INT Workshop INT-17-69W • October 23 - 27, 2017
Neutron Oscillations: Appearance, Disappearance, and Baryogenesis

NNbar and massive B–L Photons

Based on paper of Andrea Addazi, Zurab Berezhiani, YK, https://arxiv.org/abs/1607.00348; Eur. Phys. J. C (2017) 77:301.
Similar subject was discussed by K. Babu and R.N. Mohapatra in https://arxiv.org/abs/1606.08374; Phys. Rev. D 94, 054034 (2016)

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The concept of nucleon stability (conservation of baryon charge) was conjectured by Weyl in 1929 by analogy with electric charge conservation, and then independently by Stueckelberg in 1938 and by Wigner in 1949. Gell-Mann and Pais in 1955 pointed out that conservation of baryon number would be the only reason which forbids the transformation of neutrons to antineutrons.

- Conservation of electric charge (tested with high precision) implies that transversal photons are massless.

- Can the Baryon (and Lepton) number conservation be described in a similar way through existence of massless Baryonic or Leptonic Photons? For discussion of massless Leptonic and Baryonic Photons see e.g. L.B. Okun, Leptons And Quarks (Special Edition), 2014, ASIN: B011FQZZKW

- If interaction between baryonic charges exist as a Coulomb-like field of baryonic photons it will lead to the repulsion of nucleons in the matter. This additional force is proportional to the number of baryons and not to baryon mass. At the first sight, this effect will only make gravitational attraction between baryons weaker, but in fact, it will lead to violation of equality of the inertial mass and gravitational masses. The latter will be modified by additional baryonic force that can be seen in Weak Equivalence Principle tests.

The test of Equivalence Principle can provides a limit on the existence of additional baryonic force between matter

Pisa Leaning Tower.
Place of the first EP
Galileo's experiments

Experimental tests of Equivalence Principle by Galileo, Newton, Eötvös, Dickey, Braginsky, Adelberger ...

Equivalence of inertial and gravitational masses was recently tested to the accuracy $\sim 10^{-13}$

STEP (mini-STEP) space-based experiments (not pursued by NASA) was proposed to test E.P. down to $\sim 10^{-17}$

Cu Pb

V

$$F = G\cdot \frac{m_1 m_2}{r^2} + \alpha_B \frac{B_1 B_2}{r^2} = G\cdot \frac{m_1 m_2}{r^2}\left\{1 + \frac{\alpha_B}{G}\left(\frac{B_1}{m_1}\right)\left(\frac{B_2}{m_2}\right)\right\}$$

$$\left(\frac{m_{Pb}}{B_{Pb}} - \frac{m_{Cu}}{B_{Cu}}\right) \cong 10^{-3} m_p$$ ← Example from Okun's book:

E.g. from Pb - Cu comparison experiment with measured

$$\frac{\alpha_B}{G\cdot m_p}\left[\frac{B_{Cu}}{m_{Cu}} - \frac{B_{Pb}}{m_{Pb}}\right] < 10^{-12}$$

it would follow that $\alpha_B < 10^{-9} G m_p^2 \le 10^{-47}$

Compare this with $\alpha_{EM} = \frac{1}{137}$ and $\alpha_G = G m_p^2 \le 10^{-39}$

Weakness of B, L, or B–L coupling constant (many orders of magnitude weaker than Gravity) is usually used as an argument against the existence of B, L, or B–L vector fields. E.g. in Okun's book (ibid.):

"It is natural to conclude on the basis of the above estimates that massles vector particles coupled to the leptonic and baryonic charges do not exist. These charges are possibly coupled to some massive vector particles."

