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# Neutron-antineutron oscillations as a probe of baryogenesis

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**Abstract.** A signal of neutron-antineutron $(n - \bar{n})$ oscillations at experiments like the Deep Underground Neutrino Experiment or the European Spallation Source, would directly imply baryon number violation and will point towards physics beyond the Standard Model. The discovery of such a signal would have important implications for baryogenesis mechanisms in the early Universe, which can explain the observed baryon asymmetry of the Universe today. Here we discuss how an observed rate for $n - \bar{n}$ oscillations can directly be correlated with the washout of baryon asymmetry in the early Universe and therefore, can probe high- and low-scale baryogenesis scenarios in synergy with collider searches.

## 1. Introduction

An observation of baryon number $(B)$ violation would be a clear signal of new physics (NP) beyond the Standard Model (SM). Many well motivated ultraviolet complete extensions of the SM predicts $|\Delta B| = 2$ process $n$-$\bar{n}$ oscillations. An observation of $|\Delta B| = 2$ process like $n$-$\bar{n}$ oscillations can not only probe these models, but also will provide interesting insights into the baryogenesis mechanism which can explain the observed baryon asymmetry of the Universe. Currently, the best limits on the $n$-$\bar{n}$ oscillation lifetime is due to the Super-Kamiokande experiment [1] $\tau^{\rm SK}_{n\text{-}\bar{n}} \geq 4.7 \times 10^8$ s, while the most stringent bound from the free $n$-$\bar{n}$ oscillation is due to the ILL experiment [2] $\tau^{\rm ILL}_{n\text{-}\bar{n}} \geq 0.86 \times 10^8$ s. Interestingly, a bunch of upcoming experiments are expected to improve the current limits by order of magnitudes. For instance, the DUNE experiment [3] is expected to achieve a sensitivity of $\tau^{\rm DUNE}_{n\text{-}\bar{n}} \geq 7 \times 10^8$ s which will further be improved by the Hyper-K, while the NNBAR experiment at the ESS facility [4] is expected to improve the current free $n$-$\bar{n}$ oscillation limit to $\tau^{\rm NNBAR}_{n\text{-}\bar{n}} \geq 3 \times 10^9$ s. On the other hand, there have been a tremendous progress in computation of the transition matrix elements relevant for $n$-$\bar{n}$ oscillations using lattice-QCD techniques [5]. Therefore, it is interesting to explore the implications of observing a signal for $n$-$\bar{n}$ oscillations in a near future experiment for baryogenesis mechanisms, since $n$-$\bar{n}$ oscillations is amongst a very few observables which can directly probe baryogenesis mechanisms and help in distinguishing underlying NP scenarios in alliance with other low- and high-energy experimental observable.

## 2. An effective field theory (EFT) approach for $n - \bar{n}$ oscillations and washout processes

Currently the best estimations for the hadronic matrix elements for $n - \bar{n}$ oscillations are available from the lattice-QCD studies which employs nonzero quark masses and then matches to massless chiral perturbation theory which approximately preserves the chiral symmetry $SU(2)_L \times SU(2)_R$ [6]. Therefore it is convenient to use a $SU(3)_C \times U(1)_{\rm EM}$ invariant chiral basis with $SU(2)_L \times SU(2)_R$ symmetry to explore the $n - \bar{n}$ oscillation operators. The $n$-$\bar{n}$ oscillation operators can be expressed using the effective Lagrangian

$$\mathcal{L}_{\rm eff}^{\bar{n}\text{-}n} = \sum_{i=1,2,3,5} \big(C_i(\mu)\mathcal{O}_i(\mu) + C_i^P(\mu)\mathcal{O}_i^P(\mu)\big) + \text{h.c.}, \tag{1}$$

where $C_i$ are the Wilson coefficients corresponding to the set of effective operators $\mathcal{O}_i$ defined in the above mentioned basis as:

