Neutron Oscillations

Mary Bishai (BNL)

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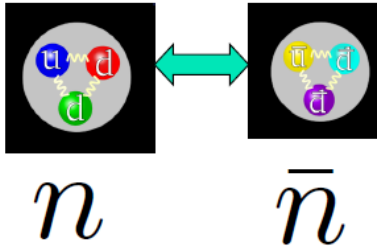
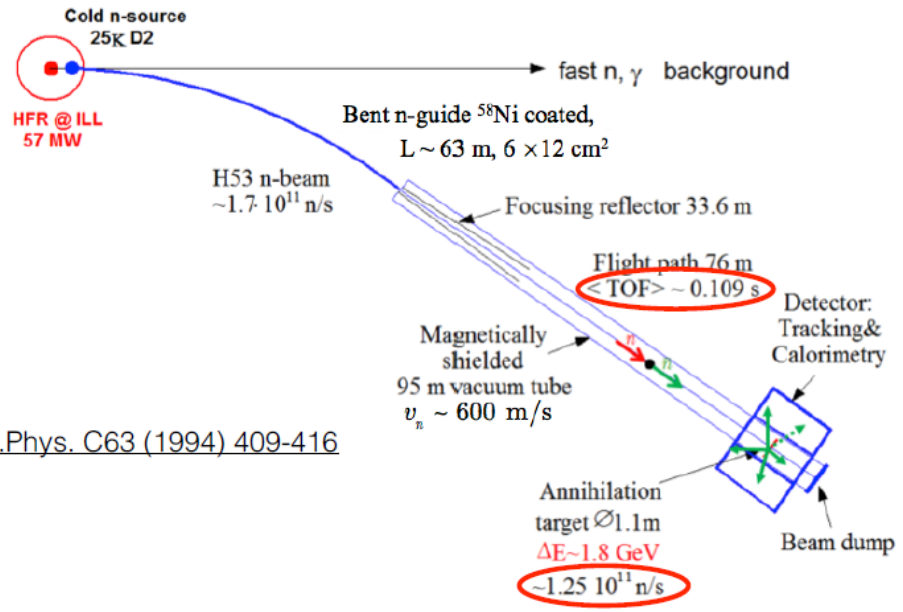
What is N-Nbar oscillation ?

- **Neutrons in vacuum and low magnetic field spontaneously converting to anti-neutron.**
- Free oscillation time $\tau_{n\bar{n}} = \frac{\hbar}{\delta m_{n\bar{n}}}$



- Transition probability: $P_{n\to\bar{n}} \approx \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$
- # of events: N $P_{n\to\bar{n}}$ x running time (N=neutron flux)
- Current direct search limit ILL $\tau > 8.6 \times 10^7$ sec
- → $\delta m_{n\bar{n}} < 10^{-32} GeV$
- $\tau_{n\bar{n}}$ can be probed up to $10^{10\text{-}11}$ sec. (Kamyshkov and Snow's talk)
- $\delta m_{n\bar{n}}$ is the particle physics probe !!

Free neutron limits



Baldo-Ceolin et al, Z.Phys. C63 (1994) 409-416

- $Nt^2 = 1.5\ 10^9$s (run lasted ~1 year), $P < 1.6\ 10^{-18}$ and $\tau > 0.86\ 10^8$s
  - Many subtle optimizations to minimize losses and backgrounds
  - Experiment was background-free
- Bound neutron limits ~3 times better
  - But model-dependent, and now limited by atmospheric ν background

Why has it not been observed in nuclei?

Given this limit on $\tau_{n\bar{n}}$ why are nuclei stable ?