We discuss massive vector baryonic/leptonic photons
Since the combination of (B-L) but not B or L is a gauge symmetry of the SM, we more precisely should be discussing (B-L) photons coupled to

B-L charge:

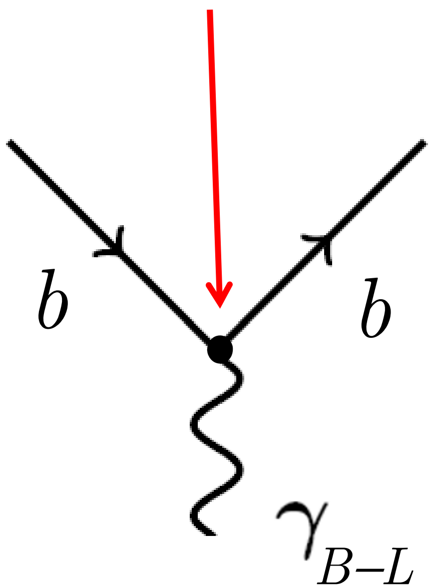
of proton and neutron is	+1
of antiproton and antineutron is	-1
of electron	-1
of positron	+1
of neutral hydrogen atom is	0
of the Earth	~50% N_B
Sun chemical composition by mass:	
H 73.46%; He 24.85%; all the rest 1.69%	~ 13% of N_B

The Annual Review of Astronomy and Astrophysics, 2009.47:481-522.

Since baryon number in the Universe is violated, (B-L) photons should be massive.

Yukawa force:

$$g e^{-r/\lambda}$$



Mass of (B-L) photon:

$$m = \frac{1}{\lambda}$$

λ effective $B - L$ force radius

Most recent result on the strength of interaction of massive vector (B-L)

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **29** (2012) 184002 (15pp) doi:10.1088/0264-9381/29/18/184002

Torsion-balance tests of the weak equivalence principle

T A Wagner, S Schlamminger[1], J H Gundlach and E G Adelberger

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- WEP – same fall acceleration in uniform gravitational filed;

$$V_{i,A} = V_G + V_{OBE} = V_G(r)\left[1 + \tilde{\alpha}\left(\frac{\tilde{q}}{\mu}\right)_i\left(\frac{\tilde{q}}{\mu}\right)_A \exp(-r/\lambda)\right], \quad (3)$$

Yukawa term

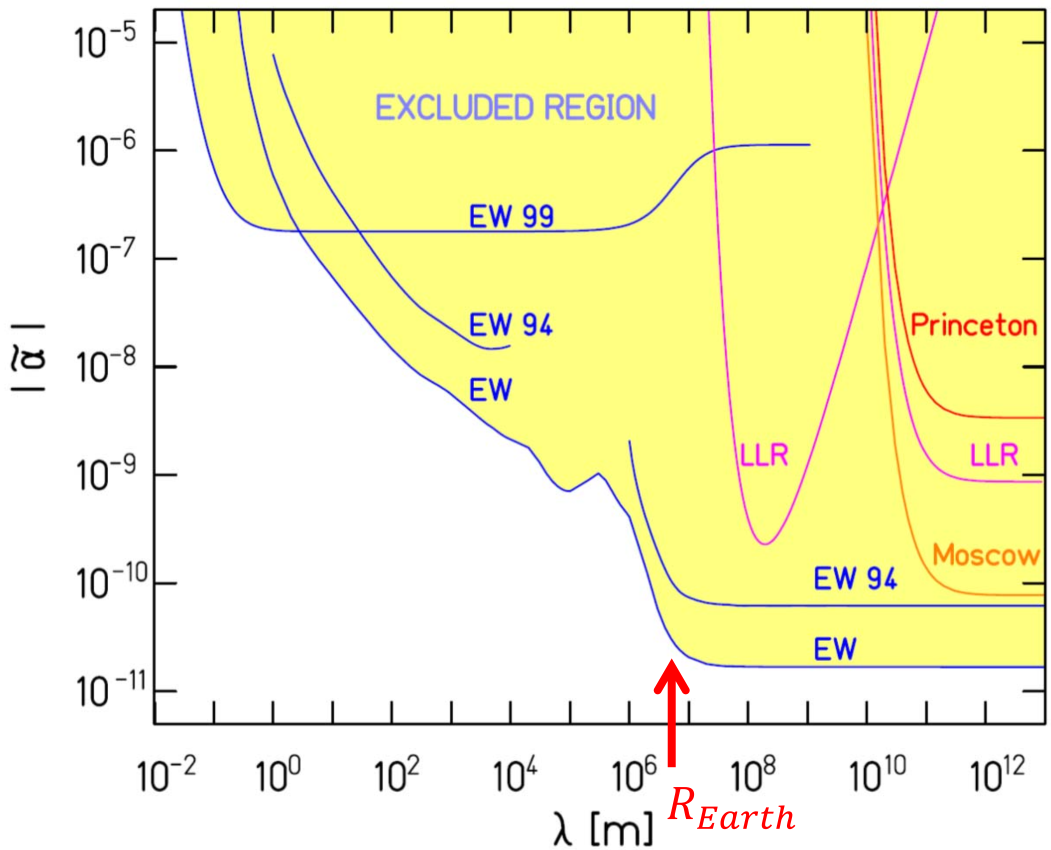
where the dimensionless ratio $(\tilde{q}/\mu)$ is an object's charge per atomic mass unit (u), and the dimensionless Yukawa strength parameter

