Exotic BSM Physics and $N\text{-}\bar{N}$ oscillation

R. N. Mohapatra

University of Maryland

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NNbar search and BSM physics

- Nnbar is a gold mine of information on new physics in the multi-TeV range i.e. new colored scalars, new B-violating forces etc
- Requires a new way to look at the origin of matter- Post sphaleron baryogenesis;
- TeV scale origin of neutrino mass
- Possible connection to dark matter
- Today's talk: ***IT PROVIDES A PROBE OF SOME KINDS OF EXOTIC BSM PHYSICS AS WELL.***

Searching for NN-bar oscillations

- Two ways:

(i) Oscillation inside a nucleus leading to
B-violating nuclear decays

(ii) Oscillation of a free neutron beam from
a reactor or spallation source

Free neutron Oscillation

- Two state quantum mechanics:
- $\frac{d}{dt}\left(\begin{array}{c} n \\ \bar{n} \end{array}\right) = \mathcal{H}\left(\begin{array}{c} n \\ \bar{n} \end{array}\right);\ \mathcal{H} = \left(\begin{array}{cc} M_1 & \delta m \\ \delta m & M_2 \end{array}\right)$
- Coherence requires high degree of degeneracy
- ;

Any new physics that splits N-$\bar{N}$ masses will be upper bounded?

Examples of new physics

(a) Lorentz violation (connected to $\cancel{\text{CPT}}$)

(b) Violation of equivalence principle

(c) Strength of long range baryonic forces

Lorentz-violation for neutrons

- .

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{LIV}$$

$$\mathcal{L}_0 = i\bar{n}\gamma^\mu\partial_\mu n + m\ \bar{n}n + \delta_{n\bar{n}} n^T C^{-1} n + h.c.$$

$$\mathcal{L}_{LIV} = i\bar{n}\Gamma^\mu\partial_\mu n - \bar{n}Mn \qquad \Delta B = 0$$

$$\Gamma^\mu = e^\mu + \cancel{\gamma^\mu} + c^{\nu\mu}\gamma_\nu + d^{\mu\nu}\gamma_5\gamma_\nu + f^\nu\gamma_5 + \frac{1}{2}g^{\lambda\nu\mu}\sigma_{\lambda\nu}$$

$$M = \cancel{m} + \underline{a_\mu\gamma^\mu} + b_\mu\gamma^5\gamma^\mu + \frac{1}{2}H^{\mu\nu}\sigma_{\mu\nu}.$$

Kostelecky, Colladay et al

There could also be LIV terms with $\Delta B \neq 0$

Analysis of B=0 operator a_0

$$\mathcal{O}_{LIV} \sim \delta\ n^\dagger n \quad (\delta = a_0)$$

$$M = \begin{array}{c} (\boldsymbol{n+},\ \boldsymbol{\bar{n}+},\ \boldsymbol{n-},\ \boldsymbol{\bar{n}-}) \\ \begin{pmatrix} m+\delta & \delta_{n\bar{n}} & 0 & 0 \\ \delta_{n\bar{n}} & m-\delta & 0 & 0 \\ 0 & 0 & m-\delta & \delta_{n\bar{n}} \\ 0 & 0 & \delta_{n\bar{n}} & m+\delta \end{pmatrix} \end{array}$$

- Note the splitting of diagonal elements:

Condition for observability

- Oscillation probability is modified to: $(a_0 = \delta)$

$$P_{n-\bar{n}} = \left[\frac{4\delta^2_{n\bar{n}}}{\delta^2 + 4\delta^2_{n\bar{n}}}\right]\sin^2\left(\frac{\sqrt{(\delta^2 + 4\delta^2_{n\bar{n}})}t}{\hbar}\right)/2$$

- Nuclear decay searches→ $\delta_{n\bar{n}} \leq 7 \times 10^{-33}\mathrm{GeV}$

$$P_{n-\bar{n}} = \left(\frac{\delta_{n\bar{n}}t}{\hbar}\right)^2\left(\frac{\sin\ y}{y}\right)^2$$

