Nucleon instability and (B-L) non-conservation

Yu. Kamyshkov[a]

[a]Department of Physics, University of Tennessee, Knoxville, TN 37996-1200

Proton decay with the modes and rates predicted by the original SU(5) grand unification scheme conserving (B-L) is not observed experimentally. There are reasons to expect that (B-L) might not be conserved in nature. Among possible observable manifestations of (B-L) non-conservation are Majorana masses of neutrinos, neutrinoless double-beta decay, decay of protons to lepton + (X), and neutron to anti-neutron transitions. Feasible progress in experimental search for some (B-L) non-conserving processes is discussed here.

1. Introduction

Searches for nucleon instability [1] are motivated by two outstanding concepts of contemporary physics beyond the Standard Model of particle physics: the interpretation of baryon asymmetry of the universe (BAU) [2,3] and the idea of Unification of particles and their forces [4,5]. However, even within the scope of the Standard Model at the non-perturbative level [6] baryon number is not conserved (the latter non-conservation is so weak that it does not lead to directly observable nucleon decay effects).

So far, nucleon instability has not been experimentally observed [7]. Conservation of angular momentum in nucleon decay (nucleon spin 1/2) requires leptons (fermions) to appear in the final state. Two possibilities can be realized here: with $\Delta B = \Delta L$ or $\Delta B = -\Delta L$ (B and L are baryon and lepton numbers respectively). The first leads to the conservation of $(B-L)$ and the second to processes which violate $(B-L)$ conservation by two units. Stringent nucleon decay limits are experimentally established [8,7] for the nucleon decay modes where $(B-L)$ is conserved (e.g. $p \rightarrow e^+\pi^0$) ruling out the original SU(5) Unification model [5]. It is important to notice that in the original SU(5) model, as well as in the Standard Model, $(B-L)$ is strictly conserved. New generation of experiments with huge-mass detectors, such as those discussed at this Workshop, will continue to test the stability of nucleons with the respect to the $(B-L)$ conservation. That is particularly important in a view of the new theoretical predictions of the supersymmetric models [9]. In this paper we discuss the prospects for experimental searches for the processes which do not conserve $(B-L)$.

2. Is (B-L) conserved?

Naively we would expect that $(B-L)$ number is violated (the number of neutrons in our laboratory samples is in excess of equal number of protons and electrons). However, most of the leptons in the universe likely exist as, yet undetected, relic ν and $\overline{\nu}$ radiation. Thus, the conservation of $(B-L)$ on a scale of the whole universe is an open question.

Can $(B-L)$ be conserved in a way similar to the conservation of electrical charge? From tests of Equivalence Principle [10] one can exclude the existence of massless long-range gauge field of "$B-L$ photons" at a level of strength $\sim 10^{-12}$ of the gravitational strength. It is interesting to notice that "baryonic photons" responsible for conservation of baryon charge are excluded from the same tests only on the level $\sim 10^{-10}$ [11]. Unless $(B-L)$ is globally conserved in nature, it is very natural to expect that $(B-L)$ is violated.

In nucleon decay processes (with $\Delta B = -1$) the non-conservation of $(B-L)$ implies the existence of transitions of the type *nucleon* $\rightarrow$ *lepton* + ... (the conservation of $(B-L)$ corresponds to *nucleon* $\rightarrow$ *anti-lepton* + ... transitions). If $(B-L)$ is violated by two units, it is natural to assume (and it follows from Unification models [4,12]) that processes with $\Delta L = 2$ and

$\Delta B = 2$ are also the components of the physics of $(B-L)$ non-conservation. Examples of these are heavy Majorana neutrinos with $\Delta L = 2$ transitions $\nu_M \rightarrow \overline{\nu}_M$ and oscillations of neutrons to anti-neutrons $n \rightarrow \overline{n}$.

Since 1973, when $(B-L)$ non-conservation was first considered in theory [4], it was discussed within the framework of Unification models in a number of theoretical papers [12–16]. In Unification models, like SO(10) [9], massive Majorana neutrinos with $\Delta L = 2$ transitions violating $(B-L)$ by two units are used in a "see-saw" mechanism to generate the masses of conventional neutrinos. In the left-right symmetric Unification models the violation of $(B-L)$ arises at the same energy scale where the left-right symmetry is restored [4,13,12]. Probably the most compelling reason for the existence of $(B-L)$ non-conservation in nature follows from the fact [17] that electroweak non-perturbative mechanisms ("sphalerons") erase the baryon asymmetry of the universe if $(B-L)$ is globally conserved. Thus, the most natural explanation of BAU would require non-conservation of $(B-L)$ at an energy scale above the electro-weak scale. In this sense, experimental discovery of the nucleon decay into "standard" decay modes (like $p \rightarrow e^+ + \pi^0$ or $p \rightarrow \mu^+ + K^0$) with conservation of $(B-L)$ would leave BAU unexplained.

