass states ≠ interaction states

Oscillations!
Particle—Antiparticle Oscillations

important parameter:

\[ x \equiv \frac{\Delta m}{\Gamma} \]

\[ \Delta m = M_H - M_L \approx 2m \]

Goldilocks principle for oscillations

- \( x \gg 1 \): Too fast
- \( x \sim 1 \): Just right
- \( x \ll 1 \): Too slow
CP Violation in Oscillations

\[ \epsilon = \int_0^\infty dt \left( \frac{\Gamma(\psi/\psi^c \rightarrow f) - \Gamma(\psi/\psi^c \rightarrow \bar{f})}{\Gamma(\psi/\psi^c \rightarrow f) + \Gamma(\psi/\psi^c \rightarrow \bar{f})} \right) \]

For \[ r = \frac{|g_2|}{|g_1|} \ll 1 \]

\[ \epsilon \approx \frac{2x r \sin \phi_\Gamma}{1 + x^2} \]

CP violation is maximized for \[ x \sim 1 \]
Out-of-equilibrium decays?

Baryon Number Violation

Say the final state $f$ has baryon number $+1$

e.g. RPV SUSY

Out-of-equilibrium decays?

Why not?
Oscillations in the early Universe are complicated

Described by the time evolution of the density matrix

\[
zh \frac{dY}{dz} = -i(\text{HY} - \text{YH}^\dagger) - \frac{\Gamma_{\pm}}{2} [O_{\pm}, [O_{\pm}, Y]]
- s\langle \sigma v \rangle_{\pm} \left( \frac{1}{2} \{Y, O_{\pm} \bar{Y} O_{\pm} \} - Y_{eq}^2 \right)
\]

\( H \): Hamiltonian
\( Y \): Density matrix
\( O_{\pm} = \text{diag}(1, \pm 1) \)

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Oscillations

Vanishes if scatterings are flavor blind

Annihilations

\( z = M/T \) not redshift!
Oscillations in the early Universe are complicated.

$$M \sim 300 \text{ GeV}$$
Oscillations in the early Universe are complicated

\[ M \sim 300 \text{ GeV} \]

Out-of-equilibrium decay: \[ \Gamma \lesssim H (T \sim M) \]
Oscillations in the early Universe are complicated

\[ M \sim 300 \text{ GeV} \]

Oscillations start when

\[ \omega_{\text{osc}} > H \]

Out-of-equilibrium decay:

\[ \Gamma \lesssim H(T \sim M) \]
Oscillations in the early Universe are complicated

Particles/antiparticles are in a hot/dense plasma with interactions

\[ -\mathcal{L}_{\text{scat}} = \frac{1}{\Lambda^2} \bar{\psi} \Gamma^a \psi \bar{f} \Gamma_a f \]
Oscillations in the early Universe are complicated

$M \sim 300$ GeV

Big Bang?

Time

Rates (eV)

Hubble rate

annihilation rate

elastic scattering rate

Decay rate

$\omega_{osc} = 2 \text{ m}$

oscillations are further delayed

$z = M/T$
Let there be baryons!

For $z > z_{\text{osc}}$ baryon asymmetry is given by:

$$\frac{d\Delta_B(z)}{dz} \sim \frac{\epsilon \Gamma}{zH} \Sigma(z)$$
What kind of model?

Oscillations ↔ Pseudo-Dirac fermions

Approximately broken $U(1)$ symmetry

$U(1)_R$-symmetric SUSY with a pseudo-Dirac bino!
Pseudo-Dirac bino oscillations

Mass terms: \[-\mathcal{L}_{\text{mass}} \to M_D BS + \frac{1}{2} \left( m_\tilde{B} \tilde{B} \tilde{B} + m_S SS \right) + \text{h.c.}\]

Let’s also consider R-parity violation

\[-\mathcal{L}_{\text{eff}} = G_\tilde{B} \tilde{B} \tilde{u} \tilde{d} \tilde{d} + G_S S \tilde{u} \tilde{d} \tilde{d} + \text{h.c.}\]

Remember from before:

\[-\mathcal{L}_{\text{mass}} = M \tilde{\psi} \psi + \frac{m}{2} \left( \tilde{\psi}^c \psi + \tilde{\psi} \psi^c \right)\]

with interactions

\[-\mathcal{L}_{\text{int}} = g_1 \tilde{\psi} XY + g_2 \tilde{\psi}^c X Y + \text{h.c.}\]