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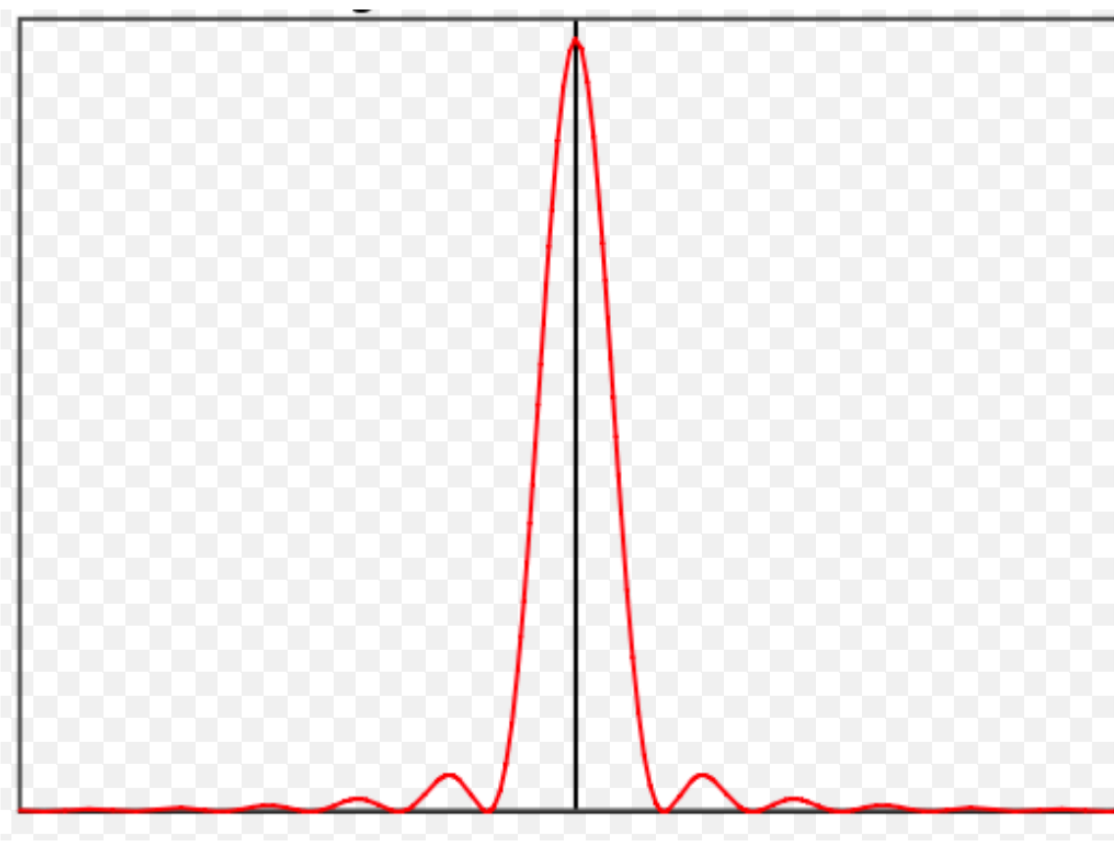
$$\leq 10^{-18}\left(\frac{sin\ y}{y}\right)^2$$

Limit on LIV

- .