$$\begin{aligned}
\mathcal{O}_1 &= (\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS},\\
\mathcal{O}_2 &= (\psi C P_L i\tau^2\psi)(\psi C P_R i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS},\\
\mathcal{O}_3 &= (\psi C P_L i\tau^2\psi)(\psi C P_L i\tau^2\psi)(\psi C P_R i\tau^2\tau^+\psi)T^{AAS},\\
\mathcal{O}_4 &= \left[(\psi C P_R i\tau^2\tau^3\psi)(\psi C P_R i\tau^2\tau^3\psi) - \frac{1}{5}(\psi C P_R i\tau^2\tau^a\psi)(\psi C P_R i\tau^2\tau^a\psi)\right](\psi C P_R i\tau^2\tau^+\psi)T^{SSS},\\
\mathcal{O}_5 &= (\psi C P_R i\tau^2\tau^-\psi)(\psi C P_L i\tau^2\tau^+\psi)(\psi C P_L i\tau^2\tau^+\psi)T^{SSS},\\
\mathcal{O}_6 &= (\psi C P_R i\tau^2\tau^3\psi)(\psi C P_L i\tau^2\tau^3\psi)(\psi C P_L i\tau^2\tau^+\psi)T^{SSS},\\
\mathcal{O}_7 &= \left[(\psi C P_L i\tau^2\tau^3\psi)(\psi C P_L i\tau^2\tau^3\psi) - \frac{1}{3}(\psi C P_L i\tau^2\tau^a\psi)(\psi C P_L i\tau^2\tau^a\psi)\right](\psi C P_R i\tau^2\tau^+\psi)T^{SSS},
\end{aligned} \tag{2}$$

with the remaining seven independent operators $\mathcal{O}_i^P$ related to the seven above by a parity transformation, accounting for a total of 14 independent operators. Here $\psi$ represents the isospin doublet $\psi = (u,d)^T$, $C$ denotes to the charge conjugation operator, $\tau^a$ corresponds to the standard Pauli matrices and $\tau^{\pm} = \frac{1}{2}(\tau^1 \pm i\tau^2)$. The colour tensors $T^{AAS(SSS)}$ are defined as

$$\begin{aligned}
T^{SSS}_{\{ij\}\{kl\}\{mn\}} &= \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{jkm}\varepsilon_{iln} + \varepsilon_{ilm}\varepsilon_{jkn} + \varepsilon_{jlm}\varepsilon_{ikn},\\
T^{AAS}_{[ij][kl]\{mn\}} &= \varepsilon_{ijm}\varepsilon_{kln} + \varepsilon_{ijn}\varepsilon_{klm},
\end{aligned} \tag{3}$$

where { } denotes symmetrisation os indices and [ ] denotes anti-symmetrisation. The independent hadronic matrix elements associated with the operators defined in Eq. (2) relevant for computing the $n$-$\bar{n}$ oscillation rate are the ones corresponding to $\mathcal{O}_1$, $\mathcal{O}_2$, and $\mathcal{O}_3$ and $\mathcal{O}_5$ as described in [7], including the running effects that need to be taken into account. The transition rate for the $n$-$\bar{n}$ oscillations, $\tau^{-1}_{n\text{-}\bar{n}}$, can then be calculated using the relation

$$\tau^{-1}_{n\text{-}\bar{n}} = \langle \bar{n}|\mathcal{L}_{\rm eff}^{\bar{n}\text{-}n}|n\rangle = \Big|\sum_{i=1,2,3,5}(C_i(\mu)\mathcal{M}_i(\mu) + C_i^P(\mu)\mathcal{M}_i^P(\mu))\Big|, \tag{4}$$

where, $\mathcal{M}_i(\mu)$ is the transition matrix element for operator $\mathcal{O}_i(\mu)$, with $\mathcal{M}_i(\mu) \equiv \langle \bar{n}|\mathcal{O}_i|n\rangle$. These relevant matrix elements are readily available form [5], which provides the numerical values for $\mathcal{M}_i(\mu)$ in the $\overline{\rm MS}$ scheme at $\mu = 2$ GeV.

