BARYOGENESIS WITH OBSERVABLE NEUTRON–ANTINEUTRON OSCILLATION*

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We discuss two different ways to understand the origin of matter in models with observable neutron–anti-neutron oscillation: *(i)* one, where colored scalars couple to a neutral scalar field whose vacuum expectation value (VEV) gives rise to n–$\bar{n}$ oscillation and whose decay is responsible for baryogenesis and *(ii)* another based on the Affleck–Dine mechanism, where an initial early universe asymmetry between the real and imaginary parts of a $\Delta B = 2$ scalar and its subsequent evolution generates the baryon asymmetry. We discuss some phenomenological implications of both these models. For example, when the first model is embedded as part of its natural gauge setting based on $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{SU}(4)_{\mathrm{c}}$ group, it leads to an upper limit on the n–$\bar{n}$ oscillation time that is accessible to a planned experiment at the ESS facility in Lund, Sweden. In the second case, a similar prediction results where a large part of the model parameter space can also be probed in the same experiment.

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1. Introduction

Nonconservation of baryon number (B) or lepton number (L) is known to be one of the key ingredients in resolving a fundamental puzzle of cosmology, the origin of matter–antimatter asymmetry of the universe. The other conditions laid out by Sakharov in a short 1967 paper are the presence of CP violation and thermal nonequilibrium of B/L violating interactions. All these conditions cannot be satisfied within the Standard Model (SM) implying that new physics is required for resolving this puzzle. This has made baryogenesis a hotbed of new ideas for beyond the Standard Model (BSM) physics. The models, in turn, have inspired a great deal of experimental efforts to search for processes that violate baryon and/or lepton number as well new paricles and their interactions. On the baryon violation front,

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which is the focus in this article, two classes of processes are under active scrutiny: proton decay which is a $\Delta B = 1$ process and involves leptons [1] *e.g.* $p \to \pi^0 + e^+$ decay and neutron–anti-neutron oscillation $n \to \bar{n}$ which is a $\Delta B = 2$ process [2] and involves no leptons. The first process probes physics at the scale of grand unification of matter and forces *e.g.* 10^{16} GeV, whereas the second one probes physics at the multi-TeV scale making a whole new set of other phenomena that can be probed in other baryon number conserving experiments. In this review, we focus on n–$\bar{n}$ oscillation and discuss models for baryogenesis with this process at an observable level. The experimental motivation for this is that there is a plan for a very high sensitive search for $n \to \bar{n}$ at the new European Spallation Source facility (ESS) in Lund, Sweden [3]. The same process will also be searched for at the Fermilab Deep Underground Neutrino Experiment (DUNE) [4] using nuclear decays. Both plan to extend the sensitivity of the search by many times the current Super-Kamiokande bound [5], and the old ILL bound [6]. There is also a search for the process in the SNO experiment [7]. It is interesting to point out that even though n–$\bar{n}$ search in proton decay experiments have nuclear physics uncertainties and is a very different type of experiment than neutron oscillation, the levels of the strengths of the B-violating interactions that are explored are the same in both, making them complementary although direct oscillation search is no doubt cleaner from both experimental and theoretical point of view.

Discovery of n–$\bar{n}$ oscillation will be revolutionary in the sense that our thinking on both the beyond the Standard Model physics as well as standard cosmological evolution of the universe will be deeply affected by it. For one thing, it will indicate a whole slew of new physics at the TeV scale such as new hadronic flavor changing effects, new color sextet fields in high-energy colliders, new source of CP violation *etc.* It will have a major impact on our thinking about the nature of grand unification of forces and matter as well. On the cosmological front, the epoch of baryogenesis will be different from other scenarios in the literature. It is therefore important to discuss how we go about understanding the origin of matter in BSM frameworks that lead to observable n–$\bar{n}$ oscillation. This is the subject of this article.

We will focus on two proposals for baryogenesis with observable $n \to \bar{n}$ in this paper. Both are multi-TeV scale models. The first is the so-called post-sphaleron baryogenesis mechanism(PSB) [8], where a real scalar particle, usually the B–L breaking Higgs field, decays to six quarks (via some intermediate states) and six antiquarks, and this in combination with other interactions in the theory *e.g.* CP violation leads to nonzero baryon asymmetry. This decay takes place after the Standard Model sphalerons have decoupled from the cosmic plasma leading to interesting constraints [9]. When the scalar field acquires a vacuum expectation value (VEV), it leads to observable n–$\bar{n}$ oscillation. The second proposal, recently advocated [10], uses the Affleck–Dine mechanism (AD) [11, 12], where the cosmological evolution of a baryon number carrying complex field with different real and imaginary part initial values in the inflationary epoch evolve to generate the baryon asymmetry. This mechanism was implemented in [10] in a multi-TeV scale effective field theory with observable $n \to \bar{n}$ oscillation.

