Neutron-Antineutron Oscillations

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what is it?why is it interesting? (B-L violation)PhenomenologyLimits from underground detectorsPossibility of UCNCold neutrons dropped down a mine shaft

Thanks for slides: Yuri Kamyshkov, Tony Mann, Albert Young, Yasuhiro Masuda



Systems that oscillate are interferometers, sensitive to very small effects. Neutron is a long-lived neutral particle with a distinct antiparticle and so can oscillate. No oscillations have been seen yet.

Need interaction beyond the Standard Model that violates Baryon number (B) by 2 units. Why should such an interaction exist?

Is B the Source of a Field Like Q?

Conservation of electric charge is closely connected in SM theory with gauge symmetry and masslessness of photon and 1/r form of EM potential.

$$V_{EM} = Q / r$$

If same idea worked for B, we expect conservation of "baryonic" charge to be associated with new long-range force coupled to B. So where is the new long-range force coupled to B?

$$V_B = B / r$$

Experimental tests of equivalence principle for gravity use masses with different B/M ratios, see no effects. This give strong constraint on any such new long-range force coupled to B.

B conservation in SM is Approximate

From SM point of view, both <u>B and L conservation are "accidental"</u> global symmetries: given SU(3)⊗SU(2)⊗U(1) gauge theory and matter content, no dimension-4 term in Lagrangian violates B or L.

Operator of dimension D+4 is nonrenormalizable term which must be divided by mass scale M^D. From effective field theory point of view it should be suppressed by large mass scale so that radiative corrections to other processes <u>in perturbation theory</u> are small.

So there is no special reason why SM extensions should conserve B perturbatively.

Nonperturbative EW gauge field fluctuations called sphalerons, present in SM, VIOLATE <u>both B and L, but conserve B-L</u>. Rate is completely negligible in our vacuum, but should be faster than expansion rate at the electroweak phase transition in early universe.

Universe is B Asymmetric out to ~10 Mpc



In the lab we make equal amounts of matter and antimatter But the universe has B asymmetry: $\eta = (N_B - N_{antiB}) / N_{\gamma} \sim 10^{-10}$ Why?

One Possibility: B conservation+ Initial Condition $\eta(t\sim0)=10^{-10}$

Possible. But now we believe in inflationary period in early universe to solve horizon, flatness, etc. problems in cosmology. Inflation asserts that the "size" of the universe increased exponentially at constant energy density:

$R(t) \propto \exp(3Ht)$

Inflation needs ~70 Hubble times with universe at ~constant energy density-> for conserved B charge, B(t=0)~exp(200)*B(t=after inflation).

But if B(t=after inflation)~ 10^{-10} , B(t=inflation-7H)~1, so at earlier times B dominates energy density but it is exponentially changing.

->B conservation + η =10⁻¹⁰ destroys inflation. [A. D. Dolgov, Physics Reports 222,309 (1992).]

Sakharov conditions for Baryon Asymmetry in Big Bang starting from B(t=after inflation)=0

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Baryon number violation

- Not allowed in SM in perturbation theory.
- Permitted in nonperturbative electroweak "Sphaeleron" tunneling processes in SM at EW phase transition, but these conserve B-L

Departure from thermal equilibrium

- Expansion of Universe
- Phase transitions
- Should not be a problem

<u>T violation</u>

 SM CP/T violation from CKM phase seems to be orders of magnitude too small to explain observed B asymmetry – we seem to need new physics here. Impact of B-L-conserving SM interaction on B asymmetry

Sphaeleron mechanism in Standard Model lead to violation of lepton and baryon number ('t Hooft, 1976)

• "On anomalous electroweak baryon-number non-conservation in the early universe" (Kuzmin, Rubakov, Shaposhnikov, 1985)

Sphaelerons conserve (B-L) but violate (B+L). Rate of (B+L)-violating processes at T > TeV exceeds the Universe expansion rate. If $B=L \neq 0$ is set at GUT scale due to B-L conserving process, B asymmetry can be wiped out by (B+L)-violating process

<u>Thus, for the explanation of universe B asymmetry, B-L-violating</u> <u>mechanisms (leptogenesis, NNbar,...) seem to be required</u>

"Proton decay is not a prediction of baryogenesis" [Yanagida'02]

Experimental searches for B Violation: Proton Decay and Neutron-Antineutron Oscillations

Mode	Proton decay	N-Nbar oscillations
Effect on B and L	$\Delta B=1, \Delta L=1,$ $\Delta (B-L)=0$	$\Delta B=2, \Delta L=0,$ $\Delta (B-L)=2$
Effective operator	$L = \frac{g}{M^2} Q Q Q L$	$L = \frac{g}{M^5} Q Q Q Q Q Q$
Mass scale probed	~GUT	>~EW



