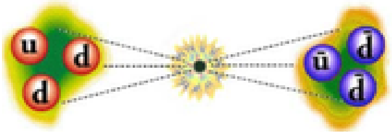
Neutron-Antineutron Oscillation:
Theoretical Status and Experimental Prospects

Bhupal Dev



First Nuclear and Particle Theory Meeting

Washington University in St. Louis

March 12, 2019

Too crazy?

But neutral meson $|q\bar{q}\rangle$ states oscillate -

$$K^0, B^0 \longleftrightarrow \left(\text{2}^{\text{nd}} \text{ order weak interactions} \right) \longleftrightarrow \bar{K}^0, \bar{B}^0$$

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$\nu_\mu \longleftrightarrow (\ldots) \longleftrightarrow \nu_\tau$

So why not -

$n \longleftrightarrow$ (New physics) $\longleftrightarrow \bar{n}$?

Conservation of Baryon Number

- In the Standard Model (SM), conservation of baryon number forbids a neutron $(B = 1)$ from transforming into an antineutron $(B = -1)$.
- Also forbids the decay of the lightest baryon, i.e. proton.
- Just like the conservation of electric charge forbids the decay of electron.

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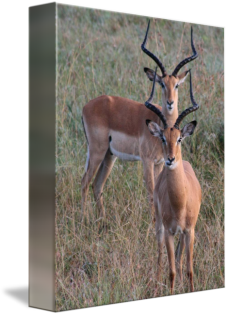
- Just like the conservation of electric charge forbids the decay of electron.
- But conservation of electric charge is closely connected with $U(1)_{\rm em}$ gauge symmetry (Noether's theorem).
- If same idea worked for B, we expect conservation of "baryonic" charge to be associated with a new long-range force coupled to B.
- No experimental evidence so far!
- Strong constraints on any new long-range force coupled to B.

  [Schlamminger *et al.* (PRL '08); Cowsik *et al.* '18; Agarwalla, Bustamante (PRL '18)]

Baryon Number Violation

- From the SM point of view, both B and L are "accidental" global symmetries.
- No special reason why they should be conserved beyond SM.
- Even in the SM, $B + L$ is violated by non-perturbative sphaleron processes, and it's only the $B - L$ combination that is conserved.
- Sphalerons play an important role in explaining the primordial baryon asymmetry (baryogenesis).
- However, the sphaleron-induced B-violation is negligible for $T \ll v_{\rm EW}$ to have any observable effects in lab.



Selection Rules

- Conservation of angular momentum requires that spin of nucleon should be transferred to another fermion (lepton or baryon).
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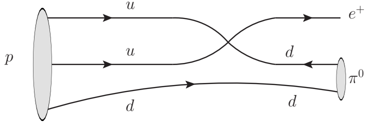
- Leads to the selection rule $\boxed{\Delta B = \pm\Delta L, \text{ or } |\Delta(B-L)| = 0, 2.}$
- In the SM, $\Delta(B-L) = 0$, or $\Delta B = +\Delta L = 0$ (e.g. neutron decay).
- Second possibility: $|\Delta(B-L)| = 2$, which can be realized in three ways:
  - $\Delta B = -\Delta L = 1$ (e.g. proton decay)
  - $|\Delta B| = 2$ (e.g. dinucleon decay, $n - \bar{n}$ oscillation) – This talk
  - $|\Delta L| = 2$ (e.g. Majorana mass for neutrino, $0\nu\beta\beta$) – Talk by E. Mereghetti
- **Conservation or violation of $B - L$ determines the mechanism of baryon instability.**
- Connected with the Majorana nature of neutrino mass. [Mohapatra, Marshak (PRL '80)]

$\Delta B = 1$ versus $\Delta B = 2$

$\boxed{\Delta B = 1}$

- Proton decay
- Induced by dimension-6 operator $QQQL$.
- Amplitude $\propto \Lambda^{-2}$.
- $\tau_p \gtrsim 10^{34}$ yr implies $\Lambda \gtrsim 10^{15}$ GeV.
- Proton decay requires GUT-scale physics.