This article is organized as follows: in Section 2, we present the basics of post-sphaleron baryogenesis and its implications for observability of neutron oscillation. In Section 3, we present the AD beryogenesis mechanism with all scalars with multi-TeV mass and emphasize its parameter ranges that can be probed in experiments. This overview only summarizes the salient points of both scenarios and leaves out the details to original papers. In Section 4, we give our concluding summary.

2. Post-sphaleron baryogenesis

It was pointed out in 1980 [13] that observable $n \to \bar{n}$ oscillation arises in the $\mathrm{SU(2)_L \times SU(2)_R \times SU(4)_c}$ [13] gauge model with a different set of Higgs structure than in the Pati–Salam model once one implements the seesaw mechanism for neutrino masses. The new Higgs structure was essential for generating this $\Delta B = 2$ process. The post-sphaleron baryogenesis idea was first proposed with the context of this model [8] and we briefly review it here. All the scales in the model are assumed to be 100 TeV or less. The fermions of the Standard Model together with the right-handed neutrino are assigned to the gauge group as in Table 1 (the first two rows) as well as the necessary Higgs multiplets (the next four rows).

Table 1. Field content of the model; top three lines are fermions and the rest are all bosonic fields. The $\varPsi$ fields contain the quarks Q and Q^c and the leptonic multiplets (L,R).

Fields	$\mathrm{SU(2)_L \times SU(2)_R \times SU(4)_c}$ representation
$\varPsi \equiv \begin{pmatrix} u_i & \nu \\ d_i & e \end{pmatrix}$	$(2, 1, 4)$
$\varPsi^c \equiv \begin{pmatrix} u_i^c & \nu^c \\ d_i^c & e^c \end{pmatrix}$	$(1, 2, 4)$
ϕ_0	$(2, 2, 1)$
ϕ_{15}	$(2, 2, 15)$
$\varDelta_\mathrm{R}$	$(1, 3, \bar{10})$
$\varDelta_\mathrm{L}$	$(3, 1, \bar{10})$

The Yukawa interactions involving these fields are given by

$$\begin{aligned}\mathcal{L}_Y &= Y_0\Psi\phi_0\Psi^c + Y_{15}\Psi\phi_{15}\Psi^c + \tilde{Y}_0\Psi\tilde{\phi}_0\Psi^c + \tilde{Y}_{15}\Psi\tilde{\phi}_{15}\Psi^c \\ &\quad + f\,(\Psi^c\Psi^c\Delta_{\mathrm{R}} + \Psi\Psi\Delta_{\mathrm{L}}) + \text{ h.c.}\end{aligned} \tag{1}$$

The first three terms after symmetry breaking are responsible for charged fermion masses. We assume that the neutrino masses arise from type II seesaw contribution that arises from the leptonic part of the f coupling, the last term in equation (1).

To discuss the interactions responsible for baryogenesis, in detail, let us write down the sub-multiplets of the Δ Higgs fields which contain the color sextet fields $(\Delta_{uu}, \Delta_{ud}, \Delta_{dd},)$, lepto-quark scalars $(\Delta_{\nu d}, \Delta_{eu}, \Delta_{\nu u}, \Delta_{ed})$, and dilepton fields $(\Delta_{ee}, \Delta_{u\nu}, \Delta_{\nu\nu})$, where subscripts denote that these particles have couplings to the corresponding right-handed fermions (u^c, d^c, ν^c, e^c). The Δ_{qq} fields are all color sextets. We omit the left-handed quarks fields for simplicity.

