Search for Neutron to Anti-Neutron Transitions at HFIR/ORNL*

Yuri Kamyshkov¹

Department of Physics, University of Tennessee, Knoxville, TN 37996
and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831²

Abstract

The transition of neutron to anti-neutron might be the first observed signal of the baryon instability long-awaited in Grand Unification models and required for the explanation of baryon asymmetry in the universe. A newly-proposed experiment to search for neutron-antineutron transitions at High Flux Isotope Reactor at Oak Ridge National Laboratory can improve the discovery potential by factor of ∼ 1,000 relative to the existing limits. Further prospects of n → n̄ search are also discussed in this paper.

1 Introduction

There are no laws of nature which would forbid the transitions of neutrons to anti-neutrons except the conservation of "baryon charge (number)" [1]. Since 1954 the conservation of baryon charge has been scrutinized in a number of experimental searches [2] looking for the proton decay. So far, no positive signal of proton decay has been observed [3]. Nevertheless, the interest in such searches in the last few decades has increased. In the Standard Model at the non-perturbative level the baryon charge is not conserved [4], although the effects of this non-conservation are expected to be very small. The baryon asymmetry of the universe (BAU) [5] and the idea of unification of particle and forces [6,7] are the two global concepts beyond the Standard Model which motivate the new experimental searches for baryon instability.

1 email: kamyshkov@utk.edu
2 managed by Lockheed Martin Energy Research, Inc., under contract number DE-AC05-96OR22464 with the U.S. Department of Energy

Preprint submitted to Elsevier Preprint
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Neutron to antineutron transitions, first considered within the context of BAU [8] and then in unification models [9] may violate the baryon number by two units $\Delta B = 2$. This phenomenon may be an alternative to the proton decay (where $\Delta B = 1$) and preferred by nature. The recent review of the theoretical and experimental situation in the search for baryon instability can be found in Ref. [10].

Possible nonconservation of the baryon number is closely related to the non-conservation of lepton number. Thus, for example, in the proton decay, the conservation of angular momentum (spin of proton) requires that at least one lepton (or anti-lepton) should be present in the final state. This creates in general two possibilities corresponding to $\Delta B = \Delta L$ and $\Delta B = -\Delta L$; the first conserves $(B-L)$ and the second violates it by two units. In neutron-antineutron transition, since leptons are not involved ($L = 0$), the $(B-L)$ quantum number would be violated by two units.

The original $SU(5)$ unification model [7], where $(B-L)$ was conserved, favored the proton decay mode $p \rightarrow e^+ + \pi^0$ with predicted lifetime $\tau/Br < 4 \cdot 10^{31}$ years. This model has been ruled out by the experiments where $\tau/Br$ was measured to be $> 10^{33}$ years [3]. This situation raises a general question whether the $(B-L)$ is conserved and motivates further experimental searches for $(B-L)$ non-conserving processes. There are also several other reasons to believe that $(B-L)$ might be not conserved by nature.

