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NEUTRON→ANTINEUTRON TRANSITIONS AND (B–L) NON-CONSERVATION

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Experimental observation of nucleon instability is one of the missing key components required for the explanation of baryon asymmetry of the universe. Proton decays with the modes and rates predicted by the original (B–L)-conserving SU(5) Grand Unification scheme are not observed experimentally. There are reasons to believe that (B–L) might not be conserved in nature, thus leading to the nucleon decay into lepton + (X) and to phenomena such as Majorana masses of neutrinos, neutrinoless double-beta decays, and most spectacularly the transitions of neutron to antineutron. The energy scale where these processes may occur is far beyond the reach of contemporary colliders. This scale cannot be predicted by theory; therefore the existence of corresponding processes has to be explored experimentally. In this paper we discuss a motivation and a new experimental approach to searching for (B–L)-violating transition of neutron to antineutron. A new search of $n \to \overline{n}$ can be performed in a reactor-based experiment at HFIR/ORNL with a sensitivity ~1000 times higher than in the previous experiments.

1. INTRODUCTION

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

In spite of significant experimental attempts nucleon instability (other than regular neutron β-decay) so far has not been discovered [7] suggesting further experimental efforts with increased mass of the detectors [8] as

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well as the experiments in alternative directions [9]. One of such possible alternative experiments is a new sensitive search for neutron to antineutron transition [10] that might explore stability of matter at a lifetime scale an order of magnitude beyond the reach of contemporary nucleon decay experiments.

2. MOTIVATION

Let us discuss why alternative directions are important. In the nucleon decay the conservation of the angular momentum (nucleon spin 1/2) would require fermions to appear in the final state. Leptons: e, μ, three neutrinos and their antiparticles are the only known fermions the nucleon can decay into. Two possibilities can be realized here: $\Delta \mathrm{B} = \Delta \mathrm{L}$ or $\Delta \mathrm{B} = -\Delta \mathrm{L}$ (B and L are the total baryon and lepton numbers respectively). The first possibility would lead to the conservation of (B–L) and second to the processes that violate (B–L) by two units. The most stringent nucleon decay limits are experimentally established [7, 8, 11] for nucleon decay modes where (B–L) is conserved such as $p \to e^+ + \pi^0$, $p \to \overline{\nu} + K^+$, $p \to \mu^+ + K^0$, etc. Experimental non-observation of these decay modes has ruled out the original SU(5) [5] and one-step-breaking SO(10) [12] Unification models. It is important to notice that in the original SU(5) model, as well as in the Standard Model, (B–L) is strictly conserved at perturbative and non-perturbative levels. A new generation of experiments with huge-mass detectors [8] is needed to continue to test the stability of nucleons with respect to the (B–L) conservation. We believe that the search for the processes with (B–L) non-conservation will also need to be pursued by the future experiments.

Why might (B–L) not be conserved? Naively we would expect that (B–L) number be strongly violated: the number of neutrons in our laboratory samples is in excess of equal number of protons and electrons. However, most leptons in the universe likely exist as, yet undetected, relic ν and $\overline{\nu}$ radiation similar to cosmic microwave background radiation of photons. Thus, the conservation of (B–L) on a scale of the whole universe remains an open question.

We know that global and local conservation of electric charge is due to the existence of massless gauge vector field of photons [13]. Can (B–L) be conserved in a similar way? That would imply the existence of “special photons” coupled to “(B–L) charge”. From Equivalence Principle tests [14] one can exclude the existence of massless long-range gauge field of (B–L) photons at a level of interaction strength $< 10^{-12}$ of the gravitational strength [15]. It is interesting to notice that "baryonic photons' " that would be responsible for the conservation of baryon charge are excluded from the same tests only at the level of $\sim 10^{-10}$ [16]. From this point of view the conservation of (B–L) (similarly to the conservation of baryon number B [16]) looks very unnatural.

In nucleon decay (with nucleon disappearance $\Delta\mathrm{B} = -1$) non-conservation of (B–L) implies the existence of transitions of the type $N \rightarrow lepton + X$ with $\Delta(\mathrm{B–L}) = -2$. The conservation of (B–L) in nucleon decays would correspond to $N \rightarrow antilepton + X$ transitions. If (B–L) can be violated by two units, it is natural to assume, as also follows from the Unification models [17, 18], that processes with $|\Delta\mathrm{L}| = 2$ and $|\Delta\mathrm{B}| = 2$ as well as the processes with $\Delta\mathrm{B} = -\Delta\mathrm{L}$ are the components of the common physics coming from the same energy scale. Examples of the former processes would be heavy Majorana neutrinos with $|\Delta\mathrm{L}| = 2$ transitions of $\nu \leftrightarrow \overline{\nu}$ and the transitions of $n \leftrightarrow \overline{n}$ with $|\Delta\mathrm{B}| = 2$; examples of the latter could be processes $p \rightarrow \nu\nu e^{+}$, $n \rightarrow \nu\nu\overline{\nu}$, $p \rightarrow e^{-}\pi^{+}\pi^{+}$ and some others. In Unification models of SO(10) type, massive Majorana neutrinos with $|\Delta\mathrm{L}| = 2$ transitions violating (B–L) by two units can generate the masses of conventional neutrinos through the "see-saw" mechanism [18]. Thus, the explanation of the masses of neutrinos can be linked with (B–L) and B nonconservation.