These multiplets can be decomposed in terms of their SM group sub-multiplets in the notation of $(\mathrm{SU}(3)_{\mathrm{c}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y)$ representations

$$\begin{aligned}\Delta_{uu} &= \delta_0 + \delta_3(3^*, 1, 4/3) + \delta_6(6^*, 1, 8/3)\,, \\ \Delta_{ud} &= \xi_+ + \xi_3(3^*, 1, -2/3) + \xi_6(6^*, 1, -2/3)\,, \\ \Delta_{dd} &= \sigma_{++} + \sigma_6(6^*, 1, 4/3) + \sigma_3(3^*, 1, 8/3)\,, \\ \Delta_{\nu\nu} &= \frac{v_{BL} + S}{\sqrt{2}} \mathrm{e}^{i\eta/v_{BL}}\,.\end{aligned} \tag{2}$$

It is is clear from the above equations that the quark couplings to color sextet scalars will lead to flavor changing hadronic processes. These were analyzed in detail in [9]. We address the constraints that follow in the next subsection and what it implies for the neutrino mass texture assuming it arises via the type II seesaw.

2.1. FCNC constraints, Majorana Yukawa texture and Higgs spectrum

Anticipating our forthcoming discussion, we write down the following couplings from the Yukawa interaction in Eq. (1), which are relevant for our discussion of n–$\bar{n}$ oscillation and PSB:

$$\mathcal{L}_{\mathrm{Y}}^{\mathrm{PSB}} = f\,(\Delta_{\nu\nu}\nu^c\nu^c + \Delta_{\nu d}\nu^c d^c + \Delta_{ud}u^c d^c + \Delta_{uu}u^c u^c + \Delta_{dd}d^c d^c) + \mathrm{h.c.} \tag{3}$$

These Yukawa couplings generate flavor changing hadronic neutral current effects, analyzed in Ref. [9], and we note from this paper that for the Δ fields with mass in the multi-TeV range, the constraints on their couplings can be severe in some cases. As an illustration of the parameter range where our

PSB mechanism works (see below), we choose the B–L symmetry breaking scale $v_{BL} \sim 300$ TeV and masses of the $\Delta_{\rm R}$ fields as follows:

$$M_{\Delta_{ud}} \sim 3 \text{ TeV}\,; \qquad M_{\Delta_{dd}} \sim 50 \text{ TeV}\,; \qquad M_{\Delta_{u\nu}} \sim 1 \text{ TeV}\,. \tag{4}$$

One flavor texture for f couplings that is consistent with this mass pattern and FCNC constraints is as follows:

$$f = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & .01 \\ 1 & .01 & .06 \end{pmatrix}\,. \tag{5}$$

We choose all the $\Delta_{\rm L}$ masses to be in the 100 TeV range so that it has no effect on the baryogenesis; their only role is to generate type II seesaw. It is clear that with type II seesaw for neutrino masses and with this pattern for the f matrix above, it leads to an inverted mass hierarchy for neutrinos.

The diagram that contributes to n–$\bar{n}$ oscillation in this model is given in Fig. 1 and involves the exchange of color sextet fields only.

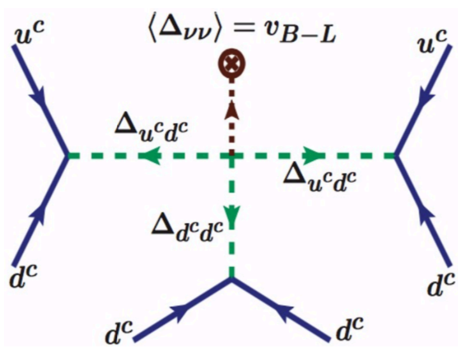

Fig. 1. Feynman diagram responsible for n–$\bar{n}$ oscillation in the color sextet model [13].

2.2. Post-sphaleron baryogenesis and limit on $\tau_{n\to\bar{n}}$

The post-sphaleron baryogenesis mechanism uses the interference between the following tree- and one-loop diagrams to generate the baryon asymmetry. We do not elaborate on these calculations further and refer instead to [9].

The upper limit on $\tau_{n\to\bar{n}}$ follows from the fact that the PSB mechanism is highly constrained if it has to lead to the right baryon asymmetry. The constraints are as follow:

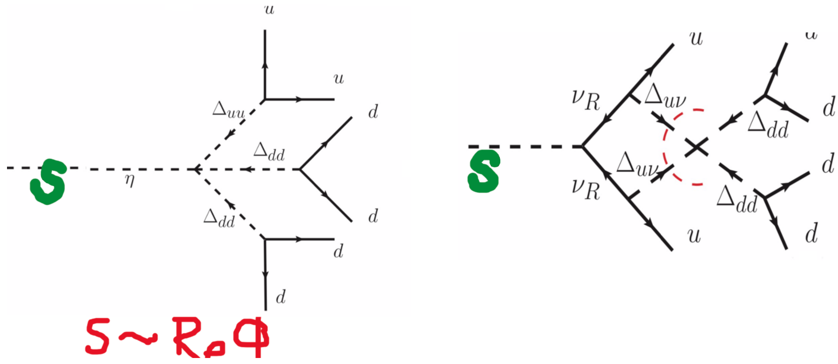

Fig. 2. Generic Feynman diagrams responsible for the post-sphaleron baryogenesis in the model of [13] for n–$\bar{n}$ oscillation. The ϕ field in the figure is the field $\Delta_{\nu\nu}$.