3. Nucleon Instability with $\Delta(B-L) = -2$

For some nucleon decay modes (see complete list of experimental limits in [7]) the experimental limits can be interpreted as limits for both $(B-L)$ conserving or $(B-L)$ violating processes. This is due to the presence of undetectable anti-neutrinos or neutrinos in the final states (for example, mode $N \rightarrow \nu + \pi$). In this sense only processes with $\Delta B = 2$ or $\Delta L = 2$ would unambiguously indicate in experiment the conservation or violation of $(B-L)$.

Let us discuss several $(B-L)$ violating processes where we believe significant progress can be made in the near future. These are: (a) the neutron to anti-neutron transition or the intranuclear disappearance of two nucleons; (b) proton decay $p \rightarrow e^+\nu\nu$; and (c) intranuclear neutron decay $n \rightarrow \nu\nu\overline{\nu}$. The latter two processes might be enhanced by a large phase space factor as compared to many other modes of nucleon decay (if all of them are originated by the same mechanism).

3.1. $n \rightarrow \overline{n}$ or $NN \rightarrow pions$

Transitions $n \rightarrow \overline{n}$ can be searched for with free neutrons from reactors or in the intranuclear disappearance of two nucleons (neutron to anti-neutron transition followed by two-nucleon annihilation into pions inside nuclei). Probability of coherent transition of free neutrons to anti-neutrons as function of observation time t is given by $(t/\tau_{n\bar{n}})^2$ [12], where $\tau_{n\bar{n}}$ is a characteristic oscillation time experimentally limited to $\tau_{n\bar{n}} \geq 8.6 \cdot 10^7$ sec [18]. The intranuclear $n \rightarrow \overline{n}$ transition is strongly suppressed by the difference of nuclear potential for neutrons and anti-neutrons (see most recent theoretical paper [19] and references therein). This suppression leads to the regular exponential probability of decay with the lifetime τ_A related to $\tau_{n\bar{n}}$ by $\tau_A = R \cdot \tau_{n\bar{n}}^2$, where R is a dimensional suppression factor predictable from nuclear theoretical models to an accuracy of $\sim \pm(20-25)\%$ [19].

Experimental limits for τ_A in intranuclear search of $n \rightarrow \overline{n}$ transitions were set by IMB, Kamiokande, and Fréjus experiments [7] at a level 2.4-6.5$\cdot 10^{31}$ years for oxygen and iron nuclei, corresponding to a limit on oscillation time $\tau_{n\bar{n}} \geq 1.2 \cdot 10^8$ sec [7]. The Super-Kamiokande detector is expected after several years of running to improve this limit to $\tau_A \geq 1-2 \cdot 10^{33}$ years [20] or $\tau_{n\bar{n}} \geq 5 \cdot 10^8$ sec.

Future prospects of $n \rightarrow \overline{n}$ transition search with free neutrons in reactor experiments are discussed elsewhere [21]. With existing research reactor facilities it is possible to extend the search limit for $n \rightarrow \overline{n}$beyond $\tau_{n\bar{n}} \geq\sim 3 \cdot 10^9$ sec and to explore the stability of matter (in this intranuclear nucleon instability mode with $\Delta B = -2$) beyond the limit of $\sim 7 \cdot 10^{34}$ years.

As was pointed out in [22], the existence of $n \rightarrow \bar{n}$ transitions would provide a unique opportunity to test the CPT-theorem with unprecedented accuracy by looking at the mass difference of neutron and anti-neutron. Such a mass difference (or small gravitational non-equivalence of neutron and anti-neutron, or small non-compensated magnetic field on the neutron flight path) can suppress the $n \rightarrow \bar{n}$ transition for free neutrons but is too small to produce a sizable additional effect in intranuclear transitions where very large nuclear suppression is already taking place. Therefore, searches in both directions with free neutrons and with the neutrons bound inside nuclei are desirable [22].

3.2. $p \rightarrow e^{+}\nu\nu$

The present experimental lifetime limit $\tau \geq 1.1 \cdot 10^{31}$ years for this process was set in Fréjus experiment. Difficulty with this decay mode is the fact that the observable final state (with existing experimental techniques a single positron with energy of few hundred MeV is indistinguishable from an electron) overlaps with the final state of atmospheric neutrino (ν_e and $\overline{\nu}_e$) interactions in the detectors. In a 1992 paper [23] an attempt was made to attribute the entire atmospheric neutrino anomaly to this mode of proton decay by interpreting the Sub-GeV data sample of Kamiokande detector (within neutrino flux normalization uncertainties) as an excess in the electron spectrum with a characteristic Michel-type energy shape rather than as a deficit in the muon spectrum.

