Post-Sphaleron Baryogenesis and $n - \bar{n}$ Oscillations

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Based on:
K. S. Babu, R. N. Mohapatra (2017) (to appear);
K. S. Babu, R. N. Mohapatra and S. Nasri, hep-ph/0606144; hep-ph/0612357;
K. S. Babu, P. S. Bhupal Dev and R. N. Mohapatra, arXiv:0811.3411 [hep-ph];
K. S. Babu, P. S. Bhupal Dev, E. C. F. S. Fortes and R. N. Mohapatra, arXiv:1303.6918 [hep-ph]

Outline

- Idea of post-sphaleron baryogeneis
- Explicit models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ symmetry
- Relating baryogenesis with neutron-antineutron oscillation
- Other experimental tests
- Conclusions

Generating Baryon Asymmetry of the Universe

- Observed baryon asymmetry:

$$Y_{\Delta B} = \frac{n_B - n_{\overline{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

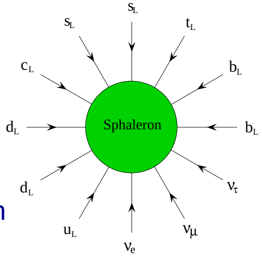
- Sakharov conditions must be met to dynamically generate $Y_{\Delta B}$
  - Baryon number (B) violation
  - C and CP violation
  - Departure from thermal equilibrium
- All ingredients are present in Grand Unified Theories. However, in simple GUTs such as $SU(5)$, $B - L$ is unbroken
- Electroweak sphalerons, which are in thermal equilibrium from $T = (10^2 - 10^{12})$ GeV, wash out any $B - L$ preserving asymmetry generated at any $T > 100$ GeV

Kuzmin, Rubakov, Shaposhnikov (1985)

Generating baryon asymmetry (cont.)

- Sphaleron: Non-perturbative configuration of the electroweak theory
- Leads to effective interactions of left-handed fermions:

$$O_{B+L} = \prod_i (q_i q_i q_i L_i)$$



- Obeys $\Delta B = \Delta L = 3$
- Sphaleron can convert lepton asymmetry to baryon asymmetry – Leptogenesis mechanism (Fukugita, Yanagida (1986))
- Post-sphaleron baryogenesis: Baryon number is generated below 100 GeV, after sphalerons go out of equilibrium (Babu, Nasri, Mohapatra (2006))

Post-Sphaleron Baryogenesis

- A scalar (S) or a pseudoscalar (η) decays to baryons, violating B
- $\Delta B = 1$ is strongly constrained by proton decay and cannot lead to successful post-sphaleron baryogenesis
- $\Delta B = 2$ decay of S/η can generate baryon asymmetry below $T = 100$ GeV: $S/\eta \to 6\,q$; $S/\eta \to 6\,\overline{q}$
- Decay violates CP, and occurs out of equilibrium
- Naturally realized in quark-lepton unified models, with S/η identified as the Higgs boson of $B - L$ breaking
- $\Delta B = 2 \Rightarrow$ connection with $n - \overline{n}$ oscillation
- Quantitative relationship exists in quark-lepton unified models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$

Conditions for Post-Sphaleron Baryogenesis

- At high temperature, T above the masses of S/η and the mediators, the B-violating interactions are in equilibrium:

$$\Gamma_{\Delta B \neq 0}(T) \gg H(T) = 1.66 (g^*)^{1/2} \frac{T^2}{M_{\rm Pl}}$$

- As universe cools, S/η freezes out from the plasma while relativistic at $T = T_*$ with $T_* \geq M_{S/\eta}$. (Number density of S/η is then comparable to n_γ.)
- For $T < T_*$, decay rate of S/η is a constant. S/η drifts and occasionally decays. As the universe cools, $H(T)$ slows; at some temperature T_d, the constant decay rate of S/η becomes comparable to $H(T_d)$. S/η decays at $T \sim T_d$ generating B.
- Post-sphaleron mechanism assumes $T_d = (10^{-1} - 100)$ GeV.