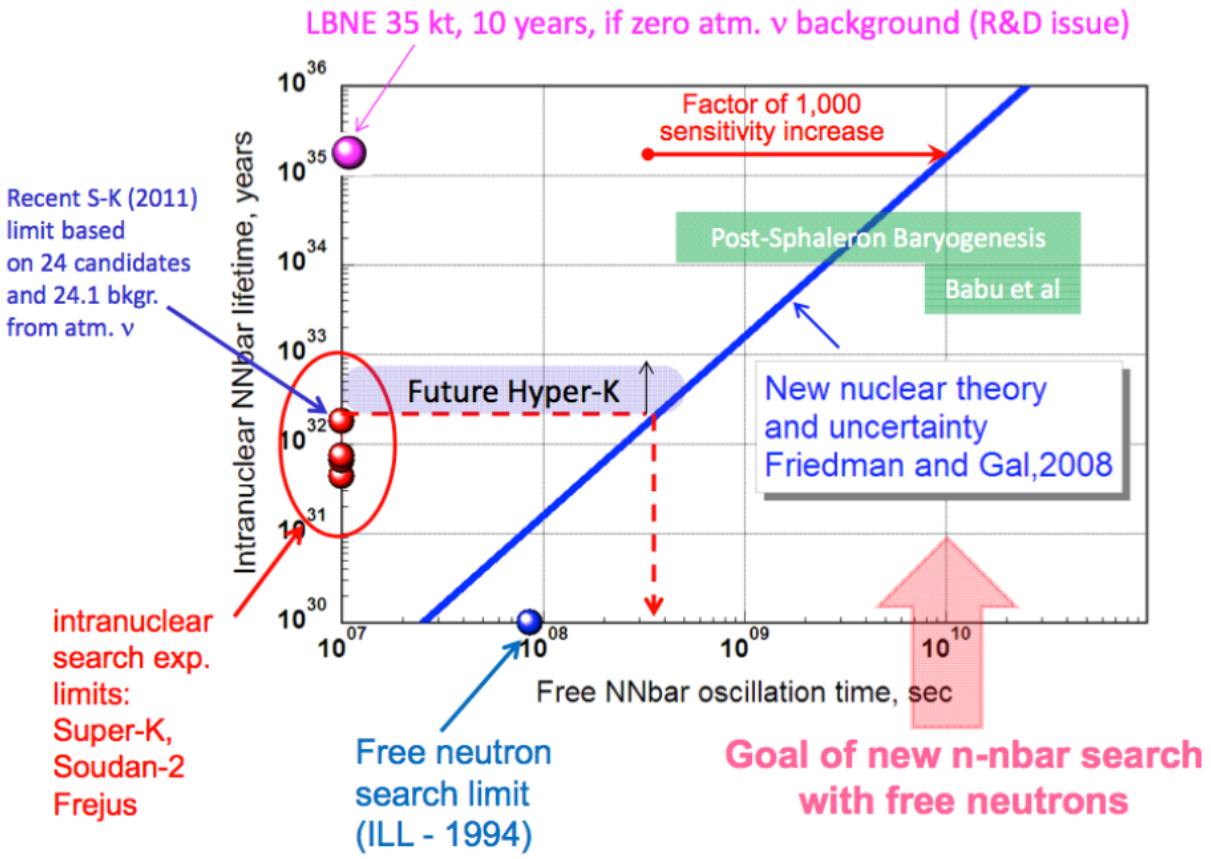
- Oscillation inside nuclei are suppressed by the factor $\left(\frac{\delta m_{n\bar{n}}}{V_n - V_{\bar{n}}}\right)^2 \leq 10^{-62}$
- More detailed calculation: (Dover, Gal, Richard; Vainstein's talk)

$$\tau_{Nuc} = R\tau_{n\bar{n}}^2 \quad R = 0.3\times10^{23}\ \mathrm{sec}^{-1} \rightarrow \tau_{Nuc} \geq 10^{32} yrs$$

- Super-K search (Kearns' talk) $\tau_{n\bar{n}} > 2.44\times10^8$ sec.

Free and Bound Neutron limits

$$\tau_{bound} = R \times \tau^2_{free}$$



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Why is it important to search for NNbar ?

- Many reasons to believe that **baryon number (B) is not a good symmetry of nature** :

Sphalerons in SM , GUTs, origin of matter etc.

- If B is violated, important to determine the selection rules: B=1 (p-decay) or B=2 (NNbar) ?

i) What is the scale at which B- symmetry is broken ?

NNbar → lower scale physics than usual p-decay

ii) NNbar oscillation intimately connected to neutrino mass physics when combined with quark-lepton unification

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(ii) Neutrino mass NNbar connection

- SM has exact global B-L symmetry !!
- If neutrino is Majorana fermion, it breaks **L**-part of **B-L**
- observation of $\beta\beta_{0\nu}$ decay will be a significant discovery which will confirm this but will not tell us much about associated new physics.
- N-N-bar oscillation breaks B-part of B-L and provide complementary information-

  e.g. if NN-bar is observed, either all or surely some of nu-mass physics is at the TeV scale and will be accessible in other expts e.g. LHC, FCNC, edm