^{2003,} M. Shiozawa 28th International Cosmic Ray Conference

Theories giving $n \leftrightarrow \overline{n}$ without proton decay

• Connection with neutrino mass physics via seesaw mechanism

K. Babu and R. Mohapatra, PLB 518 (2001) 269 B. Dutta, Y. Mimura, R. Mohapatra, PRL 96 (2006) 061801

• Connection to low quantum gravity scale ideas

G. Dvali and G. Gabadadze, PLB 460 (1999) 47 S. Nussinov and R. Shrock, PRL 88 (2002) 171601 C. Bambi et al., hep-ph/0606321

• Baryogenesis models at low-energy scale

A. Dolgov et al., hep-ph/0605263 K. Babu et al., hep-ph/0606144

$$\Psi = \begin{pmatrix} n \\ \overline{n} \end{pmatrix} \text{ mixed n-nbar QM state} \qquad \boxed{\begin{array}{l} \alpha - \text{mixing amplitude} \\ \end{array}}$$
$$H = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\overline{n}} \end{pmatrix} \text{ Hamiltonian of the system}$$
$$E_n = m_n + \frac{p^2}{2m_n} + U_n \quad ; \quad E_{\overline{n}} = m_{\overline{n}} + \frac{p^2}{2m_{\overline{n}}} + U_{\overline{n}}$$

Important assumptions :

- $\alpha(n \rightarrow \overline{n}) = \alpha(\overline{n} \rightarrow n) = \alpha$ (i.e. T-invariance)
- $m_n = m_{\overline{n}}$ (CPT not violated)
- magnetic moment $\mu(\overline{n}) = -\mu(n)$ as follows from CPT

Neutron-Antineutron transition probability

For
$$H = \begin{pmatrix} m_n + V & \alpha \\ \alpha & m_{\overline{n}} - V \end{pmatrix}$$
 $P_{n \to \overline{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \times \sin^2 \left[\frac{\sqrt{\alpha^2 + V^2}}{\hbar} t \right]$

where V is the potential difference for neutron and anti-neutron

For
$$\left[\frac{\sqrt{\alpha^2 + V^2}}{\hbar}t\right] <<1 ("quasifree condition") $P_{n \to \overline{n}} = \left(\frac{\alpha}{\hbar} \times t\right)^2 = \left(\frac{t}{\tau_{n\overline{n}}}\right)^2$$$

 $\tau_{n\bar{n}} = \frac{\hbar}{\alpha}$ is characteristic oscillation time. Present limit -> $\alpha < 10^{-23} eV!$

How to Search for N-Nbar Oscillations

Figure of merit for experiment: N=total # of free neutrons observed MT^2 T= observation time per neutron while in "quasifree" condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors(2) Cold and Ultracold neutrons



Nucleus $A \rightarrow A^* + \overline{n}$



Example: Soudan 2

- Soudan 2 is located in the Soudan mine in Northern Minnesota under 2100 mwe overburden.
- Data-taking: April 1989 to June 2001.
- Analyzed exposure is 5.56 fiducial kiloton-years



Conclusion(Tony Mann, NNbar conference, 2002):

Limit for nnbar oscillations in iron (90% confidence):

 $T_A(\text{Fe}) > 7.2 \times 10^{31} \text{ years}$

Corresponding limit on oscillation time (assuming $T_R = 1.4 \times 10^{23}$ s)

 $\tau_{n\bar{n}} > 1.3 \times 10^8$ seconds.

<u>Background</u> arising from multiprong interactions of atmospheric neutrinos is observed: ~ 0.7 v evts/kty.

SNO and SuperK can achieve $\tau_{nn} > (4 - 5) \times 10^8$ sec. Harder to make discovery in presence of background

Extending search limit sensitivity beyond $\tau_{nn} = 10^9$ secs requires a different approach. For nn exploration, the future lies with new reactor neutron beam experiments.

Why is it such hard work to get slow neutrons?

E=0



р

n

Neutrons are bound in nuclei, need several MeV for liberation. We want E~kT~25 meV (room temperature)

How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions...

 $[1/2]^{N}=(1 \text{ MeV})/(25 \text{ meV})$ for N collisions

Neutrons are unstable when free->they can't be accumulated easily







NIST Cold Neutron Guide Hall

Reactor makes neutrons, cooled to ~20K by liquid hydrogen



Neutron mirrors ("guides") conduct the neutrons ~100 meters with small losses.

Best free neutron search at ILL/Grenoble reactor by Heidelberg-ILL-Padova-Pavia



"Ultracold" Neutrons (UCN)

For very low energies (E_k -<V> negative, <V>~300 neV), matter forms a potential barrier for neutrons.