$$\left(\frac{\sin\ y}{y}\right)^2$$

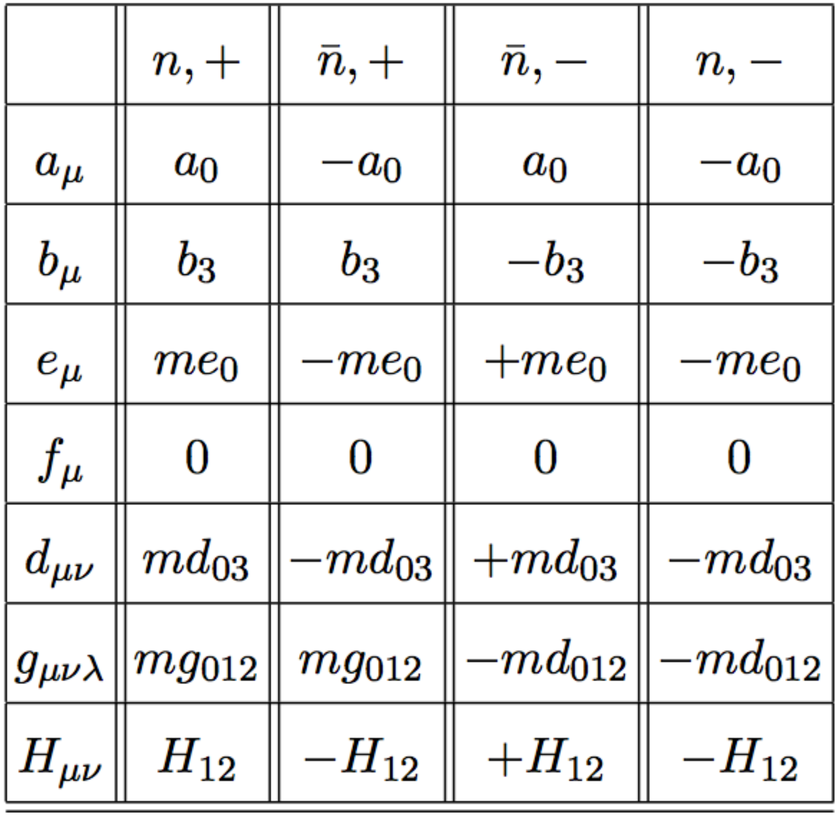


Condition for observability

- Current sensitivity for detection of nnbar require and typically t~ 1 sec. $\left(\frac{\delta_{n\bar{n}}t}{\hbar}\right)^2 \sim 10^{-18}$
- From the shape of $P_{n-\bar{n}}$, we see that for $y \sim \delta \cdot t > 3$ (since $\delta_{n\bar{n}} \cdot t \ll 1$) , we have → $P_{n-\bar{n}}$ << 10^{-18} and hence unobservable
- Hence observation of nnbar at this level would imply that

$$\boxed{\delta < 3 \text{ sec}^{-1} \sim 3 \times 10^{-24}\text{GeV}}$$

Restrictions on general LIV operators



	$n,+$	$\bar{n},+$	$\bar{n},-$	$n,-$
a_μ	a_0	$-a_0$	a_0	$-a_0$
b_μ	b_3	b_3	$-b_3$	$-b_3$
e_μ	me_0	$-me_0$	$+me_0$	$-me_0$
f_μ	0	0	0	0
$d_{\mu\nu}$	md_{03}	$-md_{03}$	$+md_{03}$	$-md_{03}$
$g_{\mu\nu\lambda}$	mg_{012}	mg_{012}	$-md_{012}$	$-md_{012}$
$H_{\mu\nu}$	H_{12}	$-H_{12}$	$+H_{12}$	$-H_{12}$

✓

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Example of an operator that flips spin, changes B

- $$\mathcal{L}_{B=2,LIV} = \frac{1}{2}\delta'_{LIV} n^T \gamma_0 \gamma_5 n + h.c.$$
- Breaks Lorentz invariance and changes mass matrix to

$$M_{4\times 4} = \begin{pmatrix} m+\mu B & \delta_{B=2} & 0 & \delta'_{LIV} \\ \delta_{B=2} & m-\mu B & \delta'_{LIV} & 0 \\ 0 & \delta'_{LIV} & m-\mu B & \delta_{B=2} \\ \delta'_{LIV} & 0 & \delta_{B=2} & m+\mu B \end{pmatrix}$$

- With such operator, degaussing unnecessary.

Non-observation→ $\delta'_{LIV} \leq 10^{-32}\ \mathrm{GeV}$

Speculation on possible origin of a_0 type LIV terms

- If baryon number is a spontaneously broken global sym., there will be massless field, ϕ derivatively coupled to neutrons: $\frac{1}{M}\bar{n}\gamma^\mu n\partial_\mu\phi$
- As the universe cools, this field could have time dependent coupling i.e. $\partial_0\phi \neq; 0$ This will induce LIV terms of the form $n^\dagger n$
- → will induce cosmological constant leading to

$$(\partial_0\phi)^2 \leq (10^{-3}\mathrm{eV})^4$$

Limit on Equivalence principle violation for neutrons

- If there is such a violation between matter and anti-matter, in the gravitational field of Earth, Sun, galaxies, δ (mass splitting) can be nonzero
- In a gravity field, $\frac{\delta}{m_n} = (\alpha_n - \alpha_{\bar{n}}) \frac{GM}{Rc^2}$
- Most stringent limit comes from superclusters for which M=5.4x10^{46}Kg; R~43 Mpc→

$$\frac{GM}{Rc^2} \simeq 3 \times 10^{-5} \qquad (\alpha_n - \alpha_{\bar{n}}) \leq 10^{-19}$$

- Limits from KK-bar <10^{-13}; Dicke et.al. < 10^{-12}

Limit on the strength of long range baryonic forces

- . If there are long range baryonic forces, the astrophysical bodies (Sun, Superclusters etc) will split the n-$\bar{n}$ masses and suppress free oscillation.
- Observation of n$\bar{n}$ will then limit the strength of the strength of the forces: g_B .