Since we are interested in the short distance operators for $n$-$\bar{n}$ oscillations involving NP mediators much heavier than the external quarks in the effective operators, at any temperature below the EFT scale (corresponding to the NP mediators) the operators relevant for $n$-$\bar{n}$

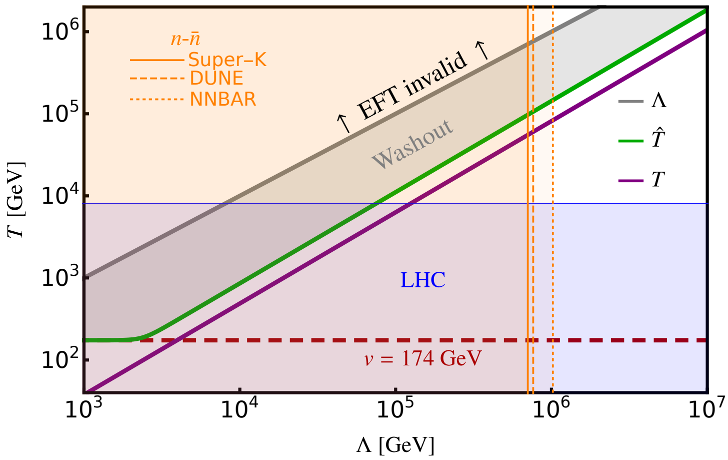


**Figure 1.** Estimates for out-of-equilibrium temperature for the washout processes corresponding to $\mathcal{O}_1$ as a function of the the EFT scale.. The blue and orange shaded areas correspond to the experimental reach of the LHC and different $n$-$\bar{n}$ experiments, respectively.

oscillations correspond to potential washout processes for any baryon asymmetry generated at a comparably higher scale. Therefore, an observed rate of $n$-$\bar{n}$ oscillations at low-energy searches directly be correlated with the washout rates. In order to estimate the washout effect of the $n$-$\bar{n}$ oscillation operators on a pre-existing baryon asymmetry, one can use the generalised Boltzmann equation formalism as described in Ref. [7]. Following the approach of [8, 9, 10] for the computation of thermal rate of washout process$\gamma^{\rm eq}$, the total washout effect from the operator $\mathcal{O}_1$, for example, can be expressed as

$$zHn_\gamma \frac{d\,\eta_{\Delta B}}{d\,z} = -c\frac{T^{14}}{\Lambda^{10}}\eta_{\Delta B}\,, \tag{5}$$

where only the $3 \leftrightarrow 3$ scatterings are included since the $2 \leftrightarrow 4$ scatterings are phase space suppressed and $c$ denotes a numerical factor determined by the chemical potentail relations [7]. A more accurate estimate for the out-of-equilibrium temperature for the wash out processes can be obtained by integrating Eq. (5) given by

$$\hat{T} \simeq \left[9T^9 \ln\left(\frac{d_{\rm rec}}{\eta_B^{\rm obs}}\right) + v^9\right]^{\frac{1}{9}}\,, \tag{6}$$

where $d_{\rm rec} \approx 1/27$ is the dilution factor due to entropy release, $v$ is the vacuum expectation value of the SM Higgs, and $T$ is the out-of-equilibrium temperature obtained by solving $\frac{\Gamma_W^{\mathcal{O}_1}}{H} \gtrsim 1$, where $H$ is the Hubble parameter and $\Gamma_W^{\mathcal{O}_1}$ is interaction rate corresponding to the operator $\mathcal{O}_1$. In Fig. 1 the estimates for out-of-equilibrium temperature for the washout processes corresponding to $\mathcal{O}_1$ is shown as a function of the the EFT scale. From this plot one can straightforwardly conclude that an $n$-$\bar{n}$ oscillation rate corresponding to NP scale of $\Lambda \approx 10^6$ GeV, would imply a very strong washout for temperatures all the way down to $\hat{T} \approx 1.4 \times 10^5$ GeV. Therefore, under the conservative assumption of a pre-existing baryon asymmetry in the first generation quarks generated at a high scale, this would imply that any surviving asymmetry today must be generated below this scale. Hence, such a signal at the $n$-$\bar{n}$ oscillation searches will hint towards new physics accessible at future colliders.