\( G_B \sim \frac{g_Y \lambda''}{m_{sf}^2} \quad G_S \sim \frac{g_S \lambda''}{m_{\phi}^2} \)
Pseudo-Dirac bino oscillations

Oscillation Hamiltonian:

\[ \mathcal{H} = \left( \begin{array}{cc} M_D & m \\ m & M_D \end{array} \right) - \frac{i}{2} \Gamma \left( \begin{array}{cc} 1 & 2r e^{i \phi} \\ 2r e^{-i \phi} & 1 \end{array} \right) \]

\[ \Gamma \approx \frac{M^5}{(32 \pi)^3} |G_B|^2 \quad r = \frac{|G_S|}{|G_B|} \ll 1 \]

with annihilations + elastic scatterings:

\[ -\mathcal{L}_{\text{scat}} = \frac{g_Y^2}{m_{\text{sf}}^2} \bar{\psi} \gamma_{\mu} P_L \psi \bar{F} \gamma^{\mu} (g_V + g_A \gamma_5) F \]

\[ g_{V,A} = \frac{Y_R^2 \pm Y_L^2}{2} \quad F = \left( \begin{array}{c} f_L \\ f_R^\dagger \end{array} \right) \]
Let there be baryons!

\[ \Sigma(z) \]

\[ \Delta(z) \]

\[ \Delta_B(z) \]

\[ M = 300 \text{ GeV} \]
\[ m = 2 \times 10^{-6} \text{ eV} \]
\[ \Gamma = 10^{-6} \text{ eV} \]
\[ \phi_r = \pi/6, \ r = 0.1 \]

\[ m_{\text{sf}} = 10 \text{ TeV} \]
\[ m_{\text{sf}} = 20 \text{ TeV} \]

\[ z = M/T \]

BARYONS!!!
Outlook

• Sfermions are a few TeV (no lighter than ~ 3 TeV)

• $O(100 \text{ GeV} - \text{TeV})$ particles $\rightarrow$ Colliders!

• Decay rate $< 10^{-4} \text{ eV}$ $\rightarrow$ travels $> \text{mm}$ displaced vertices!

• How about lepton number violation? same-sign lepton asymmetry?

• Neutron — antineutron oscillations???
backup slides
Oscillations+Decays

\[
\frac{d^2 \Delta(y)}{dy^2} + 2 \xi \omega_0 \frac{d\Delta(y)}{dy} + \omega_0^2 \Delta(y) = -\epsilon \omega_0^2 \Sigma(y)
\]

For: \( \Sigma(z) = 2 Y_{eq}(1) \exp \left( -\frac{\Gamma}{2H(z)} \right) \) for \( z > 1 \)

Solution is

\[
\Delta(z) \simeq A \epsilon Y_{eq}(1) \exp \left( -\frac{\Gamma}{2H(z)} \right) \sin^2 \left( \frac{m}{2H(z)} + \delta \right)
\]
Different mass difference

\[ M = 300 \text{ GeV} \]

\[ \phi_{\Gamma} = \pi/6, \ r = 0.1 \]

\[ \sigma_0 = 1 \text{ ab} \]

\[ \Delta B = 10^{-7} \text{ eV} \]

\[ \Gamma = 10^{-4} \text{ eV} \]

\[ \Gamma = 10^{-5} \text{ eV} \]

\[ \Gamma = 10^{-6} \text{ eV} \]

\[ \Gamma = 10^{-7} \text{ eV} \]
Oscillation start times

Hubble

\[ z_{osc} \sim 6 \sqrt{\frac{2 \times 10^{-6} \text{ eV}}{m}} \left( \frac{M}{300 \text{ GeV}} \right) \]

Flavor-blind

\[ z_{osc} \sim \ln \left[ 10^7 \left( \frac{M}{300 \text{ GeV}} \right)^3 \left( \frac{2 \times 10^{-6} \text{ eV}}{m} \right) \left( \frac{\sigma_0}{1 \text{ fb}} \right) \right] \]

Flavor-sensitive

\[ z_{osc} \sim 80 \left( \frac{M}{300 \text{ GeV}} \right)^{3/5} \left( \frac{2 \times 10^{-6} \text{ eV}}{m} \right)^{1/5} \left( \frac{\sigma_0}{1 \text{ fb}} \right)^{1/5} \]