"Superthermal" Process for Making UCN

R. Golub and J. M. Pendlebury, Phys. Lett, A53, 133 (1975)

• Cold neutrons lose almost all their energy in one collision, becoming UCN.



- Rate of UCN energy gain is suppressed by cooling the moderator to low temperatures.
- Dissipative process->neutron phase space density is increased

UCN production in liquid helium



R. Golub and J.M. PendleburyPhys. Lett. **53A** (1975),Phys. Lett. **62A** (1977)

- 1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K
- Upscattering suppressed: Boltzmann factor e^{-E/kT} is small if T<<11K

He-II spallation UCN source at KEK

Yasuhiro Masuda (KEK), Sunchang Jeong (KEK), Yutaka Watanabe (KEK), Akira Yamamoto (KEK) Kichiji Hatanaka (Osaka University), Kensaku Matsuta (Osaka University) Ryouhei Matsumiya (Osaka University) Toshio Kitagaki (Tohoku University) Tomoyuki Sanuki (Tokyo University) Takeyasu Ito (Los Alamos)

He-II UCN source 2006@RCNP



UCN density from 4He Source (2002 Estimate)

Present: 0.7 UCN/cm³ for $E_n < 100 \text{ neV}$ at 392MeV × 200nA, $\tau = 14 \text{ s} (1.2\text{K})$ (few UCN/cm³ in ILL experimental chamber)

density scaling to full operation 2×10^5 UCN/cm³ total volume of 20 l production rate *p* beam power of 30 kW × 30000/78 neutron reflector $\times 2$ storage time of 100 s × 100/14 diffusion effect × 2.5 (expected) He-II bottle of beryllium × 2.5 (increase in Fermi potential) **D**₂ cold moderator × 8 (expected)

Possible apparatus for the "neutrons in the bottle" experiment



Possible Future UCN Sources (M. Snow, from NNbar Workshop 2002)

- source/moderator/density/mode/fill rate/timing
- type (UCN/cc) (UCN/s)
- PSI D2 1E+3 3s/600s 1E+7 >2006
- Munich D2 7E+4 CW <3E+7 >2006
- LANL D2 2E+2 1s/10s 2E+5 2003
- NSCU D2 2E+3 CW 1E+7 >2005
- KEK 4He 2E+5 CW 5E+7 >2008

Under development for other experiments (neutron EDM, neutron decay, neutron gravity tests,...)

NNbar search could be attractive possibility for UCN facility



May 5, 2006 SUNY Stony Brook workshop



Search for neutron \rightarrow antineutron transitions at DUSEL

N-Nbar proto-collaboration

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Scheme of N-Nbar search experiment at DUSEL

- Dedicated small-power TRIGA research reactor with cold neutron moderator $\rightarrow v_n \sim 1000$ m/s
- Vertical shaft ~1000 m deep with diameter ~ 6 m at DUSEL
- Large vacuum tube, focusing reflector, Earth magnetic field compensation system
- Detector (similar to ILL N-Nbar detector) at the bottom of the shaft (no new technologies)



Average velocity of cold neutrons ~ 1000 m/s (Maxwell)

For high sensitivity $N_n \cdot \langle t^2 \rangle$ most important are neutrons with small velocities in the Maxwellian spectrum

These are mostly affected by gravity

In horizontal layout it leads to the defocusing of the spectrum. and reduction of $N_n \cdot \langle t^2 \rangle$ Neutron source needed: small power 3.4 MW TRIGA reactor

TRIGA Reactor picture courtesy of General Atomics

Fig. 17. Dry central cavity in annular core

Annular core, TRIGA reactor for N-Nbar search experiment



Annular core TRIGA reactor 3.4 MW with convective cooling, vertical channel, and large cold moderator. Unperturbed thermal flux in the vertical channel 3E+13 n/cm²/s

Cold moderator has been placed in vertical arrangement before:

PNPI WWR-M reactor : 18 MW reactor, Vertical cold source in core 20K Liquid hydrogen moderator

Courtesy of W. Whittemore (General Atomics)

Vertical Cold Neutron Source (PNPI)

Delivered to new Australian research reactor, 18 MW power



Neutron Reflector Using MultilayersGraded multilayers operate on the principle of Bragg reflection
alternating layers of low and high index of refraction
 $n\lambda = 2d \sin \theta$ d = bilayer thickness

Wide range of bilayer thickness provides broadband reflectance

We need to make a large elliptical reflector. Neutrons only bounce once-> reflectivity not crucial



Magnetic Shielding for n-4He Parity-odd Neutron Spin Rotation Experiment. B~1nT using 3 passive shields