Dilution of Baryon Asymmetry

- $S/\eta \to 6q$ decay occurs at $T_d \ll M_{S/\eta}$. There is no wash out effect from back reactions

- However, S/η decay dumps entropy into the plasma. This results in a dilution:

$$d \equiv \frac{s_{\rm before}}{s_{\rm after}} \simeq \frac{g_*^{-1/4} 0.6 (\Gamma_\eta M_{\rm Pl})^{1/2}}{r M_\eta} \simeq \frac{T_d}{M_\eta}$$

- M_η cannot be much higher than a few TeV, or else the dilution will be too strong

- There is a further dilution of order 0.1, owing to the change of g_* from 62.75 at 200 MeV to 5.5 after recombination

Summary of Constraints on PSB

- Pseudoscalar η must have $\Delta B = 2$ decays
- Such decays should have CP violation to generate B asymmetry
- η should freeze-out while relativistic: $T_* \geq M_\eta$. This requires η to be feebly interacting, and a singlet of Standard Model
- T_d, the temperature when η decays, should lie in the range $T_d = (100 \text{ MeV} - 100 \text{ GeV})$
- η should have a mass of order TeV, or else baryon asymmetry will suffer a dilution of T_d/M_η

Quark-Lepton Symmetric Models

- Quark-lepton symmetric models based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_C$ have the necessary ingredients for PSB
- There is no $\Delta B = 1$ processes since $B - L$ is broken by 2 units. Thus there is no rapid proton decay. Symmetry may be realized in the 100 TeV range
- There is baryon number violation mediated by scalars, which are the partners of Higgs that lead to seesaw mechanism
- Scalar fields S/η arise naturally as Higgs bosons of $B - L$ breaking
- Yukawa coupling that affect PSB and $n - \overline{n}$ oscillations are the same as the ones that generate neutrino masses

Quark-Lepton Symmetric Models

- Models based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ (Pati-Salam)
- Fermions, including ν_R, belong to $(2,1,4) \oplus (1,2,4)$
- Symmetry breaking and neutrino mass generation needs Higgs field $\Delta(1,3,\overline{10})$. Under $SU(2)_L \times U(1)_Y \times SU(3)_C$:

$$\begin{aligned}\Delta(1,3,\overline{10}) \;=\; & \Delta_{uu}(1,-\tfrac{8}{3},6^*) \oplus \Delta_{ud}(1,-\tfrac{2}{3},6^*) \oplus \Delta_{dd}(1,+\tfrac{4}{3},6^*) \oplus \Delta_{ue}(1,\tfrac{2}{3},3^*) \\ & \oplus \Delta_{u\nu}(1,-\tfrac{4}{3},3^*) \oplus \Delta_{de}(1,\tfrac{8}{3},3^*) \oplus \Delta_{d\nu}(1,\tfrac{2}{3},3^*) \oplus \Delta_{ee}(1,4,1) \\ & \oplus \Delta_{\nu e}(1,2,1) \oplus \Delta_{\nu\nu}(1,0,1)\,.\end{aligned}$$

- Δ_{uu}, Δ_{ud}, Δ_{dd} are diquarks, Δ_{ue}, $\Delta_{u\nu}$, Δ_{de}, $\Delta_{d\nu}$ are leptoquarks, and $\Delta_{\nu\nu}$ is a singlet that breaks the symmetry
- Diquarks generate B violation, leptoquarks help with CP violation, and singlet $\Delta_{\nu\nu}$ provides the field S/η for PSB

Quark-Lepton Symmetric Models (cont.)

- Interactions of color sextet diquarks and B violating couplings:

$$\mathcal{L}_I = \frac{f_{ij}}{2}\Delta_{dd} d_i d_j + \frac{h_{ij}}{2}\Delta_{uu} u_i u_j + \frac{g_{ij}}{2\sqrt{2}}\Delta_{ud}(u_i d_j + u_j d_i) + \frac{\lambda}{2}\Delta_{\nu\nu}\Delta_{dd}\Delta_{ud}\Delta_{ud} + \lambda' \Delta_{\nu\nu}\Delta_{uu}\Delta_{dd}\Delta_{dd} + \mathrm{h.c.}$$