1. S scalar whose decay produces baryon asymmetry must go out of equilibrium when relativistic *i.e.* $T^* \geq M_S$. It then drifts and decays below the sphaleron decoupling temperature *i.e.* at GeV $\leq T_{\rm D} \leq 100$ GeV (hence the name PSB) to produce asymmetry; It should not decay much later than a GeV temperature, otherwise it will affect the success of BBN.

2. The above implies that M_S cannot be too large (*i.e.* must be in the TeV mass range) to avoid strong dilution of the generated baryon asymmetry d *i.e.* $d \sim \frac{T_{\rm D}}{M_S}$). Typically, d should be at most 0.01 but not less.

3. The above implies that the relevant diquarks that mediate the S decay should not be much heavier than a few TeV — an argument that has been used in the choice above benchmark values. Since typically the strength of n–$\bar{n}$ amplitude$G_{n-\bar{n}}$ goes like M_Δ^{-5}, an upper limit on Δ_{qq} masses produces a lower limit on $G_{n-\bar{n}}$ and hence an upper limit on $\tau_{n-\bar{n}} = 1/(G_{n-\bar{n}}\Lambda_{\rm QCD}^6)$.

4. Another point behind this limit is that we cannot dial any of the f couplings to very small values since they will then be induced radiative corrections which will then produce a lower limit on the f couplings. A lower limit on f will produce a lower limit on the n–$\bar{n}$ transition rate.

It was shown in Ref. [9] that taking all these effects into account, one finds an upper limit on $\tau_{n\to\bar{n}}$ (a lower limit on the n–$\bar{n}$ rate) as shown in Fig. 3. The range of the predictions in Fig. 3 is clearly in the range of the ESS experiment shown in Fig. 3 by vertical red lines.

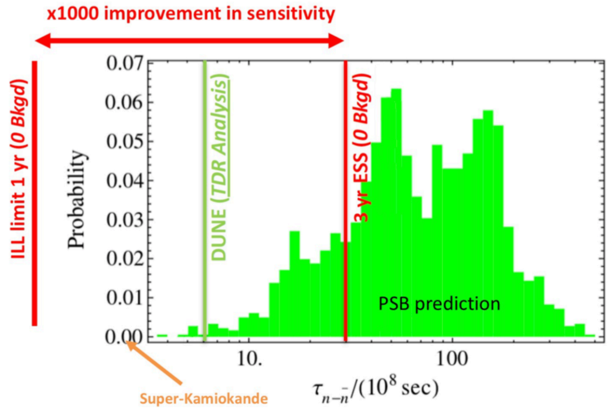

Fig. 3. Limit on $\tau_{n\to\bar{n}}$ in the PSB model.

3. Affleck–Dine scenario for baryogenesis and neutron oscillation

In this section, we explore an alternative scenario of Affleck–Dine (AD) baryogenesis [11, 12] and apply it to n–$\bar{n}$ oscillation to see if an observable n–$\bar{n}$ is compatible with adequate baryogenesis. In the literature, there have been many realizations of AD baryogenesis (for a review, see [14, 15]). The essential point of AD mechanism is the existence of a flat direction carrying baryon number which after inflation dynamically generates baryon excess as it evolves with the Hubble expansion from suitable initial conditions [12]. The initial conditions split the initial values of the complex field, the ASD field thereby introducing CP violation into the theory. In our discussion, we follow the model proposed by Lloyd–Stubbs and McDonald [16] with a slight modification so that it is compatible with the CMB measurements of the inflation parameters and apply it to n–$\bar{n}$ oscillation.