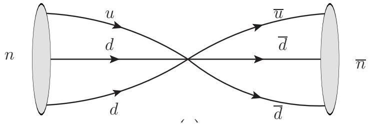
[Nath, Perez (Phys. Rep. '07)]



$\boxed{\Delta B = 2}$

- Di-nucleon decay and $n - \bar{n}$
- Induced by dimension-9 operator $QQQQQQ$.
- Amplitude $\propto \Lambda^{-5}$.
- $\Lambda \gtrsim 100$ TeV enough to satisfy experimental constraints.
- $n - \bar{n}$ oscillation (and conversion) could come from a TeV-scale new physics.

[Phillips et al. (Phys. Rep '16)]



General Formalism of $n - \bar{n}$ Oscillation

- Start with the Schrödinger equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}|n\rangle \\ |\bar{n}\rangle\end{pmatrix} = \underbrace{\begin{pmatrix}M_{11} & \delta m \\ \delta m & M_{22}\end{pmatrix}}_{H_{\text{eff}}}\begin{pmatrix}|n\rangle \\ |\bar{n}\rangle\end{pmatrix}$$

with $\mathrm{Im}(M_{jj}) = -i\lambda/2$, where $\lambda^{-1} = \tau_n \simeq 880$ sec is the mean lifetime of a free neutron.

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- Mass eigenstates

$$\begin{pmatrix}|n_1\rangle \\ |n_2\rangle\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}|n\rangle \\ |\bar{n}\rangle\end{pmatrix} \quad \text{with } \tan(2\theta) = \frac{2\delta m}{\Delta M}$$

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- Real energy eigenvalues:

$$E_{1,2}=\frac{1}{2}\left[M_{11}+M_{22}\pm\underbrace{\sqrt{(\Delta M)^2+4(\delta m)^2}}_{\Delta E}\right]$$

Transition Probability

- Starting with a pure $|n\rangle$ state at $t=0$, the probability to evolve into the $|\bar{n}\rangle$ state at a later time t is

$$P_{\bar{n}}(t) = |\langle \bar{n}|n(t)\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta E\, t}{2}\right)e^{-\lambda t}$$
$$= \left[\frac{4(\delta m)^2}{(\Delta E)^2}\right]\sin^2\left(\frac{\Delta E\, t}{2}\right)e^{-\lambda t}$$

- **Quasi-free limit** $\Delta E\, t \ll 1$:

$$P_{\bar{n}}(t) \sim (\delta m\, t)^2 e^{-\lambda t} = \left(\frac{t}{\tau_{n\bar{n}}}\right)^2 e^{-\lambda t}$$

where $\tau_{n\bar{n}} = 1/|\delta m|$ is the oscillation lifetime.

- Current experimental limits give $\tau_{n\bar{n}} \gtrsim 10^8$ sec (or $|\delta m| \lesssim 10^{-29}$ MeV), so $\tau_{n\bar{n}} \gg \tau_n$.

In Field-Free Vacuum

- In this case, $\Delta M = 0$ and

$$H_{\text{eff}} = \begin{pmatrix} m_n - i\lambda/2 & \delta m \\ \delta m & m_n - i\lambda/2 \end{pmatrix}$$

- Leads to the mass eigenstates $|n_\pm\rangle = (|n\rangle \pm |\bar{n}\rangle)/\sqrt{2}$ with eigenvalues $(m_n \pm \delta m) - i\lambda/2$ and maximal mixing $\theta = \pi/4$.
- The oscillation probability is simply

$$P_{\bar{n}}(t) = \sin^2\left(\frac{t}{\tau_{n\bar{n}}}\right) e^{-\lambda t}$$

- Never realized in practice.

In a Static Ambient Magnetic Field

- The n and $\bar{n}$ interact with the external $\vec{B}$ field via their magnetic dipole moments $\vec{\mu}_{n,\bar{n}}$, where $\mu_n = -\mu_{\bar{n}} = -1.91\mu_N$ and $\mu_N = e/(2m_N) = 3.15 \times 10^{-14}$ MeV/T.

$$H_{\text{eff}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

- Leads to $\Delta M = -2\,\vec{\mu}_n \cdot \vec{B} \gg \delta m$, even for a reduced magnetic field of $|\vec{B}| \sim 10^{-8}$ T (as in the ILL experiment), for which $|\vec{\mu}_n \cdot \vec{B}| \simeq 10^{-21}$ MeV, as opposed to $|\delta m| \lesssim 10^{-29}$ MeV.