$$\tilde{\alpha} = \pm\tilde{g}^2/(4\pi G u^2). \quad (4)$$

and $\lambda \sim \frac{1}{m}$ radius of the interaction related to (B-L) photon mass

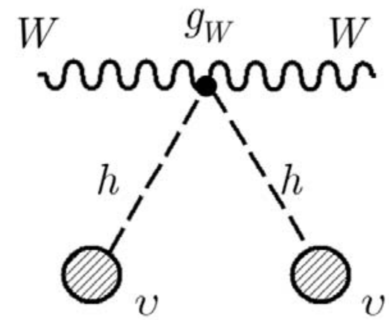
Two parameters

Class. Quantum Grav. **29** (2012) 184002



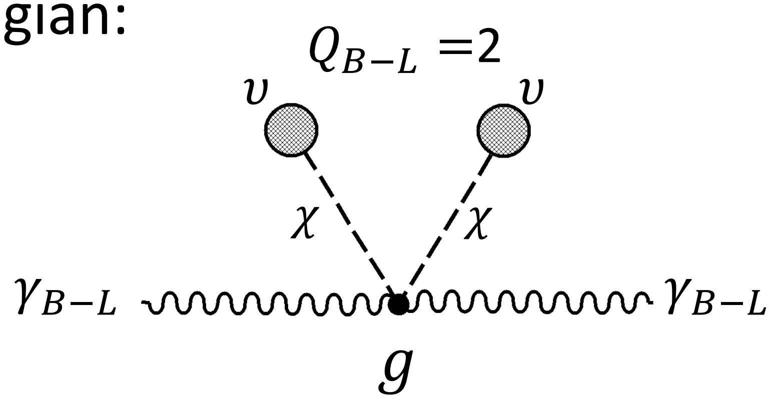
95% CL upper bounds on the strength of a vector Yukawa interaction coupled to $\tilde{q} = B - L$.

Massive vector (B-L) photons



mass term in the Lagrangian:

$$g^2 v^2 Q_B^2 b^\mu b_\mu$$



VEV of scalar Higgs-like field χ spontaneously breaks $U(1)_{B-L}$

and induces the photon mass: $m_b = 2gv$, where $\alpha_{B-L} = \frac{g^2}{4\pi}$

$$\alpha_{B-L} = f(\lambda, v)$$

The exchange of massive baryophoton mediates a spin-independent Yukawa-type environmental fifth force for baryonic matter.

The existence of $n\bar{n}$ mixing implies violation of $U(1)_{B-L}$ with $\Delta B = 2$ and requires $B - L$ photons to be massive

Complex scalar field χ after being spontaneously broken can be expanded around VEV into radial Higgs-like massive component ρ and massless Goldstone component β.

Z. Berezhiani, Eur. Phys. J. C76 (2016) no.12, 705, https://arxiv.org/abs/1507.05478

$$\varepsilon_{n\tilde{n}} = y v_\chi \sim \frac{v_\chi \Lambda_{QCD}^6}{M^6} \sim \left(\frac{v_\chi}{1\,\text{GeV}}\right)\left(\frac{100\,\text{TeV}}{M}\right)^6 \times 10^{-25}\,\text{eV}$$

M is the scale of $n\bar{n}$ operator $\sim$ 100 TeV, y is coupling of field χ with neutron; $10^{-25}\ eV$ is domain of the $n\bar{n}$ mixing ($\sim$ ESS)

What could be the value of v_χ ?