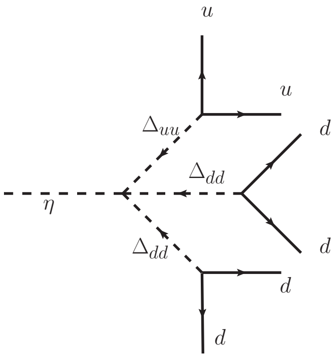
- $f_{ij} = g_{ij} = h_{ij}$ and $\lambda = \lambda'$ from gauge symmetry.
- We also introduce a scalar $\chi(1,2,4)$ which couples to $\Delta(1,3,\overline{10})$ via $(\mu\chi\chi\Delta \supset \chi_\nu\chi_\nu\Delta_{\nu\nu} + \ldots)$
- Among the phases of $\Delta_{\nu\nu}$ and χ_ν, one combination is eaten by $B-L$ gauge boson. The other, is a pseudoscalar η:

$$\Delta_{\nu\nu} = \frac{(\rho_1 + v_R)}{\sqrt{2}} e^{i\eta_1/v_R}, \chi_\nu = \frac{(\rho_2 + v_B)}{\sqrt{2}} e^{i\eta_2/v_B}, \eta = \frac{2\eta_2 v_R - \eta_1 v_B}{\sqrt{4v_R^2 + v_B^2}}$$

- Advantage of using $\eta \to 6\,q$ is that η has a flat potential due to a shift symmetry

Baryon violating decay of η

$\eta \to 6q$ and $\eta \to 6\overline{q}$ decays violate B:



Baryon violating decay of η (cont.)

- B-violating decay rate of η:

$$\Gamma_\eta \equiv \Gamma(\eta \to 6q) + \Gamma(\eta \to 6\bar{q}) = \frac{P}{\pi^9 \cdot 2^{25} \cdot 45} \frac{12}{4} |\lambda|^2 \mathrm{Tr}(f^\dagger f)[\mathrm{Tr}(\hat{g}^\dagger \hat{g})]^2 \left(\frac{M_\eta^{13}}{M_{\Delta_{ud}}^8 M_{\Delta_{dd}}^4} \right)$$

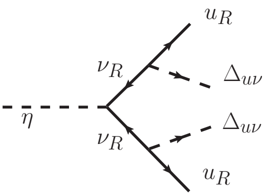
- Here P is a phase space factor:

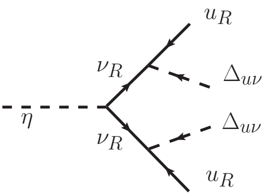
$$P = \begin{cases} 1.13 \times 10^{-4} & (M_{\Delta_{ud}}/M_S, M_{\Delta_{dd}}/M_S \gg 1) \\ 1.29 \times 10^{-4} & (M_{\Delta_{ud}}/M_S = M_{\Delta_{dd}}/M_S = 2) \ . \end{cases}$$

- T_d is obtained by setting this rate to Hubble rate. For $T_d = (100$ MeV -100 GeV), $f \sim g \sim h \sim 1$, $M_{\Delta_{ud}} \sim M_\eta$ needed
- η has a competing $B = 0$ four-body decay mode, which is necessary to generate CP asymmetry: $\eta \to (uu)\Delta_{u\nu}\Delta_{u\nu}$
- The six-body and four-body decays should have comparable widths, or else B asymmetry will be too small

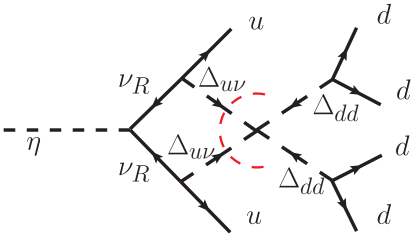
Baryon conserving decay of η

$\eta \to (uu)\Delta_{u\nu}\Delta_{u\nu}$





This generates absorptive part and CP violation in $\eta \to 6q$:



Baryon Asymmetry

- $\eta \to uu\Delta_{u\nu}\Delta_{u\nu}$ has a width:

  $\Gamma_\eta \equiv \Gamma(\eta \to uu\Delta_{u\nu}\Delta_{u\nu}) + \Gamma(\eta \to \overline{uu}\Delta - u\nu^*\Delta^*_{u\nu}) = \frac{P}{1024\pi^5}[\mathrm{Tr}(\hat{f}^\dagger \hat{f})]^3 \left(\frac{M_\eta^5}{M_{\nu_R}^4}\right)$
- Here P is a phase space factor, $P \simeq 2 \times 10^{-3}$
- For $\lambda = 1$, $\Gamma_6 \simeq (7 \times 10^{-9}) \times \Gamma_4 \times \frac{M^4_{\nu_R}}{M^4_{\Delta_{dd}}}$
- Baryon asymmetry:

$$\epsilon_B \simeq \frac{|f|^2 \mathrm{Im}(\lambda\tilde{\lambda})}{8\pi(|\lambda|^2 + \Gamma_4/\Gamma_6)} \left(\frac{M^2_{\Delta_{dd}}}{M^2_{\nu_R}}\right)$$

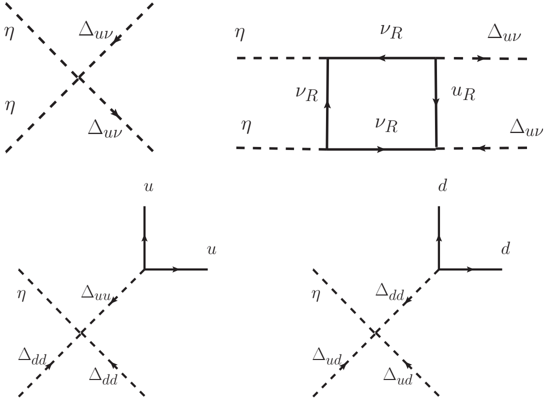
- With $M_{\nu_R} \sim 100 \times M_{\Delta_{dd}}$, $\Gamma_4 \sim \Gamma_6$. This choice maximizes ϵ_B:

$$\epsilon_B \sim (8 \times 10^{-5}) \times \frac{|f|^2}{8\pi} \mathrm{Im}(\frac{\tilde{\lambda}}{\lambda})$$

- For $f \sim \lambda \sim 1$, reasonable baryon asymmetry is generated with a dilution $d \sim 10^{-3}$

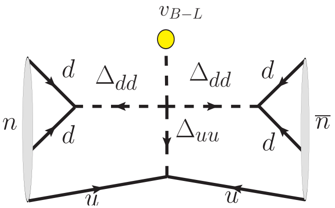
Other constraints for successful baryogenesis

η must freeze out at $T \geq M_\eta$. Interactions of η with lighter particles must be weak. The scattering processes freeze out as desired, owing to the shift symmetry in η.



Connection with $n - \overline{n}$ oscillation

As η is associated with $B - L$ symmetry breaking, replacing η by the vacuum expectation value, $n - \overline{n}$ oscillation results:



$M_\eta \sim 3\,TeV$, $M_{\Delta_{ud}} \sim 4\,TeV$, $M_{\Delta_{dd}} \sim 50\,TeV$, $M_{\Delta u\nu} \sim 1\,TeV$, $v_{B-L} \sim 300\,TeV$ is a consistent choice

Flavor dependence of baryon asymmetry can be fixed via neutrino mass generation

Connection with neutrino oscillations

- Quark-Lepton symmetry implies that the Yukawa couplings entering η decay and $n - \overline{n}$ oscillation is the same as in neutrino mass generation
- In type-II seesaw mechanism for neutrino masses, $M_\nu \propto f$. A consistent choice of f that yields inverted neutrino spectrum:

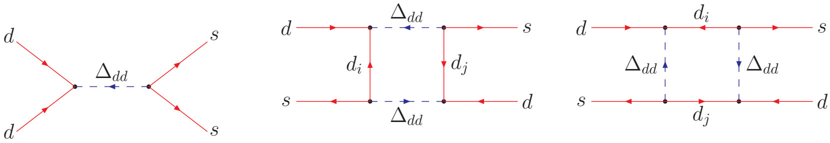
$$f = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & 0.01 \\ 1 & 0.01 & 0.06 \end{pmatrix}$$

- This choice satisfies all flavor changing constraints mediated by color sextet scalars
- The (1,1) entry will be relevant for $n - \overline{n}$ oscillation. It is induced via a W boson loop