## 3. A simplified model approach to study the impact of $n-\bar{n}$ oscillation searches on baryogenesis

In the previous section we discussed the case where we do not assume any source of CP violation and assume a pre-existing asymmetry. However, in a realistic baryogenesis scenario it is important to take into account (a) a source of CP violation and (b) mass hierarchies between the new physics fields. The latter in particular can be quite important, since the the EFT approach in the previous section is applicable only below the cutoff scale of the EFT. To this end, in [7] we have explored a simplified model corresponding to one of the two general topologies for $n$-$\bar{n}$ oscillations proposed originally in Ref. [11] and realised in many UV complete and TeV scale models [12, 13, 14, 15, 16, 17, 18, 19, 20]. The Lagrangian for the relevant simplified model is given by

$$\mathcal{L}_{II} = f^{dd}_{ij} X_{dd} \bar{d}^c_i \bar{d}^c_j + \frac{f^{ud}_{ij}}{\sqrt{2}} X_{ud} (\bar{u^c_i} \bar{d^c_j} + \bar{u^c_j} \bar{d^c_i}) + \lambda \xi X_{dd} X_{ud} X_{ud} + \text{h.c.}\,, \tag{7}$$

where $\xi$ is a neutral complex scalar field, which acquires a vacuum expectation value $v' \gg v$ breaking the $B-L$ symmetry. Here $X_{dd}$ and $X_{ud}$ correspond to scalar diquarks. The transformation properties of the scalar diquark fields under the SM gauge group and their associated baryon number charges are summarised in Tab. 1. Once $B-L$ is broken, the trilinear term in Eq. (7) will violate baryon number in units of $|\Delta B| = 2$.

| Field | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $Q = T_{3L} + Y$ | $B$ |
|---|---|---|---|---|---|
| $X_{dd}$ | $\bar{6}$ | 1 | $+\frac{2}{3}$ | $+\frac{2}{3}$ | $-\frac{2}{3}$ |
| $X_{ud}$ | $\bar{6}$ | 1 | $-\frac{1}{3}$ | $-\frac{1}{3}$ | $-\frac{2}{3}$ |

**Table 1.** Transformation properties of the relevant scalar diquark fields the SM gauge group.

In [7], we have presented a comprehensive derivation of the Boltzmann equation framework in the single flavour application, which can then be readily used to explore two regimes of baryogenesis as follows.

One of the regimes of interest is the high-scale scenario, where $m_{X_{uu}} \gg m_{X_{dd}} \gg m_{X_{ud}}$, with $m_{X_{ud}} \sim \mathcal{O}(\text{TeV})$ and $m_{X_{dd}} \sim \mathcal{O}(10^{13-14}\text{GeV})$. Such a choice can naturally be motivated by gauge coupling unification in e.g. $SO(10)$ GUT, as discussed in [7]. We found that high-scale scenario remains a viable scenario for baryogenesis, with currently LHC searches providing a better constraint on the parameter space of high-scale scenario as compared to $n$-$\bar{n}$ oscillation experiments. If a signal is discovered in either of these experiments in near future, then the other experiment can be used to probe this scenario as a viable explanation of the observed baryon asymmetry of the universe.

Another regime of interest is the low scale scenario, where $m_{X_{dd}} > m_{X_{ud}}$ but with both $m_{X_{ud}}$ and $m_{X_{dd}}$ close to mass scale $\sim \mathcal{O}(\text{TeV})$. Such a scenario is particularly interesting since it puts both the scalar diquark states in the reach of future colliders searches. In this scenario, however, if $m_{X_{dd}} \sim \mathcal{O}(\text{few}) m_{X_{ud}}$ is less than $\mathcal{O}(10^8)$ GeV, then a signal at the $n$-$\bar{n}$ oscillation experiments would imply very strong washout processes to generate any sizeable asymmetry even if the CP violation maximal. In such a situation a post sphaleron baryogenesis might provide an interesting alternative [14, 15, 19].

## 4. Concluding Remarks

The discovery of $n$-$\bar{n}$ oscillations will not only provide a smoking gun signal for baryon number violation and existence of NP beyond the SM in collider reach, but also will have far-reaching implications on baryogenesis mechanisms which can explain the observed baryon asymmetry of the Universe. If the scale of the NP responsible for baryogensis is found to be within current and future collider reach then a signal at the upcoming $n$-$\bar{n}$ oscillation experiments would imply very strong washout processes to accumulate any sizeable asymmetry even in the presence of maximal $CP$ violation as demonstrated by the coherence of the conclusions from a naive EFT based approach and a simplified model. On the other hand, the high-scale baryogenesis scenario with a large hierarchy between the decaying NP fields generating the asymmetry and the decay products, remain a viable option for generating the observed baryon asymmetry, with the exciting potential to probe new parts of the parameter space for this scenario in upcoming $n$-$\bar{n}$ oscillation experiments and future collider searches.

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