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- $\Delta E \simeq 2|\vec{\mu}_n \cdot \vec{B}|$ and to realize the quasi-free limit, need to arrange an observation time t such that $|\vec{\mu}_n \cdot \vec{B}|t \ll 1$ and also $t \ll \tau_n$.
- The transition probability reduces to

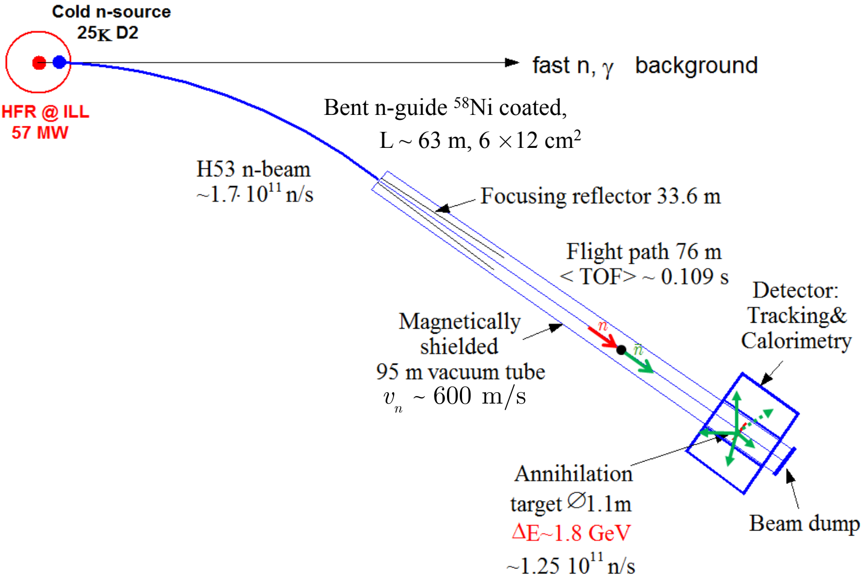
$$P_{\bar{n}}(t) \simeq \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

- Number of $\bar{n}$'s produced by $n - \bar{n}$ oscillation is essentially

$$N_{\bar{n}} = P_{\bar{n}}(t) N_n = P_{\bar{n}}(t)\phi_n T_{\text{run}}$$

- Main challenge: Need to establish smaller magnetic fields.

ILL/Grenoble $n - \bar{n}$ Oscillation Search Experiment



In Bound Nuclei

$$H_{\text{eff}} = \begin{pmatrix} m_n + V_n & \delta m \\ \delta m & m_n + V_{\bar{n}} \end{pmatrix} \equiv \begin{pmatrix} m_{n,\text{eff}} & \delta m \\ \delta m & m_{\bar{n},\text{eff}} \end{pmatrix}$$

- The nuclear potential is practically real, $V_n = V_{nR}$, but $V_{\bar{n}}$ has a large imaginary part $V_{\bar{n}} = V_{\bar{n}R} - iV_{\bar{n}I}$ with $V_{nR}, V_{\bar{n}R}, V_{\bar{n}I} \sim \mathcal{O}(100)$ MeV. [Dover, Gal, Richard (PRC '85); Friedman, Gal (PRD '08)]

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- The mixing is strongly suppressed:

$$\tan(2\theta) = \frac{2\delta m}{m_{n,\text{eff}} - m_{\bar{n},\text{eff}}} = \frac{2\delta m}{\sqrt{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}} \ll 1$$

- Energy eigenvalue for the mostly n mass eigenstate is

$$E_1 \simeq m_n + V_n - i\frac{(\delta m)^2 V_{\bar{n}I}}{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}$$

- The imaginary part leads to matter instability via $n - \bar{n}$ annihilation, whose rate is

$$\Gamma_{\text{m}} = \frac{1}{\tau_{\text{m}}} = \frac{2(\delta m)^2 |V_{\bar{n}I|}}{(V_{nR} - V_{\bar{n}R})^2 + V_{\bar{n}I}^2}$$

- Since $\tau_{\mathrm{m}} \propto (\delta m)^{-2} \propto \tau_{n\bar{n}}^2$, we can write

$$\tau_{\mathrm{m}} = R\,\tau_{n\bar{n}}^2$$

- The exact value of R depends on the nucleus, but is of order $10^{23}\ \mathrm{sec}^{-1}$ ($\sim$ 100 MeV).
- The lower limit on $\tau_{n\bar{n}}$ from free neutron experiments can be translated into a lower bound on τ_{m} and vice versa.