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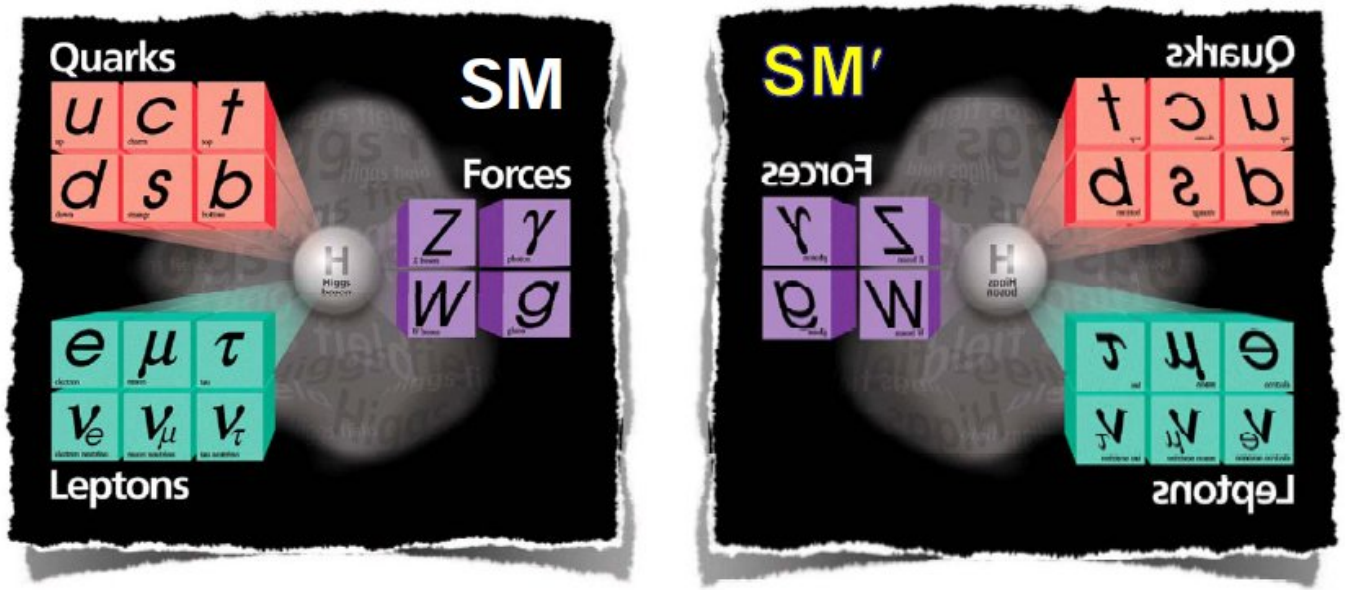
Seesaw in SO(10) –Another predictive model for NNbar

- Coupling unification fixes the mass scales as in the case of proton decay:
- In a minimal SO(10) embedding of seesaw, f_{ab} determined from fermion mass fits
  - (Babu, Mohapatra'93; Fukuyama, Okada'02; Bajc, Senjanovic, Vissani'02; Goh, Mohapatra, Ng'03 Babu,Macesanu'05; Bertolini, Malinsky,Schwetz'06; Joshipura, Patel'11)
- Predicts correct θ_{23}, θ_{12} and $\sin^2 2\theta_{13} \simeq 0.09$
- Model has diquarks at sub-TeV scale to have unification and they lead to observable NNbar !

Is There Mirror Matter?

Two coexisting worlds look theoretically very attractive



- Two identical gauge factors, $G \times G'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ – $SU(5) \times SU(5)'$, *etc* .
- Can naturally emerge in string theory: O & M matter fields localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$
- Exact parity $G \leftrightarrow G'$: Mirror matter is dark (for us), but its particle physics we know exactly (on our skin) – no new parameters!

Z. Berezhiani, May 2014

Mirror World $\leftrightarrow$ Our World (Y. Kamyshkov)

Concept of Mirror Matter

Original idea of the shadow world was that mirror matter is an exact replica of our regular matter: mass of mirror electron is the same as of normal electron; mirror photon is massless but different from normal photon; mirror charged particles have their own electric charge that our normal charges do not see and do not interact with; mirror magnetic field is due to the motion of mirror charges, it is different from ordinary magnetic field (however, can be measured in the same units: Gauss); mirror neutron and proton have the same mass, spin, magnetic moment and similar e-m strong and weak forces in mirror sector, not interacting with our particles; there are similar mirror nuclei, atoms, stars, galaxies… ? life … ?