In the Standard Model $(B-L)$ is strictly conserved (both at perturbative and at non-perturbative levels). The recent discovery of neutrino oscillations by Super-Kamiokande Collaboration [11] reveals a new physics beyond the Standard Model. The existing explanation of the smallness of neutrino masses through the "see-saw" mechanism implies the existence of heavy right-handed Majorana neutrinos violating both $L$ and $(B-L)$ by two units (see discussion in [12]). Also, it was shown [13] that in baryogenesis the non-perturbative Standard Model effects at the electroweak energy scale erase any baryon excess generated at the early moments of the universe ($T \gg 1$ TeV) through $(B-L)$ conserving processes. At the same time, generating baryon excess through electroweak effects alone does not seem to be adequate to account for the observed baryon asymmetry and the dark matter in the universe [14,15]. Thus, some processes with $\Delta(B-L) \neq 0$ are required to explain the baryogenesis [12]. Weak interactions unlike all other interactions (electromagnetic, strong, and gravitational) are not left-right symmetric. It is natural to believe that the restoration of left-right symmetry of the weak force should occur before the unification of all forces. In the left-right symmetric unification models [6,16] the left-right symmetry is broken at the intermediate energy scale simultaneously with violation of $(B-L)$ [17,9]. In such models the transitions $n \rightarrow \bar{n}$, as well as other $(B-L)$ non-conserving processes, might exist with the rates attainable by modern experiments [18].
The question of whether the \( (B - L) \) non-conserving physics exists can be answered only experimentally. \( n \to \bar{n} \) transition would be the most spectacular manifestation of \( (B-L) \) non-conservation since the detection signature of \( n \to \bar{n} \) transition is clear and unambiguous [19] and because the discovery potential can be experimentally improved with existing sources of neutrons by factor of \( \sim 1,000 \) relative to present limits [3]. Other \( (B - L) \) non-conserving processes might include: nucleon decay into modes \( N \to ll\bar{\ell} \) and \( N \to l + mesons \); heavy Majorana neutrino masses; neutrinoless double beta decay; neutrino flavor oscillations; intranuclear transitions of two nucleons into pions, etc. [10].

2 New \( n \to \bar{n} \) Search Experiment

Search for \( n \to \bar{n} \) with slow reactor neutrons in vacuum is known to be the most effective method for discovery potential improvement. Recent revision and reconfirmation of this situation can be found in [10,20].

In \( n \to \bar{n} \) the yield of antineutrons \( N_{\bar{n}} \) in the beam of free neutrons in vacuum (in the absence of external magnetic field) depends on the observation time \( t \) as \[ N_{\bar{n}} \propto N_n \cdot \left( \frac{t}{\tau_{n\bar{n}}} \right)^2, \] where \( N_n \) is the number of neutrons used in an experiment and \( \tau_{n\bar{n}} \) is the characteristic \( n \to \bar{n} \) transition time. It is assumed in this expression that neutrons and antineutrons have equal masses (as required by CPT theorem) and that the gravitational interaction with Earth is the same for neutrons and anti-neutrons. In this way the discovery potential of an \( n \to \bar{n} \) search is proportional to the number of neutrons used in experiment per second and to the square of the neutron free time-of-flight. High steady-flux reactors together with cold neutron moderators, would be, therefore, most appropriate for an \( n \to \bar{n} \) search.

The generic scheme of such an experiment is the following: neutrons emitted from the cold moderator are entering the vacuum volume (shielded against the Earth's magnetic field down to the level of a few nT) where the \( n \to \bar{n} \) transition occurs. Produced antineutrons propagate along the initial neutron path and are detected as a several-meson star with a total energy release of \( \sim 1.8 \) GeV resulting from the antineutron annihilation with a thin carbon-target film. The recent state-of-the-art experimental search for \( n \to \bar{n} \) with free neutrons was performed [19] at RHF (ILL, Grenoble). The experiment had a discovery potential of \( N_{n\bar{n}} t^2 \sim 1.5 \cdot 10^9 \) seconds and for one year of operation set a limit of \( \tau_{n\bar{n}} \geq 8.6 \cdot 10^7 \)s.

A new experiment to search for \( n \to \bar{n} \) transition at 100 MW HFIR reactor at Oak Ridge was proposed by a UT-ORNL group [21]. The proposed improvement in the discovery potential is based on the new technique of neutron focusing [22] by means of a large elliptically shaped reflector which intercepts
Fig. 1. Conceptual layout of a new n → n̄ search experiment with a large elliptical focusing reflector at HFIR reactor (not to scale).

the neutrons emitted from the cold source within a large solid angle and focuses them on the annihilation target situated at the large distance of 300-500 m from the source (see Figure 1).