ILL experiment achieved sufficient shielding over 1m diameter, 100 m beam





Magnetic Shielding Panels (PNPI)



POLARIZED ³He for Neutron Polarimetry

Need to measure B over nnbar flight path. Use neutrons as magnetometers. Polarize neutron beam using 3He



Large neutron phase space acceptance Polarizer/analyzer pair can measure B using neutron spin rotation

NIST, Indiana, Hamilton, Wisconsin

NSF CAREER→DEFG0203ER46093

The conceptual scheme of antineutron detector



$$\overline{n} + A \rightarrow \langle 5 \rangle \ pions \quad (1.8 \text{ GeV})$$
Annihilation target: ~100µ thick Carbon film
$$\sigma_{\text{annihilation}} \sim 4 \text{ Kb} \qquad \sigma_{\text{nC capture}} \sim 4 \text{ mb}$$

What is required for NNbar experiment at DUSEL?

- × Vertical shaft > 0.5 km deep, with dia \ge 5 m to be instrumented
- Construction access from the top and the bottom of the shaft
- Location far from main underground labs
- \checkmark Reactor vs are background for geo-neutrino studies...
- Licensing, liability, decommissioning of the reactor ?
- Heat removal from 3.5 MW TRIGA reactor
- Cryogen equipment for cold moderator
- Many other things...

$n \rightarrow \overline{n}$ Search Sensitivity

Soudan II limit \approx Grenoble limit = 1 unit (1 u) of sensitivity

Method	Present limit	Possible future limit	Possible sensitivity increase factor
Intranuclear (in N-decay expts)	$7.2 \cdot 10^{31} \text{ yr} = 1 \text{u}$ Soudan II	7.5 $\cdot 10^{32}$ yr (Super-K) 4.8 $\cdot 10^{32}$ yr (SNO)	× 16 <mark>u (*)</mark>
Geo-chemical (ORNL)	none	$4 \cdot 10^8 \div 1 \cdot 10^9 s$ (Tc in Sn ore)	× 20÷100 u (*)
UCN trap (6×10 ⁷ ucn/sec)	none	$\sim 1 \cdot 10^9 \mathrm{s}$	× 100 <mark>u (**)</mark>
Cold horizontal beam	$8.6 \cdot 10^7 \text{ s} = \frac{1 \text{u}}{\text{@ILL/Grenoble}}$	$> 3.10^9$ s (e.g. HFIR@ORNL)	× 1,000 u
Cold Vertcal beam	none	> 3.10 ⁹ s (TRIGA 3.4 MW)	× 1,000 <mark>u (***)</mark>

New physics beyond the SM can be discovered by NNbar Oscillation Search

Expected improvement in N-Nbar oscillation time can be ~ factor of 100-1,000

If discovered:

B violation, strong hint for direction of new physics beyond SM

may help to provide understanding of matter-antimatter asymmetry

If NOT discovered:

in combination with new nucleon decay experiments, will set a new limit on the stability of matter

Conclusions

B, L are probably not conserved, B-L violation seems needed to explain matter/antimatter asymmetry in universe

Proton decay and n-nbar oscillations are complementary ways to search for B violation. Many theories predict one or the other but not both

Can no longer get much improvement on n-nbar "for free" from proton decay detectors, need measurement on free neutron

Improved free neutron searches for n-nbar oscillation time of 2-3 orders of magnitude are possible

Discovery would be very important, no discovery still helps set new limit on stability of matter

B-L Workshop: Sept. 20-22, 2007, LBL/Berkeley

Polarized ³He as Neutron Spin Filter

• strongly spin-dependent neutron absorption cross section.



$$P_n = \frac{T^+ - T^-}{T^+ + T^-} = \tanh[\sigma(\lambda)N_{He}LP_{He}]$$

$$T_n = T_E \exp(-\sigma N_{He}L)\cosh(\sigma N_{He}LP_{He})$$

n→nbar in nuclei

Neutrons inside nuclei are "free" for the time : $\Delta t \sim \frac{1}{E_{binding}} \sim \frac{1}{10 MeV} \sim 10^{-22} s$ each oscillating with probability $= \left(\frac{\alpha t}{\tau_{n\bar{n}}}\right)^2$ and "experiencing free condition" $N = \frac{1}{\Lambda t}$ times per second. Transition probability per second: $P_A = \left(\frac{\alpha t}{\tau_{n\bar{n}}}\right)^2 \times \left(\frac{1}{\Delta t}\right)$ Intranuclear transition (exponential) lifetime: $\tau_{A} = \frac{\tau_{n\bar{n}}^{2}}{\Delta t} = R \times \tau_{n\bar{n}}^{2}$ where R ~ $\frac{1}{\Lambda t}$ ~ $10^{22} s^{-1}$ is "nuclear suppression factor"