$$\tau_{\mathrm{m}} > (1.6 \times 10^{31}\ \mathrm{yr}) \left(\frac{\tau_{n\bar{n}}}{10^8\ \mathrm{sec}}\right)^2 \left(\frac{R}{0.5 \times 10^{23}\ \mathrm{sec}^{-1}}\right)$$

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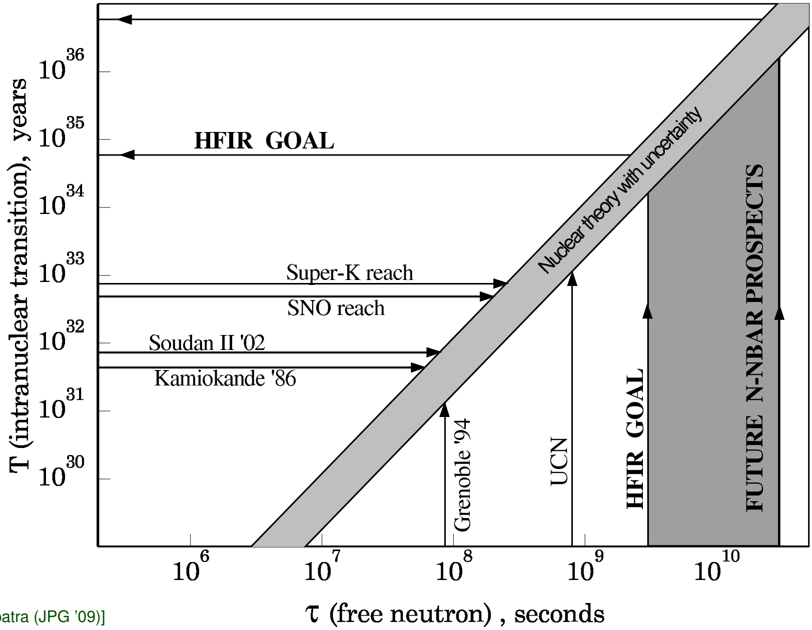
Experiment	10^{32} n-yr	$\tau_m(10^{32}$ yr)	$R(10^{23}/\mathrm{s})$	$\tau_{n-\bar{n}}(10^8$ s)
ILL (free-n) [63]	n/a	n/a	n/a	0.86
IMB (^{16}O) [96]	3.0	0.24	1.0	0.88
Kamiokande (^{16}O) [97]	3.0	0.43	1.0	1.2
Frejus (^{56}Fe) [98]	5.0	0.65	1.4	1.2
Soudan-2 (^{56}Fe) [92]	21.9	0.72	1.4	1.3
SNO (^{2}H) [94]	0.54	0.30	0.25	1.96
Super-K (^{16}O) [93]	245	1.9	0.517	2.7

[Phillips *et al.* (Phys. Rep '16)]

Free versus Bound $n - \bar{n}$ Limits



[Mohapatra (JPG '09)]

EFT of $n - \bar{n}$ Oscillation

- At the quark level, the $n \to \bar{n}$ transition is $(udd) \to (u^c d^c d^c)$.
- Mediated by color-singlet, electrically-neutral six-quark operators $\mathcal{O}_i$.
- $H_{\rm eff} = \int d^3x \mathcal{H}_{\rm eff}$ with $\mathcal{H}_{\rm eff} = \sum_i c_i \mathcal{O}_i$ and $c_i \sim \kappa_i/\Lambda^5$.
- The transition amplitude is

$$\delta m = \langle \bar{n} | \mathcal{H}_{\rm eff} | n \rangle = \frac{1}{\Lambda^5} \sum_i \kappa_i \langle \bar{n} | \mathcal{O}_i | n \rangle \sim \frac{\kappa \Lambda_{\rm QCD}^6}{\Lambda^5}$$

- The $n - \bar{n}$ lifetime is then given by

$$\tau_{n\bar{n}} = (2 \times 10^8 \text{ sec}) \left(\frac{\Lambda}{4 \times 10^5 \text{ GeV}} \right)^5 \left(\frac{3 \times 10^{-5} \text{ GeV}^6}{|\sum_i \kappa_i \langle \bar{n} | \mathcal{O}_i | n \rangle|} \right)$$