In the absence of the effect of gravity the discovery potential of the new experimental scheme with focusing reflector would be proportional to the square of the free-neutron flying path and inversely proportional to the effective temperature of the neutron spectrum to the power 3/2. The effect of gravity and the properties of the reflection surface of the focusing mirror material are included in the neutron transport Monte-Carlo simulations which allow us to optimize the parameters of the focusing reflector in the practical layout of the experiment. For example, for a supercritical hydrogen cold source at HB-3 HFIR beam, a 100-m long elliptical focusing reflector with small half-axis of 1 m, and a total source-detector distance of 500 m, the discovery potential \( N_{n^2} \) is \( \sim 9 \cdot 10^{11} \) seconds. For two-three years of operation the discovery potential of a new HFIR-based experiment can be increased by a factor of \( \sim 1,000 \) relative to the best existing result [19] or can reach the limit \( \tau_{n^2} \geq 3 \cdot 10^9 \) s.

3 Further n → n̄ search prospects

As was pointed out in [23], the existence of n → n̄ transitions would provide a unique opportunity to test the CPT-theorem with unprecedented accuracy by looking at the mass difference of neutron and antineutron. Such mass difference (or small gravitational non-equivalence of neutron and antineutron, or small non-compensated magnetic field on the neutron flight path) will suppress the n → n̄ transition for free neutrons but will be too small to produce a sizable additional effect in intranuclear transitions where very large suppression is already taking place due to the difference of nuclear potentials for the
neutron and the antineutron. Therefore, both measurements are required [23]
with free neutrons and with the neutrons bound inside nuclei. Correspond-
ing experimental techniques and their potentials for $n \rightarrow \bar{n}$ search have been
compared in [10,20]. As was mentioned above, searches with free neutrons
from reactors have higher achievable discovery potential than other methods.
Thus, for example, the result $\tau_{n\bar{n}} \geq 3 \cdot 10^9$ s achievable in the proposed new
experiment at HFIR would correspond [10,20] to the nucleus life time for in-
tranuclear $n \rightarrow \bar{n}$ transition $\geq 5 \cdot 10^{34}$ years and would represent the highest
experimental limit on the baryon stability of matter not attainable by any
other experimental method.

Furthermore, there are more potential resources for further improvement of
the discovery potential in $n \rightarrow \bar{n}$ search. The large-area "supercold moderator"
[22] which could thermalize neutron spectrum to temperatures like 10K in
combination with vertical (underground) layout of the experiment can result
in the increase of the discovery potential by additional factor of 100. If a new
ANS-type [24] reactor would be built, it can bring still another factor of 5 to
the discovery potential by increasing the flux of thermal neutrons.

4 Conclusions

If $n \rightarrow \bar{n}$ transition would be found, it will establish a new phenomenon lead-
ing to a new physics at the energy scale of $\sim 10^5$ GeV, i.e., beyond the range
of colliders. The new symmetry principles determining the history of the uni-
verse during the first moments of creation might be revealed; the left-right
symmetry, broken in the Standard Model, may be restored. The discovery
of $n \rightarrow \bar{n}$ transition might provide a major steering impact to the unifica-
tion models and contribute to the understanding of baryon asymmetry in the
universe. If and when such phenomenon will be established, the subsequent
experiments with $n \rightarrow \bar{n}$ transition should allow, according to [23], a most pre-
cise test of CPT invariance and gravitational equivalence of baryonic matter
and antimatter.

I would like to thank W. M. Bugg, Yu. V. Efremenko, V. A. Kuzmin, R. N.
Mohapatra, and C. D. West for useful and stimulating discussions.

References

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.


[10] Proceedings of International Workshop on Future Prospects of Baryon Instability Search in p-Decay and $n \to \bar{n}$ Oscillation Experiments, Oak Ridge, 1996.


to the Oak Ridge National Laboratory to Search for the $n \rightarrow \bar{n}$ transition using a detector to be built at ORNL's High Flux Isotope Reactor, UTK-PHYS-96-L1, 1996.