Actual nuclear theory calculations for ${}^{16}O, {}^{2}D, {}^{56}Fe, {}^{40}Ar$ by C. Dover et al, W.Alberico et al, B.Kopeliovich et al. are consistent and give an order of maginitude higher suppression factors with uncertainty of $\times 2$

Thus, e.g. Soudan - 2 limit $\tau_{Fe} > 7.2 \times 10^{31} yr$ corresponds to $\tau_{n\bar{n}} > 1.3 \times 10^8 s$

Soudan - 2 limit:
$$\tau_{Fe} > 7.2 \times 10^{31}$$
 years
 $S/B = 4/4.5$

Future potential limits expected from SNO and Super-K

SNO:
$$\tau_D \sim 4.8 \times 10^{32}$$
 years
Super - K: $\tau_O \sim 7.5 \times 10^{32}$ years

Since sensitivity of SNO, Super-K, and future large underground detectors will be limited by atmospheric neutrino background (as demonstrated by Soudan-2 experiment), it will be possible to set a new limit, but difficult to make a discovery!

Why Focusing Reflector?

In a simple geometry without focusing with neutron velocity v_n , flux F, detector of area A, and distance source-detector L:

$$N_n \propto F \cdot d\Omega = F \cdot \frac{A}{L^2}; \quad < t^2 > \approx \frac{L^2}{v_n^2}; \quad \text{and} \quad F \propto v_n$$

Sensitivity = $N \cdot < t^2 > \propto F \cdot \frac{A}{v_n^2} \propto \sqrt{T_n} \cdot \frac{A}{T_n} = \frac{A}{\sqrt{T_n}} \quad \leftarrow \text{does not depend on L}$

With focusing reflector: fraction of neutron flux within the fixed solid angle is intercepted by single reflection and directed to the detector.

 $d\Omega = const;$ reflector interception efficiency $\propto \frac{1}{T_n}$ Sensitivity $\propto \frac{d\Omega \cdot L^2}{T^{3/2}}$ \leftarrow major source of sensitivity improvement

Observable N- \overline{N} Oscillation in High Scale Seesaw Models

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We discuss a realistic high scale $(v_{B-L} \sim 10^{12} \text{ GeV})$ supersymmetric seesaw model based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$ where neutron-antineutron oscillation can be in the observable range. This is contrary to the naive dimensional arguments which say that $\tau_{N-\bar{N}} \propto v_{B-L}^5$ and should therefore be unobservable for seesaw scale $v_{B-L} \ge 10^5$ GeV. Two reasons for this enhancement are (i) accidental symmetries which keep some of the diquark Higgs masses at the weak scale and (ii) a new supersymmetric contribution from a lower dimensional operator. The net result is that $\tau_{N-\bar{N}} \propto v_{B-L}^2 v_{wk}^3$ rather than v_{B-L}^5 . The model also can explain the origin of matter via the leptogenesis mechanism and predicts light diquark states which can be produced at LHC.

In the Supersymmetric Pati-Salam type model violation of local (B–L) symmetry with Δ L=2 gives masses to heavy right-handed neutrinos generating regular neutrino masses via seesaw mechanism. Same mechanism with Δ B=2 determines the operator for N-Nbar transition. This operator was shown to have very weak power dependence on the seesaw scale, i.e. $1/M^2_{seesaw}$ rather than $1/M^5_{seesaw}$ as in naive dimensional arguments. That makes N-Nbar observable within the reach of present experimental techniques. The model also predicts light diquark states that can be produced at LHC.



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Observable neutron-antineutron oscillations in seesaw models of neutrino mass

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Abstract

We show that in a large class of supersymmetric models with spontaneously broken B-L symmetry, neutron-antineutron oscillations occur at an observable level even though the scale of B-L breaking is very high, $v_{B-L} \sim 2 \times 10^{16}$ GeV, as suggested by gauge coupling unification and neutrino masses. We illustrate this phenomenon in the context of a recently proposed class of seesaw models that solves the strong CP problem and the SUSY phase problem using parity symmetry. We obtain an *upper* limit on $N-\overline{N}$ oscillation time in these models, $\tau_{N-\overline{N}} \leq 10^9 - 10^{10}$ s. This suggests that a modest improvement in the current limit on $\tau_{N-\overline{N}}$ of 0.86×10^8 s will either lead to the discovery of $N-\overline{N}$ oscillations, or will considerably restrict the allowed parameter space of an interesting class of neutrino mass models. © 2001 Published by Elsevier Science B.V.