3.1. Setting for AD baryogenesis

To get into more detail, the two parts to the discussion of AD baryogenesis are: the implementation of inflation by a nonminimally gravity coupled scalar field Φ carrying $B = 2$ followed by an epoch where the Φ field decreases in magnitude as the post-inflation universe expands and finally oscillates when $H \simeq m_\Phi$ to generate a baryon asymmetry. This asymmetry eventually gets transmitted to the asymmetry of the SM baryons at the reheat temperature T_R, where the AD field Φ decays via its coupling with SM fermions. While in most models the inflaton field and the AD field are separate, in the scenario proposed in Ref. [16], they are the same making the calculations more transparent. We follow this model in [10] to discuss baryogenesis. The relevant scalar field part of the action for this model is

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{2}M_{\mathrm{P}}^2\, f\, R + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(\Phi)\right] , \tag{6}$$

where $M_{\mathrm{P}} = 2.44 \times 10^{18}$ GeV is the reduced Planck mass, $f = 1 + 2\xi \frac{\Phi^\dagger \Phi}{M_{\mathrm{P}}^2}$ with ξ being nonminimal coupling to gravity. We choose $V(\Phi)$ as in [16]

$$V(\Phi) = m_\Phi^2 \Phi^\dagger \Phi - \epsilon m_\Phi^2 \left(\Phi^2 + \Phi^{\dagger 2}\right) + \lambda \left(\Phi^\dagger \Phi\right)^2 . \tag{7}$$

Note that to make the inflationary predictions of the model consistent with the current Cosmic Microwave Background (CMB) observations, we introduce nonminimal coupling of the AD field in the potential with gravity as shown above (see, for example, [17] and references therein).

To explore the implications for various baryon number violation, we endow the AD field with $B = 2$ as noted above by coupling it to suitable $\Delta B = 2$ operators. The decay of the Φ field generates the baryon asymmetry. In generating the baryon asymmetry, the ϵ term in the potential plays a crucial role. The baryon number is subsequently spontaneously broken by $\langle \Phi \rangle \neq 0$ to lead to n–$\bar{n}$ oscillation.

Several questions arise in such models. For example, what is the scale of the violation of the quantum numbers (B) compatible with constraints of adequate baryogenesis which can then determine whether the $\Delta B = 2$ process can be observable in current searches. Secondly, after baryon number is spontaneously broken, there are B violating processes in the early universe down to the decoupling temperature T_{D} of those processes. Since in AD baryogenesis gets transmitted to SM fermions at the reheat temperature T_{R}, one must have $T_{\mathrm{D}} > T_{\mathrm{R}}$ for the generated baryon or lepton asymmetry not to get erased. The reheat is predetermined in a model from other considerations. This is therefore a constraint on the model and it needs to be checked if in a given model there is washout of baryogenesis or not.

The detailed evolution of the Φ field and its role in inflation have been discussed in [10] and we refer the reader to that paper. Here, we note that we set the initial values of the real and imaginary parts of the Φ field arbitrary characterized by an angle θ and use their evolution to give the baryon asymmetry n_B/s to be [10, 16]. It turns out to be

$$\begin{aligned}\frac{n_B}{s} &\simeq \frac{3}{8}\sqrt{\frac{\pi^2}{90}g_*}\frac{Q_B}{\epsilon}\frac{T_{\mathrm{R}}^3}{m_\Phi^2 M_{\mathrm{P}}}\sin(2\theta) \\ &\simeq 10^{-13}\frac{Q_B}{\epsilon}\left(\frac{T_{\mathrm{R}}}{10^{12}\ \mathrm{GeV}}\right)^3\left(\frac{10^{15}\ \mathrm{GeV}}{m_\Phi}\right)^2 ,\end{aligned} \tag{8}$$

where Q_B is the baryonic charge on the Φ field. For $\epsilon = 10^{-3}$ and $\sin(2\theta) \sim 1$ it gives the right order of magnitude for $n_B/s \simeq 10^{-10}$. In our specific case, the detailed numbers will be different. We emphasize that we cannot make ϵ too small since in the limit of $\epsilon = 0$, the baryon asymmetry vanishes (see Eqs. (11) and (12)). We will use this value for m_Φ motivated by the model in question *e.g.* for a multi-TeV theory of n–$\bar{n}$ oscillation, we will use $m_\Phi = 10^6$ GeV. In what follows, we will take ϵ accordingly but choose the actual magnitude to make n_B/s to fit observations as well as to make $B = 2$ process in question observable compatible with above constraints on it.