- Typical value for $\langle \bar{n} | \mathcal{O}_i | n \rangle | \sim \mathcal{O}(10^{-4}) \text{ GeV}^6 \simeq \Lambda_{\rm QCD}^6$ in the MIT bag model.
  [Rao, Shrock (PLB '82, NPB '84)]
- Recent progress using lattice gauge theory. [Buchoff, Schroeder, Wasem '12; Rinaldi *et al.* '19]

- A complete basis of six-quark operators can be constructed from

$$\mathcal{O}^1_{\chi_1\chi_2\chi_3} = (u_i^T C P_{\chi_1} u_j)(d_k^T C P_{\chi_2} d_l)(d_m^T C P_{\chi_3} d_n) T^{(\text{symm})}_{\{ij\}\{kl\}\{mn\}}\,,$$
$$\mathcal{O}^2_{\chi_1\chi_2\chi_3} = (u_i^T C P_{\chi_1} d_j)(u_k^T C P_{\chi_2} d_l)(d_m^T C P_{\chi_3} d_n) T^{(\text{symm})}_{\{ij\}\{kl\}\{mn\}}\,,$$
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where quark spinor indices are implicitly contracted in the parentheses, the $P_{L,R} = (1 \mp \gamma_5)/2$ are chiral projectors, and the quark color tensors are

$$T^{(\text{symm})}_{\{ij\}\{kl\}\{mn\}} = \varepsilon_{ikm}\varepsilon_{jln} + \varepsilon_{jkm}\varepsilon_{iln} + \varepsilon_{ilm}\varepsilon_{jkn} + \varepsilon_{jlm}\varepsilon_{ikn} = T^{S_1S_2S_3}\,,$$
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\end{aligned}$$

- In the irreducible representations of the chiral isospin,

$$\begin{aligned}
(\mathbf{1}_L, \mathbf{3}_R): &\quad Q_1 = -4\mathcal{O}^3_{RRR}, \quad Q_2 = -4\mathcal{O}^3_{LRR}, \quad Q_3 = -4\mathcal{O}^3_{LLR} \\
(\mathbf{1}_L, \mathbf{7}_R): &\quad Q_4 = -\frac{4}{5}\mathcal{O}^1_{RRR} - \frac{16}{5}\mathcal{O}^2_{RRR}, \\
(\mathbf{5}_L, \mathbf{3}_R): &\quad Q_5 = \mathcal{O}^1_{RLL}, \quad Q_6 = -4\mathcal{O}_{RLL}, \quad Q_7 = -\frac{4}{3}\mathcal{O}^1_{LLR} - \frac{8}{3}\mathcal{O}^2_{LLR}
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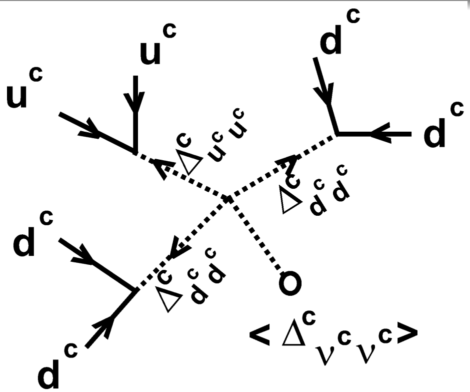
$$(\mathbf{5}_L, \mathbf{3}_R): \quad Q_5 = \mathcal{O}^1_{RLL}, \quad Q_6 = -4\mathcal{O}_{RLL}, \quad Q_7 = -\frac{4}{3}\mathcal{O}^1_{LLR} - \frac{8}{3}\mathcal{O}^2_{LLR}$$

Operator	$\mathcal{M}_I^{\overline{\text{MS}}}(2\text{ GeV})$,	$\mathcal{M}_I^{\overline{\text{MS}}}(700\text{ TeV})$,	$\frac{\mathcal{M}_I^{\overline{\text{MS}}}(2\text{ GeV})}{\text{MIT bag A}}$	$\frac{\mathcal{M}_I^{\overline{\text{MS}}}(2\text{ GeV})}{\text{MIT bag B}}$
Q_1	$-46(13)\times 10^{-5}\text{ GeV}^6$	$-26(7)\times 10^{-5}\text{ GeV}^6$	4.2	5.2
Q_2	$95(17)\times 10^{-5}\text{ GeV}^6$	$144(26)\times 10^{-5}\text{ GeV}^6$	7.5	8.7
Q_3	$-50(12)\times 10^{-5}\text{ GeV}^6$	$-47(11)\times 10^{-5}\text{ GeV}^6$	5.1	6.1
Q_5	$-1.06(48)\times 10^{-5}\text{ GeV}^6$	$-0.23(10)\times 10^{-5}\text{ GeV}^6$	-0.84	1.6