Flavor changing constraints

- $\Delta_{dd}, \Delta_{uu}, \Delta_{ud}$ fields lead to flavor violation, at tree level as well as at loop:

$$\begin{aligned}\mathcal{H}_{\Delta F=2} \quad &= \quad -\frac{1}{8}\frac{f_{i\ell}f^*_{kj}}{M^2_{\Delta_{dd}}}(\overline{d}^\alpha_{kR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{jR}\gamma^\mu d^\beta_{\ell R}) + \frac{1}{256\pi^2}\frac{[(ff^\dagger)_{ij}(ff^\dagger)_{\ell k} + (ff^\dagger)_{ik}(ff^\dagger)_{\ell j}]}{M^2_{\Delta_{dd}}} \\ &\times \left[(\overline{d}^\alpha_{jR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\beta_{\ell R}) + 5(\overline{d}^\alpha_{jR}\gamma_\mu d^\beta_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\alpha_{\ell R})\right]\end{aligned}$$



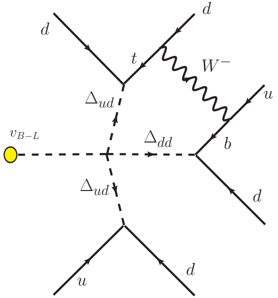
Flavor changing constraints

Process	Diagram	Constraint on Couplings
Δm_{B_s}	Tree	$\lvert f_{22} f_{33}^* \rvert \leq 7.04 \times 10^{-4} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i3} f_{i2}^* \rvert \leq 0.14 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i3} \hat{g}_{i2}^* \rvert \leq 1.09 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_{B_d}	Tree	$\lvert f_{11} f_{33}^* \rvert \leq 2.75 \times 10^{-5} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i3} f_{i1}^* \rvert \leq 0.03 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i3} \hat{g}_{i1}^* \rvert \leq 0.21 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_K	Tree	$\lvert f_{11} f_{22}^* \rvert \leq 6.56 \times 10^{-6} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i2} f_{i1}^* \rvert \leq 0.01 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i1} \hat{g}_{i2}^* \rvert \leq 0.10 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_D	Tree	$\lvert h_{11} h_{22}^* \rvert \leq 3.72 \times 10^{-6} \left(\frac{M_{\Delta_{uu}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert h_{i2} h_{i1}^* \rvert \leq 0.01 \left(\frac{M_{\Delta_{uu}}}{1\ \mathrm{TeV}}\right)$

Table : Constraints on the product of Yukawa couplings in the PSB model from $K^0 - \overline{K}^0$, $D^0 - \overline{D}^0$, $B_s^0 - \overline{B}_s^0$ and $B_d^0 - \overline{B}_d^0$ mixing.

Prediction for $n - \overline{n}$ oscillation

- We take all PSB constraints, neutrino mass and mixing constraints, and FCNC constraints to estimate $n - \overline{n}$ oscillation time
- The flavor structure of f has a zero in the (1,1) element. This entry is generated by a W boson loop.



Prediction for $n-\bar{n}$ oscillation (cont.)

- Amplitude for $n-\bar{n}$ oscillation:

$$A^{\rm tree}_{n-\bar{n}} \simeq \frac{f_{11} g_{11}^2 \lambda v_{BL}}{M^2_{\Delta_{dd}} M^4_{\Delta_{ud}}} + \frac{f_{11}^2 h_{11} \lambda' v_{BL}}{M^4_{\Delta_{dd}} M^2_{\Delta_{uu}}}$$

- Loop induced amplitude:

$$A^{1-{\rm loop}}_{n-\bar{n}} \simeq \frac{g^2 g_{11} g_{13} f_{13} V^*_{ub} V_{td} \lambda v_{BL}}{128\pi^2 M^2_{\Delta_{ud}}} \left(\frac{m_t m_b}{m_W^2}\right) F \langle \bar{n} | \mathcal{O}^2_{RLR} | n \rangle$$

- Loop function:

$$F = \frac{1}{M^2_{\Delta_{ud}} - M^2_{\Delta_{dd}}} \left[\frac{1}{M^2_{\Delta_{ud}}} \ln\left(\frac{M^2_{\Delta_{ud}}}{m_W^2}\right) - \frac{1}{M^2_{\Delta_{dd}}} \ln\left(\frac{M^2_{\Delta_{dd}}}{m_W^2}\right) \right] + \frac{1}{M^2_{\Delta_{ud}} M^2_{\Delta_{dd}}} \frac{1-(m_t^2/4m_W^2)}{1-(m_t^2/m_W^2)} \ln\left(\frac{m_t^2}{m_W^2}\right)$$

Prediction for $n - \bar{n}$ oscillation (cont.)