3.2. Connecting to neutron–antineutron oscillation

To study the phenomenological implications of the implementation of AD mechanism this way, we study the effect of the baryogenesis constraints on the magnitude of the n–$\bar{n}$ process *e.g.* whether it is observable and derive conclusions about whether AD baryogenesis is viable for the multi-TeV scale model. For this analysis, we start with the Φ coupling to the SM (or slightly beyond SM) fields, given by $\Phi\mathcal{O}_d/\Lambda^{d-3}$, where $\mathcal{O}_d = uddudd$. We then demand the theory to have the following properties:

— Adequate amount of baryon asymmetry *i.e.* $\frac{n_B}{s} \simeq 10^{-10}$ using the formula of Eq. (8);

— The baryon asymmetry generated by the AD field should not be washed out when $\langle\Phi\rangle = v_\Phi \neq 0$ since this VEV leads to processes in the early universe that violate baryon number;

— The B-violating process generated by $\langle\Phi\rangle \neq 0$ should be in the observable range of current or planned experiments.

The expression for n_B/s is already given in Eq. (8). Since below a certain temperature the model has B violating interactions, they can in principle erase the generated baryon asymmetry via the so-called washout processes if they are in equilibrium. To avoid the washout, the decoupling temperature for the relevant B-violating process must be above the reheat temperature T_R since the baryon asymmetry generated by the AD (inflaton) field is transmitted to the SM sector by the reheating.

We leave m_Φ as a free parameter and consider the scale Λ being lower *e.g.* 10^5 GeV since this is an example of the class of models (see Ref. [13]) which have been considered widely in the field over the years. To see if observable n–$\bar{n}$ oscillation is compatible with the viable AD baryogenesis in this case, we keep m_Φ, v_Φ, and Λ in the range of 100 TeV and impose the no-washout condition *i.e.* $T_\mathrm{R} \leq T_\mathrm{D}$, so that when the $\Delta B = 2$ processes involving quarks appear, their strength has become so weak that they never get into equilibrium to erase the AD generated baryon asymmetry. The reheating temperature is estimated by the decay width of Φ to 6 quarks. For the following ranges of the parameters, $100 \leq \Lambda$ TeV ≤ 1000, 100 GeV $\leq m_\Phi \leq \Lambda$, 100 GeV $\leq v_\Phi \leq 1000$ TeV, we have performed the random parameter scan to select the parameter set which satisfies $T_{\mathrm{D}} \geq 10T_{\mathrm{R}}$ and $n_B/s = 10^{-10}$ with $10^{-4} \leq \epsilon \leq 0.1$–$0.3$. Using the resultant parameter set, we estimate the n–$\bar{n}$ oscillation time as in Fig. 4 below

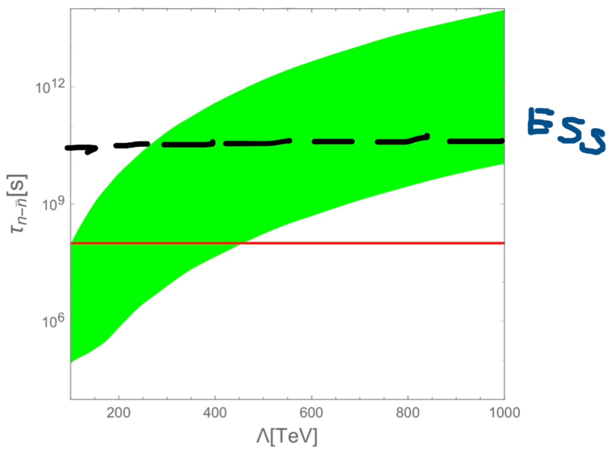

Fig. 4. n–$\bar{n}$ oscillation time predicted by the 100 TeV scale AD baryogenesis model. The dashed line is the reach of the proposed ESS experiment.

4. Conclusion

In summary, we have given a brief overview of two ways to generate baryon asymmetry of the universe in models with observable n–$\bar{n}$ oscillation. We have first discussed the idea of post-sphaleron baryogenesis where baryogenesis takes place after the Standard Model sphalerons have decoupled from the thermal plasma. We then discussed the AD baryogenesis which uses the evolution of the asymmetric initial values of the real and imaginary parts of the inflaton field leading to the baryon asymmetry. We discussed predictions for n–$\bar{n}$ oscillation time in both scenarios and found that they are accessible to the upcoming ESS proposal for a high sensitive search for this process.

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