UV-Complete Model of $n - \bar{n}$ Oscillation

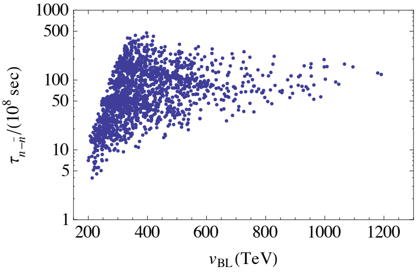


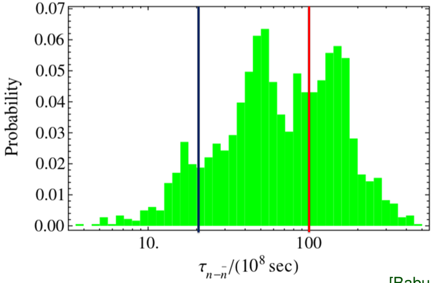
[Mohapatra, Marshak (PRL '80); Babu, BD, Mohapatra (PRD '08)]

- Take $\Delta(\mathbf{1},\mathbf{3},\mathbf{10}) \oplus \bar{\Delta}^c(\mathbf{1},\mathbf{3},\overline{\mathbf{10}})$ Higgs under Pati-Salam gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$.
- Under SM gauge group $SU(2)_L \times U(1)_Y \times SU(3)_c$, decomposes as

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

Upper Limit on $\tau_{n\bar{n}}$





[Babu, BD, Fortes, Mohapatra (PRD '13)]

Simplified Model of $n - \bar{n}$ Oscillation

- Start with the SM gauge group and add renormalizable terms that violate baryon number.
- Gauge invariance requires introduction of new colored fields.
- A minimal setup: Iso-singlet, color-triplet scalars X_α with $Y = +4/3$.
- Allows $X_\alpha d^c d^c$ terms in the Lagrangian.
- Need at least two ($\alpha = 1, 2$) to produce baryon asymmetry from X decay.

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- Total baryon asymmetry vanishes after summing over all flavors of d^c.
  [Kolb, Wolfram (NPB '80)]
- Need additional $\not{B}$ interactions.
- Introduce a SM-singlet Majorana fermion ψ (also plays the role of dark matter).

$$\mathcal{L} \supset \lambda_{\alpha i} X_\alpha \psi u_i^c + \lambda'_{\alpha ij} X_\alpha^* d_i^c d_j^c + \frac{1}{2} m_\psi \bar{\psi}^c \psi + \mathrm{H.c.}$$

[Allahverdi, Dutta (PRD '13); BD, Mohapatra (PRD '15)]

Dark Matter

- Integrate out X_α to obtain $\psi u_i^c d_j^c d_k^c$ interaction (assuming $m_\psi \ll m_X$).
- ψ decays to three quarks (baryons) if $m_\psi \gg$ GeV.
- Also $\psi \to p + e^- + \bar{\nu}_e$ if $m_\psi > m_p + m_e$.
- Absolutely stable for $m_\psi < m_p + m_e$ (no discrete symmetry required).
- In addition, need $m_p < m_\psi + m_e$ to avoid $p \to \psi + e^+ + \nu_e$.
- So the viable scenario for ψ to be the DM candidate is

$$m_p - m_e \leq m_\psi \leq m_p + m_e \,.$$

[Allahverdi, BD, Dutta (PLB '18)]

- Evidence for GeV-scale DM?

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nature
International journal of science

Letter | Published: 28 February 2018

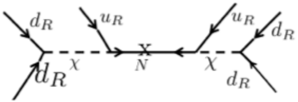
Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana

Nature **555**, 71–74 (01 March 2018) | Download Citation

$n - \bar{n}$ Oscillation

- Effective $\not{B}$ operator $\psi u^c d^c d^c$ (integrating out X_α). [Babu, Mohapatra, Nasri (PRL '07)]
- Induces $n - \bar{n}$ oscillation for Majorana ψ (N).
- Tree-level amplitude vanishes due to color-antisymmetry.