Interaction between MM and OM is by gravity and possibly through oscillation mechanism of neutral particles: ν, n, γ

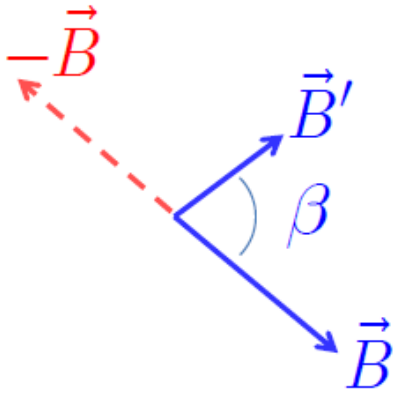
Mirror Matter $n - n'$ Oscillation in Magnetic Fields
Y. Kamyshkov (U. Tennessee)

Neutron disappearance in the presence of B' (Z. Berezhiani, 2009)

$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} + \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$



where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

$$A_B^{\text{det}}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} \quad \leftarrow \quad \text{assymetry}$$

Reasonable exploration region
$\tau > 1s$; B' ~ similar to 0.5 G

Probability is related to $n \rightarrow n'$ oscillation time τ

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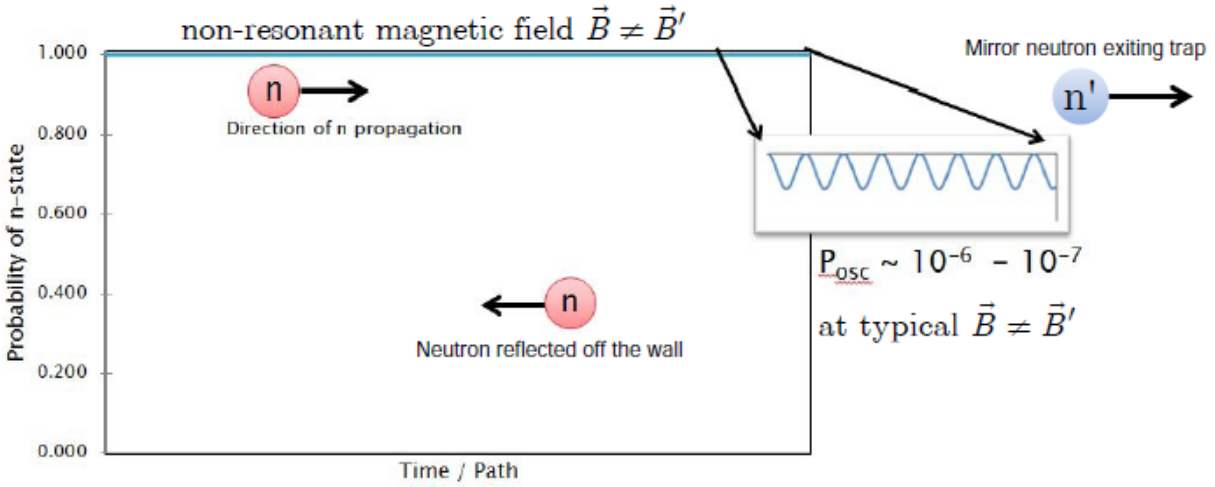
Neutron oscillating into mirror neutron is interacting with the trap wall



in case of successful guessing for $\vec{B} = \vec{B}'$ the resonance enhancement is expected: the oscillation frequency will be reduced to (1/few s) and oscillation amplitude increased by few orders of magnitude, ultimately to

$$P_{nn'} = \left(\frac{t}{\tau_{nn'}} \right)^2$$

t – observation time

$\tau_{nn'}$ – oscillation time > 1 sec

A signal for mirror matter?

Magnetic anomaly in UCN trapping: signal for neutron oscillation to parallel world?

Z. Berezhiani and F. Nesti
Eur. Phys. J. C72 (2012) 1974;
also http://arxiv.org/abs/1203.1035

$$A_B^{\text{det}}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)}$$

Measured asymmetry → ~ $(7\pm1.4)\times10^{-4}$ (~5σ)