New Super-Kamiokande results [24] provided a new evidence of the zenith angle dependence of muon events rendering the neutrino oscillation hypothesis a more viable explanation of the atmospheric neutrino anomaly. However, Super-K Collaboration has so far not ruled out the possibility of excess in the Sub-GeV electron-type spectrum. In Super-K analysis of atmospheric neutrino events the normalization factor of electron-type neutrino flux is used as a free parameter (within flux prediction uncertainties) to reduce the uncertainties of the absolute muon flux. This procedure will be certainly absolutely correct if it is known a priori that electron-type events are pure atmospheric neutrino interactions without possible admixture of any other effects. One can hope that new analysis and increased statistics in Super-K experiment as well as new more precise calculations and measurements of the absolute atmospheric neutrino fluxes will permit isolation of the possible contribution of proton decay in the electron-type Sub-GeV data or set a new higher lifetime limit for the process $p \rightarrow e^{+}\nu\nu$.

3.3. $n \rightarrow \nu\nu\overline{\nu}$

Surprisingly this elusive decay mode was experimentally explored by two different methods. First method, used in IMB and Fréjus experiment [25] treated the Earth as a source of neutrinos and the detector selection criteria were optimized for an energy range typical for neutrinos emitted from the decay process. The IMB limit for muon neutrinos was $\tau \geq 5 \cdot 10^{26}$ years; Fréjus limits for electron and muon type of neutrinos were $3 \cdot 10^{25}$ and $1.2 \cdot 10^{26}$ years respectively.

The second method used by Kamiokande II Collaboration [26] was based on the detection of nuclear de-excitation produced by the hole left by the neutron decay in the $S_{1/2}$ nuclear state of ^{16}O. De-excitations of $S_{1/2}$ hole would typically occur via the emission of proton or neutron; and with small probability $Br \simeq (2.7-10.4)\cdot 10^{-5}$ (estimated theoretically in [26]) it can proceed via the emission of an energetic photon with the energy above 19 MeV. (The entire solar neutrino spectrum is below 19 MeV threshold). The lifetime limit obtained by Kamiokande Collaboration from the observation of two background events was $\tau \geq 4.9 \cdot 10^{26}$ years and independent on the type of neutrino produced in the decay. More recent theoretical re-evaluation of the probability of de-excitation of $S_{1/2}$ hole with emission of energetic photon [27] suggested for the same data an improved lifetime limit of $\tau \geq 2.3 \cdot 10^{27}$ years.

The two methods mentioned above can be hopefully used in Super-Kamiokande detector to search for $n \rightarrow \nu\nu\overline{\nu}$ decay. In the presence of background the search limits here can be extended by factor of square root of detector mass ratio, i.e. approximately by an order of magnitude from the present limit and reach $\sim 10^{28}$ years.

A more sensitive approach in exploration of this decay mode channel should be possible with the new low-threshold large scintillating detector, KamLAND. Although the total fiducial mass of KamLAND will be $\sim$ 1 Kton, it should detect with full efficiency the de-excitation of nuclear state holes left by the disappearing neutron. Consider as an example the following process. In liquid scintillator ($\sim CH_2$) 1/3 of all neutrons are in $S_{1/2}$ state of carbon nuclei. Hole in this state will de-excite mostly by proton emission (since ^{11}C is a proton-rich nucleus), but with a branching of several percent [28] neutron emission is also possible, leaving an excited $^{10}C^*$ state. Detection of such event in KamLAND detector will start with detection of γ from de-excitation of $^{10}C^*$ (detection threshold is $\sim$ 0.2 MeV) followed be the detection of neutron (by capture on hydrogen in the liquid scintillator: capture lifetime is $\sim$ 180 μsec with a detected signal of 2.2 MeV). Following this pair of events after $\sim$ 19.2 sec $^{10}C_{gs}$ will β^+-decay with maximum energy release of 3.65 MeV. All three events in the sequence must be reconstructed to the same point in the detector within reconstruction inaccuracies. Preliminary estimates show that random background for triple-coincidence events will be negligible and it will be possible to explore the intranuclear neutron stability for 3ν final state up to a lifetime limit of $\sim 3 \cdot 10^{30}$ years. Possible sources of background events with similar signature arising from the atmospheric neutrino interactions with carbon nuclei must be carefully accounted for through nuclear model calculations.

The experimental method of detection of nuclear final states created as a result of nucleon disappearance (into neutrinos or any other invisible or undetectable particles) is very important as a complement to the exclusive modes of nucleon decay search. Together they provide an experimental basis for establishing the decay-mode-independent limit for nucleon instability which is presently, according to PDG [7], is at the level of only $1.6 \cdot 10^{25}$ years.