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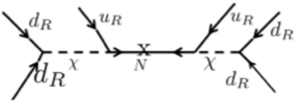
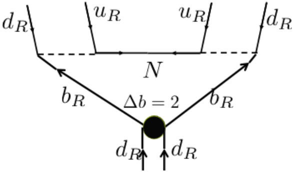


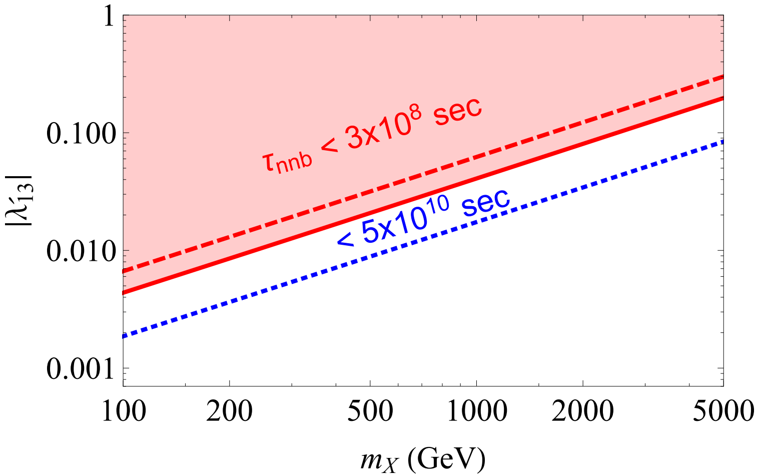
- Non-zero amplitude at one-loop level: [BD, Mohapatra (PRD '15)]



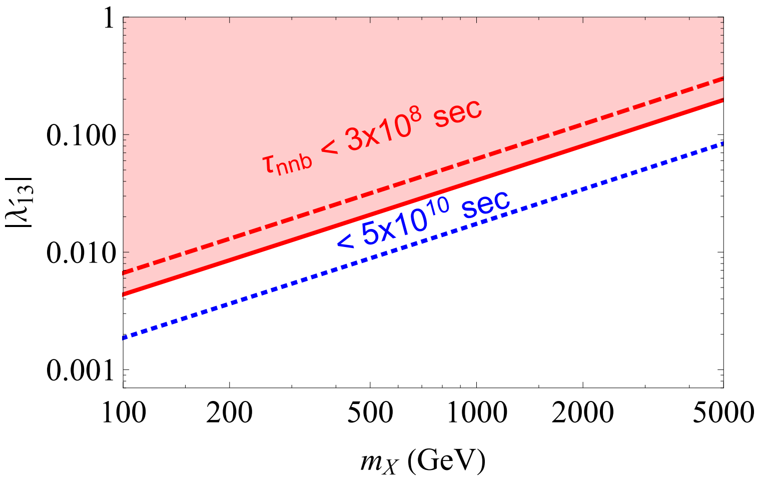
- Observable oscillation time for $m_X \sim \mathcal{O}$(TeV):

$$\tau_{n\bar{n}} \simeq (3.0 \times 10^8 \text{ sec}) \left(\frac{0.03}{|\lambda_{\alpha 1}|}\right)^2 \left(\frac{0.04}{|\lambda'_{\alpha 13}|}\right)^4 \left(\frac{m_X}{1 \text{ TeV}}\right)^6 .$$