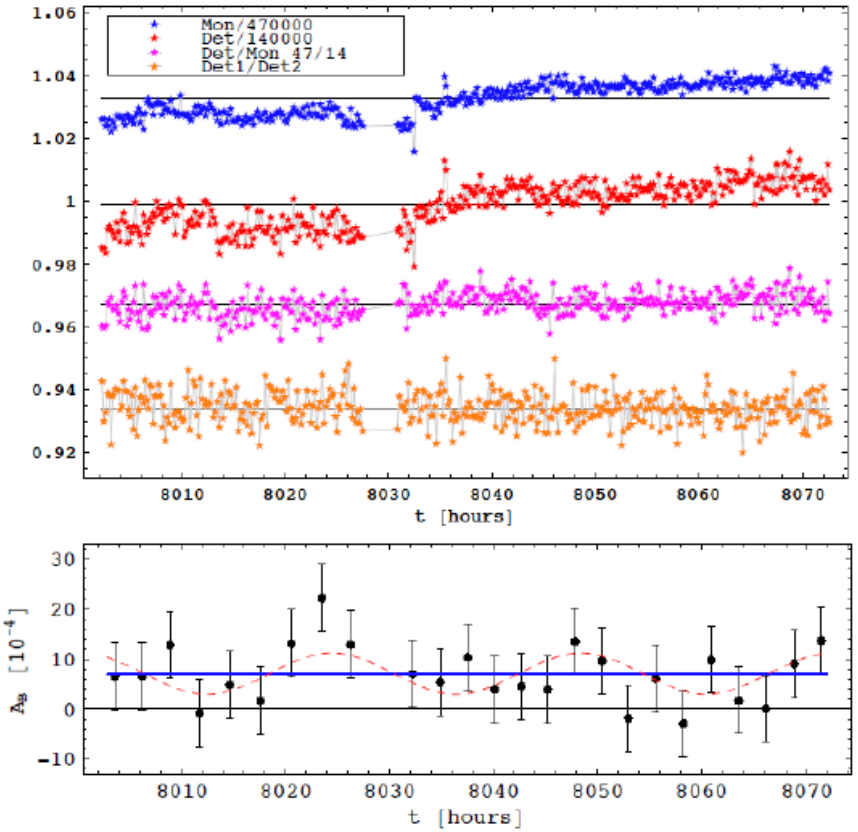
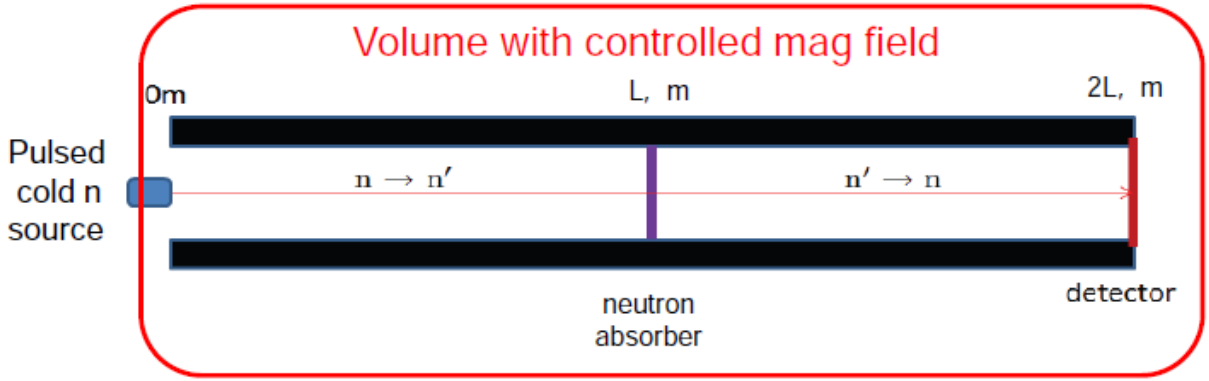


Fig. 1. Upper Panel: *from up to down, the monitor and detector counts in* $\{\boldsymbol{B}\}$ *series,* M *and* $N = N_1 + N_2$ *normalized respectively to 470000 and 140000; and the ratios* $N/M\,(\times 47/14)$ *and* N_1/N_2. Lower Panel: *results for* $A_{\mathrm{B}}^{\mathrm{det}}$ *binned by two* $\{\boldsymbol{B}\}$ *cycles (16 measurements), with the constant and periodic fits.*

New concept: Neutron Regeneration (Y. Kamyshkov)

Possible Neutron Regeneration Search

- It is an appearance search of $n \to n' \to n$
- Alternative to disappearance $n \to n'$ observed with UCN
- It excludes collisions with walls that might be the reason for some unknown effect resulting to the measured assymetry with UCN.



Mirror Matter Search at BNL?

- Small experiment that could be carried out at BNL.
- A BNL $n \to n' \to n$ regeneration experiment is complementary to $n \to n'$ disappearance experiment done earlier with a potential 5.2σ signal.
- Could be done now with 100kW for 1 day or 20 kW for 10 days for example.
- Requires cold neutrons
- Pulsed beam structure can be used to reduce backgrounds.