- Limit: $\alpha_B \leq 10^{-54}$ most stringent.

(Babu, RNM'16; Adazzi,Berezhiani,Kamyshkov'16)

Some details

- Potential energy due to the new force:

$$V_B(r) = \alpha_B \frac{N_A N_B}{r} e^{-r/R_0}$$

- $N_B \rightarrow -N_B$ for anti-neutrons leading to mass splitting.

- $R_0 \sim (g_B v_B)^{-1}$

Gauge theory for such weak B-L force

- Such a B-L symmetry must not contribute to electric charge since if it did, we would have

$$\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g_R^2} + \frac{1}{g_B^2}$$

- →

$$g_B^2 > e^2$$

NN-bar vs Non-leptonic Nucleon decay

- Important point: All these conclusions rely on observation in free neutron oscillation and not observation of NN-bar in nucleon decay searches, where a tiny new splitting gets heavily masked by nuclear potential difference and does not lead to any constraints.

◆ Free n-n-bar oscillation search therefore more potent source of theory information than nuclear search or nn’ osc.

NN’ Oscillation

- Here a more or less exact discrete symmetry is essential.
- As a result, observation of NN’ does not limit the extent of Lorentz violation.

Conclusion

- Observation of NN-bar oscillation can more firmly establish the fundamental assumptions of Quantum field theory.
- It can also bound couplings for long range gauge forces.

More details

- . In the early universe, we have

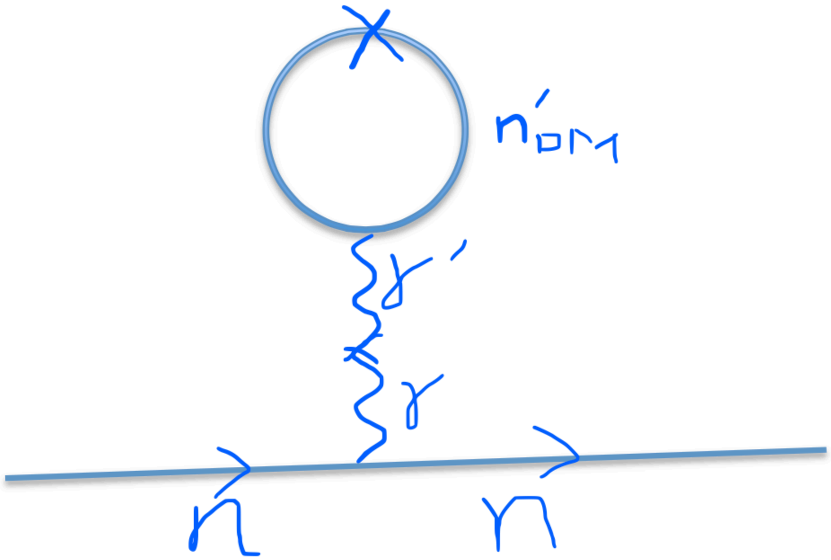
$$\phi'' + 3H\phi' + m_\phi^2\phi = 0 \qquad \phi' = \frac{\partial\phi}{\partial t}$$

- As the universe evolves, ϕ is time dependent and leads to Lorentz violation of the type here:

- If scale of B-violation ~v_B, $$\frac{\phi'}{v_B} \sim m_\phi$$

Another possible source

- Possible Lorentz violation in the dark matter sector, transmitted to the visible sector:
- n'_{DM} =mirror neutron



Any CPT violating

- Requires high degree of degeneracy between N and $\overline{N}$ required to observe it:
- For transit time ~ sec., $\Delta M \leq 10^{-24}\ \mathrm{GeV}$
- High degeneracy guaranteed by CPT inv;
- First obvious conclusion: Observation of nnbar will give the new limit on ~~CPT~~ for neutrons will put ~~CPT~~ $< 10^{-24}$ GeV

(*better than for Kaons* $<$ *4x*10^{-19} *GeV*)