Inside nuclei (but not for free neutrons) the following virtual process can take place since $\Delta E_{n\bar{n}} \sim 100\ MeV$ for heavy nuclei:

decay $n \to \bar{n} + \rho, \beta$ followed by annihilation of $\bar{n}$.

with $\Gamma(n \to \bar{n}) = \frac{y^2}{4\pi} \Delta E_{n\bar{n}}$

Taking the limits for $\Gamma(n \to \bar{n})$ from Soudan II and Super-K experiments, one can get $y < 10^{-31}$ and correspondingly

$$\upsilon_\chi > 10^{31} \varepsilon_{n\tilde{n}} = \left(\frac{\varepsilon_{n\tilde{n}}}{10^{-25}\ \mathrm{eV}}\right) \times 1\ \mathrm{MeV}.$$

Other heavier scalars (not necessarily with $\Delta B = 2$) can contribute correspondingly to higher values of υ_χ

α_{B-L} vs photon mass $(1/\lambda)$ limit

$$V_a = \alpha_{B-L} \frac{Q_a Q_A}{r} e^{-r/\lambda}$$

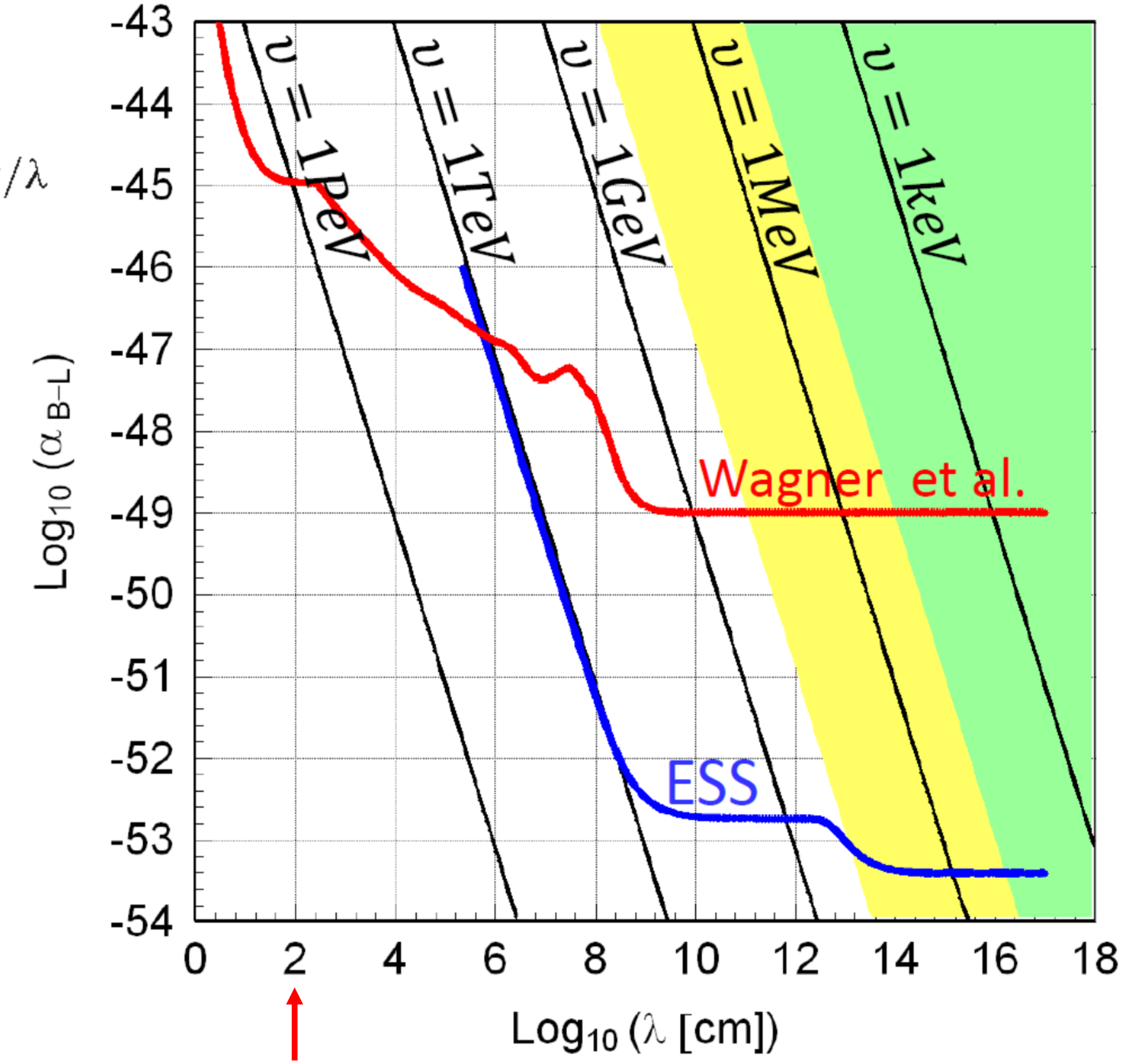
Values above red curve are excluded by WEP experiments