- Effective operator:

$$\mathcal{O}^2_{RLR} = (u^T_{iR} C d_{jR})(u^T_{kL} C d_{lL})(d^T_{mR} C d_{nR})\Gamma^s_{ijklmn}$$

- Matrix element in MIT bag model (Rao and Shrock):

$$\langle \bar{n} | \mathcal{O}^2_{RLR} | n \rangle = -0.314 \times 10^{-5}\ \mathrm{GeV}^6$$

- QCD correction:

$$c_{\rm QCD}(\mu_\Delta, 1\mathrm{GeV}) = \left[\frac{\alpha_s(\mu^2_\Delta)}{\alpha_s(m^2_t)}\right]^{8/7} \left[\frac{\alpha_s(m^2_t)}{\alpha_s(m^2_b)}\right]^{24/23} \left[\frac{\alpha_s(m^2_b)}{\alpha_s(m^2_c)}\right]^{24/25} \left[\frac{\alpha_s(m^2_c)}{\alpha_s(1\ \mathrm{GeV}^2)}\right]^{8/9}$$

$$\tau^{-1}_{n-\bar{n}} \equiv \delta m = c_{\rm QCD}(\mu_\Delta, 1\ \mathrm{GeV}) \left| A^{1-\mathrm{loop}}_{n-\bar{n}} \right|$$

Prediction for $n - \bar{n}$ oscillation (cont.)

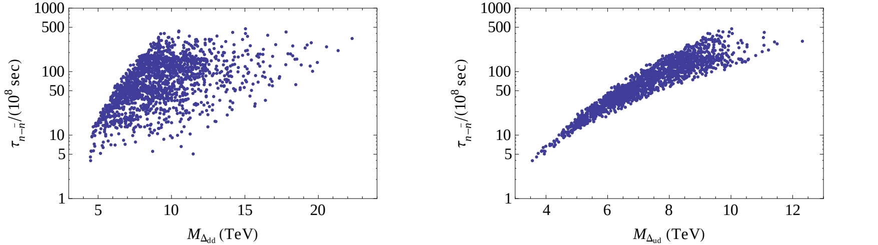


Figure : Scatter plots for $\tau_{n-\bar{n}}$ as a function of the Δ masses $M_{\Delta_{ud}}, M_{\Delta_{dd}}$.

Prediction for $n - \bar{n}$ oscillation (cont.)

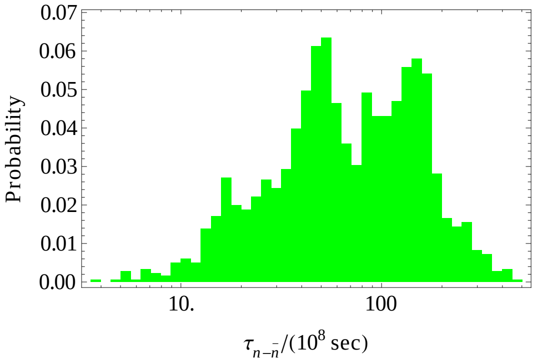


Figure : The likelihood probability for a particular value of $\tau_{n-\bar{n}}$ as given by the model parameters.

Conclusions

- Post-sphaleron baryogenesis is an alternative to high scale leptogenesis
- Directly linked with $n - \overline{n}$ oscillation
- In quark-lepton symmetric models, post-sphaleron baryogenesis can lead to quantitative prediction for $n - \overline{n}$ oscillation time
- $\tau_{n-\overline{n}} \approx (10^9 - 10^{11})$ sec. is the preferred range from PSB
- Within a concrete model, an upper limit of $\tau_{n-\overline{n}} < 4 \times 10^{10}$ sec. is derived, which may be accessible to experiments