For wide class of L-R and super-symmetric models predicted n-nbar upper limit is within a reach of new n-nbar search experiments! If not seen, n-nbar should restrict a wide class of SUSY models. UMD-PP-06-004 OSU-HEP-06-02

Post-Sphaleron Baryogenesis

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Abstract

We present a new mechanism for generating the baryon asymmetry of the universe directly in the decay of a singlet scalar field S_r with a weak scale mass and a high dimensional baryon number violating coupling. Unlike most currently popular models, this mechanism, which becomes effective after the electroweak phase transition, does not rely on the sphalerons for inducing a nonzero baryon number. CP asymmetry in S_r decay arises through loop diagrams involving the exchange of W^{\pm} gauge bosons, and is suppressed by light quark masses, leading naturally to a value of $\eta_B \sim 10^{-10}$. We show that the simplest realization of this mechanism, which uses a six quark $\Delta B = 2$ operator, predicts colored scalars accessible to the LHC, and neutron–antineutron oscillation within reach of the next generation experiments.

New baryogenesis models with mechanisms that are experimentally testable

Baryon asymmetry of universe is generated at the temperatures below E-W transitions via new color scalars with masses 0.1-1 TeV that might be observable at LHC and lead to the neutron-antineutron oscillations within reach of the next generation experiments. New baryogenesis models with mechanisms that are experimentally testable

Baryogenesis by R-parity violating top quark decays and neutron-antineutron oscillations 31 May 2006 A.D. Dolgov^{a,b,c}, F.R. Urban^{a,b,d} ^a INFN, via Saragat 1, 44100, Ferrara, Italy ^b University of Ferrara. Department of Physics. via Saraaat 1. arXiv:hep-ph/0605263 v2 44100, Ferrara, Italy ^c ITEP, Bol. Cheremushkinskaya 25, 117218. Moscow, Russia ^d School of Physics and Astronomy, CAPT. University on Nottingham. University Park. Nottingham NG7 2RD, United Kingdom

Abstract

Generation of the cosmological baryon asymmetry in SUSY based model with broken R-parity and low scale gravity is considered. The model allows for a long-life time or even stable proton and observable neutron-antineutron oscillations.

Generation of the cosmological baryon asymmetry in SUSY based model with broken R-parity and low scale gravity is considered. The model allows for a long-life time or even stable proton and observable neutron-antineutron oscillations.

Low quantum gravity scale models



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Proton decay is strongly suppressed in this model, but n-nbar should occur since n_R has no gauge charges

Non-conservation of global charges in the Brane Universe and baryogenesis

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Fig. 1. Creation of baby branes.

Fig. 2. Flux tube holding the baby brane with a local charge.

Low quantum gravity scale models

In this model where global charges are violated by Black Holes the rates for proton-decay, neutronantineutron oscillations, and lepton-violating rare decays are suppressed to below experimental bounds even for large extra dimensions with TeV-scale gravity. Neutron-antineutron oscillations and anomalous decays of muons, τ -leptons, and K and B-mesons open a promising possibility to observe TeV gravity effects with a minor increase of existing experimental accuracy.

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A Black Hole Conjecture and Rare Decays in Theories with Low Scale Gravity

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Abstract

In models with large extra dimensions, where the fundamental gravity scale can be in the electroweak range, gravitational effects in particle physics may be noticeable even at relatively low energies. In this paper, we perform simple estimates of the decays of elementary particles with a black hole intermediate state. Since black holes are believed to violate global symmetries, particle decays can violate lepton and baryon numbers. Whereas previous literature has claimed incompatibility between these rates (e.g. p-decay) and existing experimental bounds, we find suppressed baryon and leptonviolating rates due to a new conjecture about the nature of the virtual black holes. We assume here that black holes lighter than the (effective) Planck mass must have zero electric and color charge and zero angular momentum – this statement is true in classical general relativity and we make the conjecture that it holds in quantum gravity as well. If true, the rates for proton-decay, neutron-antineutron oscillations, and lepton-violating rare decays are suppressed to below experimental bounds even for large extra dimensions with TeV-scale gravity. Neutron-antineutron oscillations and anomalous decays of muons, τ -leptons, and K and B-mesons open a promising possibility to observe TeV gravity effects with a minor increase of existing experimental accuracy.



Figure 5: $(n - \bar{n})$ -oscillation with supersymmetric particles. In this case the observation of the phenomenon may be accessible to future experiments.

n-*n* Oscillations in Models with Large Extra Dimensions

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We analyze $n-\bar{n}$ oscillations in generic models with large extra dimensions in which standard-model fields propagate and fermion wave functions have strong localization. We find that in these models $n-\bar{n}$ oscillations might occur at levels not too far below the current limit.

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Quarks and leptons belong to different branes separated by an extra-dimension; proton decay is strongly suppressed, n-nbar is NOT since quarks and anti-quarks belong to the same brane.