Yellow corresponds to current experimental limit for $n\bar{n}$

$$\varepsilon_{n\tilde{n}} < 2.5 \times 10^{-24}\,\text{eV}$$

Green: possible future limit

$$\varepsilon_{n\tilde{n}} < 10^{-26}\,\text{eV}$$



m_{B-L}=2· 10^{-7}eV

How B-L photons are related to N-Nbar ?

$$P_{n \to \bar{n}}(t) = \frac{\varepsilon^2}{\varepsilon^2 + V^2} \cdot \sin^2\left(\frac{\sqrt{\varepsilon^2 + V^2}}{\hbar} \cdot t\right)$$

where V is a potential symmetrically different for n and $\bar{n}$
(e.g. due to non-compensated Earth mag. field, or nuclear potential);
t is observation time in an experiment.

The current limit on n-nbar corresponds to $\varepsilon < 2.44 \cdot 10^{-24}\ eV$

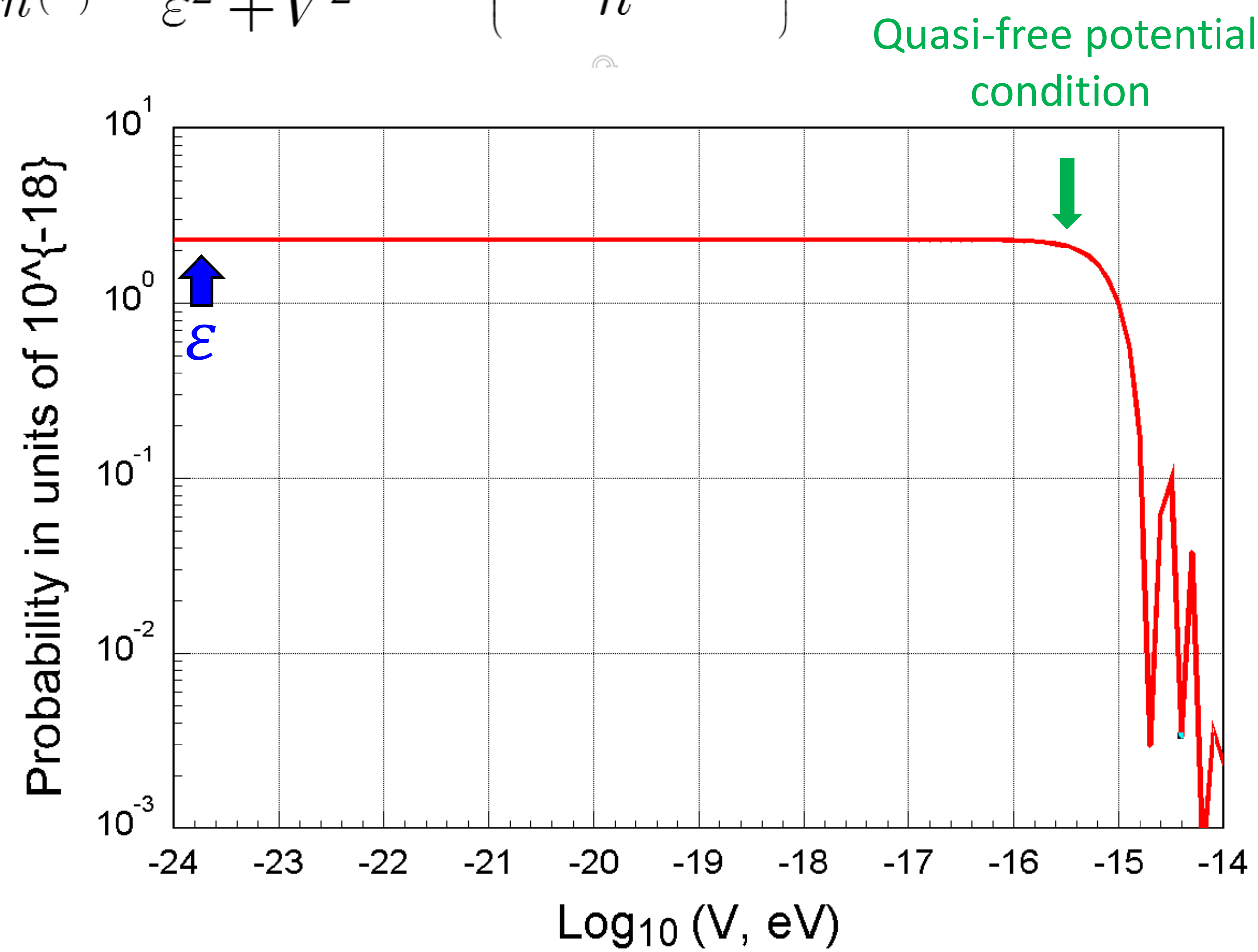
(Super-K) and with typical flight time in ESS experiment $\Delta t \sim 0.25\ s$