4. Conclusions

The experimental search for $\Delta(B-L) \neq 0$ processes is at least as important as the search for conventional baryon number violating processes with $\Delta(B-L) = 0$. For several of $\Delta(B-L) \neq 0$ processes discussed above it is possible to improve the discovery potential by a significant factor. These improvements can be made with the existing or currently constructed detectors (Super-Kamiokande, KamLAND) and with existing reactor facilities (for the case of free neutron to antineutron transitions).

I would like to thank Professor W.M. Bugg for useful discussions.

REFERENCES

1. M. Goldhaber, "Search for Nucleon Instability (Origin and History)", *in Proceedings of International Workshop on Future Prospects of Baryon Instability Search in p-Decay and* $n \to \bar{n}$ *Oscillation Experiments*, Oak Ridge, 1996, p.1. and these Proceedings
2. A.D. Sakharov, *JETP Lett.* **5** (1967) 24
3. V.A. Kuzmin, *JETP Lett.* **12** (1970) 228; *ZhETF Pis. Red.* **12**, No. 6 (1970) 335
4. J. Pati and A. Salam, *Phys.Rev.* **D8** (1973) 1240; *Phys. Rev.* **D10** (1974) 275
5. H. Georgi and S. Glashow, *Phys. Rev. Lett.* **32** (1974) 438
6. G. 't Hooft, *Phys. Rev. Lett.* **37** (1976) 8-11
7. Particle Data Group, "Review of Particle Physics", *Eur. Phys. J.* **C3** (1998) 1-794
8. See contributions of L. Sulak and Y. Suzuki in these Proceedings
9. See contributions of K. Babu, H. Murayama, J. Pati, P. Ramond, and F. Wilczek in these Proceedings
10. E. v. Eötvös, D. Pekar, and E. Fekete, *Ann. d. Phys.* **68** (1922) 11; P. G. Roll, R. Krotkov, and R. H. Dicke, *Ann. Phys. (U.S.A)* **26** (1964) 442; V. G. Braginsky and V. I. Panov, *Sov. Phys. JETP* **34** (1971) 464
11. T.D. Lee, C.N. Yang, *Phys.Rev.* **98** (1955) 1501; J.C. Pati and A. Salam, *Phys.Rev.Lett.* **31** (1973) 661; A.D. Sakharov, "Baryon Asymmetry of the Universe", Reprint of the review paper presented at the A.A. Friedmann Centenary Conference, Leningrad, USSR, June 22-26, 1988, published in *Sov.Phys.Usp.* **34**, No.5 (1991) 417
12. R. Mohapatra and R. Marshak, *Phys. Lett.* **91B** (1980) 222; *Phys. Rev. Lett.* **44** (1980) 1316; *Phys. Lett.* **94B** (1980) 183
13. A. Davidson, *Phys.Rev.* **D20** (1979) 776

14. F. Wilczek and A. Zee, *Phys. Lett.* **88B** (1979) 311
15. L.N. Chang and N.P. Chang, *Phys. Lett.* **B92** (1980) 103
16. F. Buccella, G. Mangano, A. Masiero, L. Rosa, *Phys. Lett.* **B320** (1994) 313
17. V. Kuzmin, V. Rubakov, and M. Shaposhnikov, *Phys. Lett.* **155B** (1985) 36; V. Rubakov and M. Shaposhnikov, *Phys. Usp.* **39** (1996) 461
18. M. Baldo-Ceolin et al., *Z. Phys* **C63** (1994) 409
19. J. Hufner and B.Z. Kopeliovich, *Mod.Phys.Lett.* **A13** (1998) 2385
20. J. Stone, 1996, Private Communication
21. Yu.A. Kamyshkov, in the Proceedings of CIPANP 97, "Big Sky 1997, Intersections between particle and nuclear physics", pp 335-341; in the Proceedings of Workshop on Physics Beyond the Standard Model, "Tegernsee 1997, Beyond the desert", pp. 542-553
22. Yu. Abov, F. Djeparov, and L. Okun, *JETP Lett.* **39** (1984) 493; L. Okun, "Test of CPT", preprint ITEP-TH-55/96; hep-ph/9612247 (1996)
23. W.A. Mann, T. Kafka, and W. Leeson, *Phys. Lett.* **B291** (1992) 200; W.A. Mann, W. Leeson, and D. Wall, *in Proceedings of International Workshop on Future Prospects of Baryon Instability Search in p-Decay and* $n \rightarrow \bar{n}$ *Oscillation Experiments*, Oak Ridge, 1996, p.175)
24. Y. Fukuda et al., *Phys. Rev. Lett.* **81** (1998) 1562
25. J.Learned et al., *Phys. Rev. Lett.* **43** (1979) 907; C. Berger et al., *Phys. Lett.* **B269** (1991) 227
26. Y. Suzuki et al., *Phys. Lett.* **B311** (1993) 357
27. J.-F. Glicenstein, *Phys. Lett.* **B411** (1997) 326
28. D. Dean, ORNL, 1999, Private Communication