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Gravitational Baryogenesis

Hooman Davoudiasl, Ryuichiro Kitano, Graham D. Kribs, Hitoshi Murayama,^{*} and Paul J. Steinhardt[†] School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA (Received 4 May 2004; published 10 November 2004)

We show that a gravitational interaction between the derivative of the Ricci scalar curvature and the baryon-number current dynamically breaks *CPT* in an expanding Universe and, combined with baryon-number-violating interactions, can drive the Universe towards an equilibrium baryon asymmetry that is observationally acceptable.

Effective D = 7 operators can generate n-nbar transitions in such model.

Sakharov conditions for Matter/Antimatter Asymmetry

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Baryon number (=quark #) violation

– Not allowed at tree level, but permitted in higher-order processes in Standard Model (SM)

Departure from thermal equilibrium

- Expansion of Universe
- Phase transitions

Time reversal symmetry violation

 SM T violation is orders of magnitude too small to explain observed asymmetry – we need new physics.

Neutron "Optical" Potential

Fermi pseudopotential

$$V(\mathbf{r}) = \frac{2\pi\hbar^2}{m_{\rm n}} b\delta(\mathbf{r} - \mathbf{r}_0) \qquad b = b_{\rm coh} + \mathrm{i}b_{\rm abs}$$



$$\Rightarrow \text{Potential of wall} \qquad \qquad V(r) = \frac{2\pi\hbar^2}{m_n} \sum_j b_j \delta(r - r_j) = u_0 \theta(x) \quad (\lambda > d) \qquad \qquad 10^{-7} \text{eV}$$

Index of refraction

$$n \approx 1 - \frac{\lambda^2 b\rho}{2\pi}$$



 \Rightarrow Neutron guide

Storage of ultra cold neutrons in bottles

Possible UCN N-N Bar Experiment @PULSTAR/NC State



The geometry:



SD₂nominally 4 cm thick

Preliminary results for base case (det eff = 1):

• A possible base case: NCState geometry, 4 cm thick SD2, 18 cm guides, .050s SD2 lifetime, a UCN energy cutoff of 430 neV initally

Primary flux: 6.0×10^7 (below 305 neV) Box loading efficiency: 20 - 32%Best case: diffuse walls, specular floor 3.5×10^{9} discovery pot. 325 s avg. residency

• Straightforward gains:

Source thickness x2 (see Serebrov's geom): x 2 Source lifetime \rightarrow .075s +10% Running time: 4 years ("real")

• Speculative gains:

Multiphonon: x1.5(?) Coherent amplification: x2 (?) Solid Oxygen: x5 (?)

 $5.5 - 7 \times 10^9$

Various diffuse regions, wall potentials, same "best" case as above

Soudan - 2 limit:
$$\tau_{Fe} > 7.2 \times 10^{31}$$
 years
 $S/B = 4/4.5$

Future potential limits expected from SNO and Super-K

SNO:
$$\tau_D \sim 4.8 \times 10^{32}$$
 years
Super - K: $\tau_O \sim 7.5 \times 10^{32}$ years

Sensitivity of SNO, Super-K, and future large underground detectors will be limited by atmospheric neutrino background (as shown by Soudan-2 experiment)

it will be possible to slowly improve limits on n-nbar oscillations, but difficult to make a discovery!



Typical detector for "ILL type experiment"

Task is to reconstruct vertex, total energy (1.8 GeV), total momentum (0 GeV)



Three protons, two charged pions, and two neutral pions.

(continued)

2.6.2 Recommendation

The Program Advisory Committee finds this proposal of significant scientific merit, and endorses consideration as a long-range possibility for DUSEL. For the Early Implementation Program, the PAC recommends the engineering and feasibility studies needed to develop a full proposal and technical design in approximately 5 years. In particular, the PAC agrees with the proponents that serious infrastructure questions must be addressed: identifying a suitable vertical shaft (or costing the construction of a new one), engineering km-long magnetic shielding to the level of nanotesla, vacuum to 10⁻⁴ Pa, and numerous additional considerations related to locating a 3MW research reactor on the surface at Homestake. Issues like safety, licensing, security, and backgrounds to other experiments need to be considered.