the appearance probability per neutron $P_{n \to \bar{n}}$= 8.6×10^{-19} (ESS)

Compare with $P_{n \to \bar{n}}$= 1.6×10^{-18} in experiment at ILL with

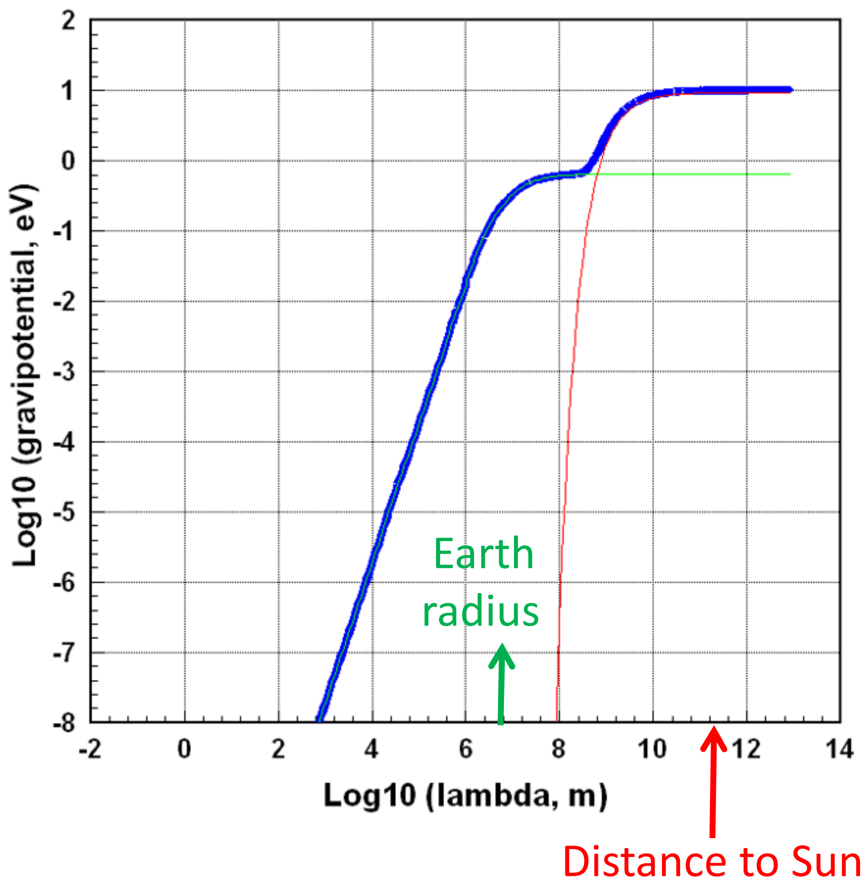
$\Delta t \sim 0.109\ s$ and the limit set at ILL $\varepsilon < 7.65 \cdot 10^{-24}\ eV$