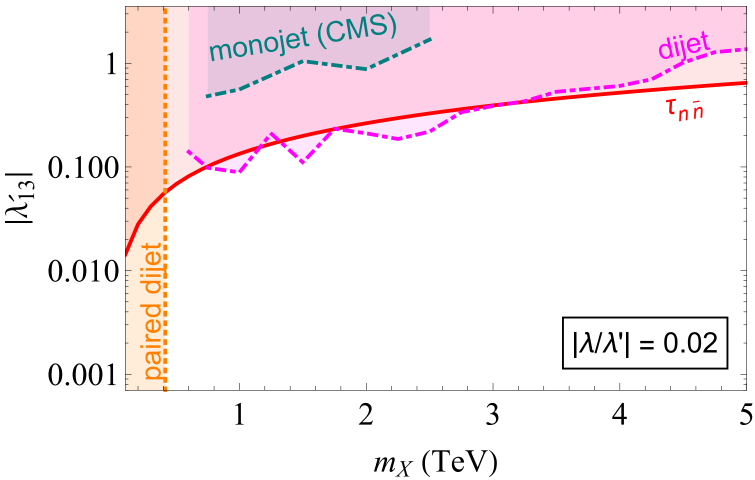
Constraint from $n - \bar{n}$



Constraint from $n - \bar{n}$

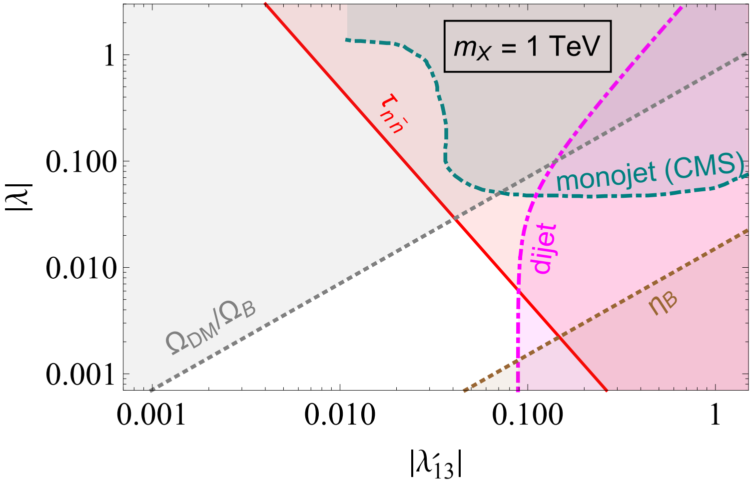


- There is a lower limit on $|\lambda'_{13}| \gtrsim 10^{-11}$ requiring that X decay temperature is above QCD scale.
- But the corresponding upper limit on $\tau_{n\bar{n}}$ is useless (10^{62} sec).



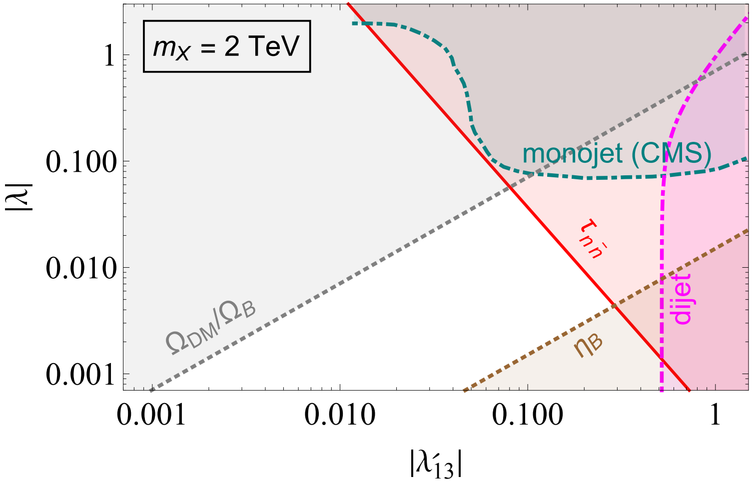
[Allahverdi, BD, Dutta (PLB '18)]

Further Complementarity with Dark Matter and Baryogenesis



[Allahverdi, BD, Dutta (PLB '18)]

Further Complementarity with Dark Matter and Baryogenesis



[Allahverdi, BD, Dutta (PLB '18)]

Conclusion

- Baryon number violation is expected in many well-motivated BSM/GUT scenarios.
- Much attention has been given to proton decay experiments.
- $n - \bar{n}$ oscillation deserves equal emphasis (if not more).
- Discovery of $n - \bar{n}$ oscillation would constitute a result of fundamental importance for physics.
- Even a null result in the next generation experiments (like ESS or DUNE) might be sufficient to eliminate a whole class of low-scale baryogenesis models.
- From the nuclear physics side, development of improved models of the antineutron annihilation process and of the propagation of the annihilation products through the nuclear medium would be helpful.
- Also need a more thorough and quantitative analysis of the relationship between free and bound neutron oscillations, including uncertainties due to the strong interaction.
- Also need state-of-the-art calculations of the matrix elements of the six-quark operators.

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THANK YOU