Suppression of $n \rightarrow nbar$ in intranuclear transitions from n-nbar potential difference in nuclear matter

Neutrons in nuclei are "quasifree" for
$$\Delta t \sim \frac{1}{E_{binding}} \sim \frac{1}{10 \, MeV} \sim 10^{-22} \, s$$

and experience quasifree condition $N = \frac{1}{\Delta t}$ times per second,
transition rate is $P_A = \left(\frac{\alpha t}{\tau_{n\bar{n}}}\right)^2 \times \left(\frac{1}{\Delta t}\right)$

Intranuclear transition lifetime: $\tau_{A} = \frac{\tau_{n\bar{n}}^{2}}{\Delta t} = R \times \tau_{n\bar{n}}^{2}, \ R \sim \frac{1}{\Delta t} \sim 10^{22} s^{-1}$

Calculations for ${}^{16}O, {}^{2}D, {}^{56}Fe, {}^{40}Ar$ by Dover et al, Alberico et al, Kopeliovich et al. are consistent, give order of magnitude greater suppression

Proton Decay vs. Neutron- Antineutron oscillations as searches for B violation

Proton decay: $\Delta B=1$, $\Delta(B-L)=0$

n-nbar oscillations : $\Delta B=2$, $\Delta (B-L)=2$

1980's	2006	
GUT models conserving (B–L) were though to work for BAU explanation [Pati & Salam'73, Georgi & Glashow'74]	 "Proton decay is not a prediction of baryogenesis" [Yanagida'02] Δ(B−L)≠0 may be needed for BAU [Kuzmin, Rubakov, Shaposhnikov'85] 	
No indications for neutrino masses	$m_v \neq 0$ [S-K'98, SNO'02, KamLAND'03] and possible Majorana nature of neutrino	
Great Desert [Georgi & Glashow'74] from weak scale to GUT scale	No Desert. Possible unification with gravity at low energy scale [Arkani-Hamed, Dimopoulos, Dvali'98]	
(B-L) = 0 in SM, SU(5), SUSY SO(10)	(B − L) \neq 0 in ext. SUSY SO(10), L-R sym, QG	
Energy scale: 10^{15} – 10^{16} GeV	Effective energy scale: above TeV+seesaw	

Could $\Delta B=2$ Processes Generate Baryon Asymmetry?

Proton decay, with $\Delta(B-L)=0$, seems disfavored because sphalerons can transform B into L at EW scale and "erase" initial B asymmetry from higher energy scale

Popular model now is leptogenesis: violate L at high E scale and let sphalerons generate B. If true, how to test experimentally?

N-Nbar oscillations to generate B might not be erased by sphalerons

How to search for N-Nbar oscillations experimentally?

Detector of Heidelberg -ILL-Padova-Pavia Experiment @ILL 1991



No background! No candidates observed. Measured limit for a year of running:

$$\tau_{n\overline{n}} \ge 8.6 \times 10^7 \text{ sec}$$

= 1 unit of sensitivity



Fig. 1. (a) Experimental apparatus showing the "quasi free" neutron propagation length with the divergent guide, the target and the detection system. (b) Cross sectional view of the detector.

How to Measure Neutrona Oscillations? Method #1: are also sensitive to neutron oscillations.

- Direct measurement from free neutrons (neutron beams).
- Measurement by ILL-Grenoble bounds oscillation time at:

 $\tau_{nn} > 0.86 \text{ x } 10^8 \text{ sec}$

- New experiments using cold/ ultracold neutrons can improve this limit
- Measurement enhanced by large number of available neutrons; however, process is suppressed because of binding energy difference of neutron and antineutron







Some $\Delta(B-L) \neq 0$ nucleon decay modes (PDG'04)

(B−L)≠0 modes	Limit at 90% CL	S/B	Experiment'year
$p \rightarrow v v e^+$	>1.7×10 ³¹ yr	152/153.7	IMB'99
$p \rightarrow \nu \nu \mu^+$	$>2.1 \times 10^{31} \text{ yr}$	7/11.23	Fréjus'91
$n \rightarrow e^+ e^- v$	$>2.57 \times 10^{32} \text{ yr}$	5/7.5	IMB'99
$n \rightarrow \mu^+ \mu^- \nu$	>7.9×10 ³¹ yr	100/145	IMB'99
$n \rightarrow \nu \nu \overline{\nu}$	>1.9×10 ²⁹ yr	686.8/656	SNO'04
$n \rightarrow \overline{n}$	>7.2×10 ³¹ yr	4/4.5	Soudan-II'02
$nn \to \sqrt{\nu}$	$> 4.9 \times 10^{25} \text{ yr}$		Borexino'03

e.g. for $p \rightarrow vve^+$ with a lifetime >1.7×10³¹ yr Super-K should detect ~ 430 events/yr

- $n \rightarrow e^+ e^- v$ mode with highest limit
- $n \rightarrow \nu \nu \overline{\nu}$ $\Delta B = -1$ mode with lowest limit
- $nn \rightarrow v\overline{v}$ $\Delta B = -2$ mode with lowest limit
- $n \rightarrow \overline{n}$ mode with highest future potential