$$P_{n\to\bar{n}}(t) = \frac{\varepsilon^2}{\varepsilon^2 + V^2} \cdot \sin^2\left(\frac{\sqrt{\varepsilon^2 + V^2}}{\hbar} \cdot t\right)$$



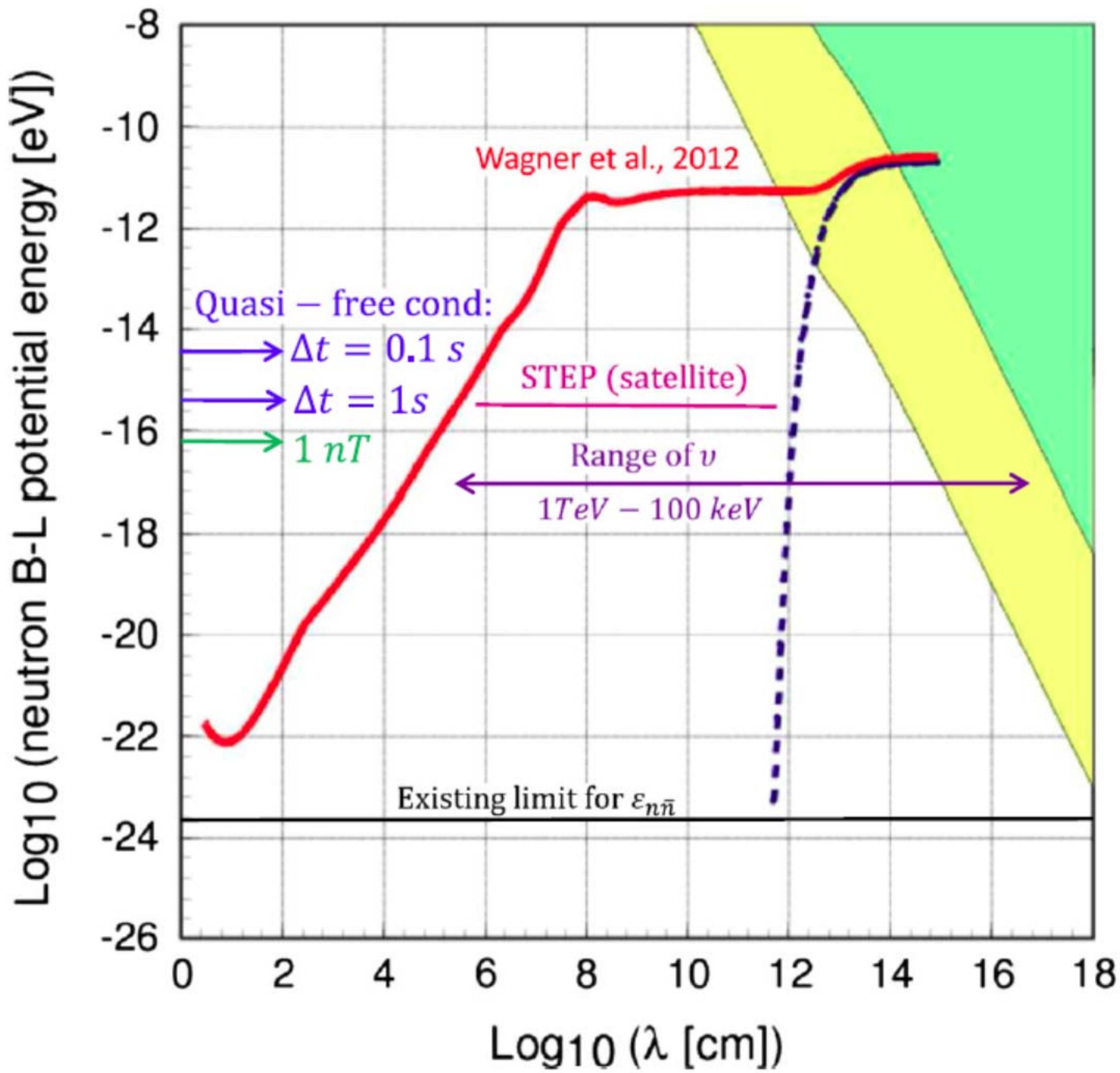
Quasi-free potential condition doesn't depend on ε in the wide range of the latter. However, it depends on the flight time t in experiment.

Detail of the calculation: gravity potential modified with Yukawa term from Earth and Sun At the surface of Earth



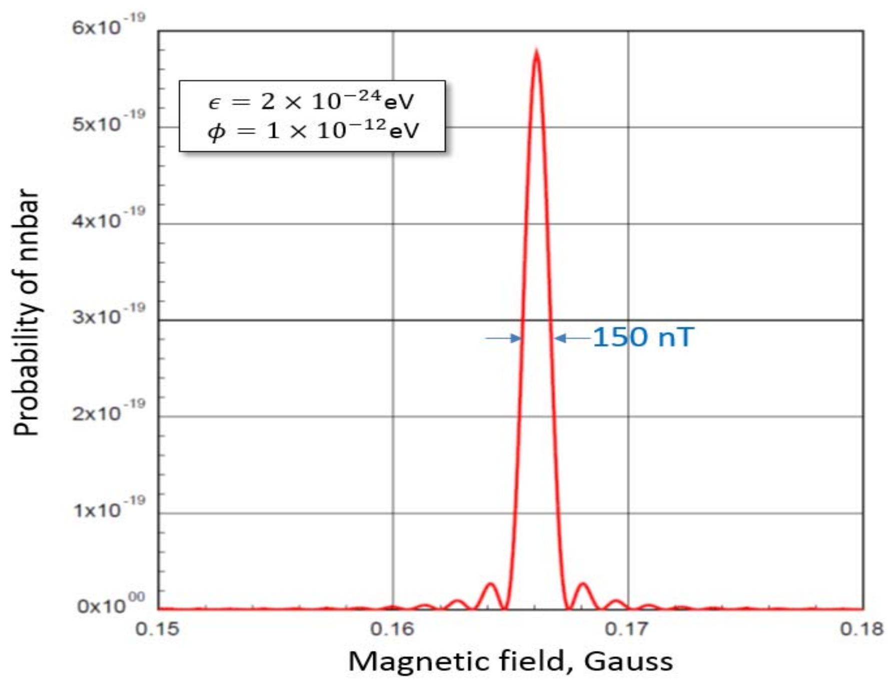
Potential Energy of Neutron in $B - L$ field of Earth and Sun

Values above red curve are excluded by WEP experiments



Current limit on n-nbar amplitude: $\epsilon < 2.44 \times 10^{-24}$eV.

- Let's assume that n-nbar occurs with $\epsilon \sim 2.0 \times 10^{-24}$eV.
- Let's assume that B-L field has a potential energy $= 1 \times 10^{-12}$ eV and n-nbar is suppressed. Then, it will be potentially possible by variation of external vertical magnetic field to find and compensate the effect of B-L field, and thus to measure the mass of B-L photons (plot below).
- If B-L potential is weaker than 10^{-16} eV, then n-nbar becomes non-sensitive to B-L field.



Conclusions

- Massive B-L photons can exist with the coupling much smaller than gravitational.

- If Yukawa radius of B-L field interaction is $\lambda > 10^4$ m, and for some values of coupling strength not excluded by WEP measurements the n-nbar transformation in free-neutron experiment can be suppressed.

- Limited by $n\bar{n}$ nuclear stability limits range of Yukawa $B - L$ force $\lambda \lesssim$ radius of Solar system.

- N-nbar transformation for neutrons bound inside nuclei is not sensitive to B-L field. When both (intranuclear and free) are measured it might set a more severe limit on B-L photon mass and the coupling strength.