Since 1973, when (B–L) non-conservation was first considered theoretically [4], it was discussed within the framework of Unification models in a number of theoretical papers [17, 19, 20, 12]. In the left-right symmetric SO(10) Unification models the violation of (B–L) arises at the same energy scale where the left-right symmetry is restored [4, 17, 19]. Thus, (B–L) non-conservation is related with the searches of the right-handed currents and $\mathrm{W_R}$ vector bosons. Present experimental lower limits for $\mathrm{W_R}$ mass [7] are in a TeV range. If $n \rightarrow \overline{n}$ transitions would be experimentally observed beyond the existing experimental limits, the energy scale of corresponding (B–L) violation and L-R restoration will be in the range of 10^5–10^6 GeV.

The latter follows from the dimensional reason: indeed, the disappearance of 3 quarks and appearance of 3 anti-quarks in $n \rightarrow \overline{n}$ can be described as a Feynman operator of dimension 9 (each of six fermions brings to Lagrangian the dimension of $m^{3/2}$), therefore $n \rightarrow \overline{n}$ transition amplitude is proportional to M^{-5}, where M is the energy scale of (B–L) violation. Similarly, (B–L) conserving proton decay of the type $p \rightarrow e^{+}\pi^{0}$

is described by the operator of dimension 6 and transition amplitude is proportional to M^{-2}, where M is the unification scale. If the unification energy scale of SU(5) $\sim 10^{15}$ GeV would make $p \to e^+\pi^0$ observable, the energy scale corresponding to $n \to \overline{n}$ observable transition should be in the range of 10^5–10^6 GeV.

Could one expect a new physics at such "low energy scale"? The concept of Great Desert introduced by SU(5) model [5] was very popular for more than two decades. According to this concept no new physics would occur between electro-weak scale (or supersymmetric energy scale in the modified concept) and Grand Unification scale of $\sim 10^{15}$–10^{16} GeV. Recently it has been realized [21] that unification of gravitational and gauge interactions might occur at much lower energy scale and in a way that preserves broken L–R gauge symmetry. Therefore, the energy scale of 10^5–10^6 GeV might be a natural scale for existence of transitions $n \to \overline{n}$.

Probably the most compelling reason for the existence of non-conservation in nature follows (B–L) non-conservation in nature follows from the theoretical observation [22] that electroweak non-perturbative "sphaleron" mechanism in the early universe would *erase* the observed BAU if (B–L) is globally conserved. Although theoretical efforts are eing made [23] to understand how BAU can be generated by (B–L)-conserving processes at the temperatures below the unification scale, it is more natural to assume that *(B–L) non-conservation* takes place at the energies above the electroweak scale. In this sense, experimental discovery of the nucleon decay into "standard" decay modes like $p \to \pi^0 + e^+$ or $p \to K^0 + \mu^+$ with conservation of (B–L) would leave BAU unexplained.

As was pointed out by Gell-Mann and Pais in 1955 [24], the only conservation law of nature that would forbid the $n \to \overline{n}$ transition is the conservation of *baryon number*. In 1970, $n \to \overline{n}$ transition was considered by Kuzmin as a possible explanation of BAU [3]. In the 1980s, it was suggested by Glashow in the context of SU(5) models [25] and independently by Marshak and Mohapatra [17] in the context of left-right symmetric models that $n \to \overline{n}$ transition could lead to theoretical schemes complementary or alternative to those exploiting the (B–L) conserving proton decay mechanism. In particular, Marshak and Mohapatra pointed out that there is an intimate connection between a nonvanishing Majorana mass for neutrinos and a possibility of the $\Delta(\text{B–L}) = -2$ in $n \to \overline{n}$ transition. The recent experimental indications for the existence of neutrino mass [26] therefore strengthen the case for a new dedicated search for $n \to \overline{n}$ oscillation at the reactors.

3. NEW $n \rightarrow \overline{n}$ SEARCH EXPERIMENT

Observation of $n \rightarrow \overline{n}$ transitions would be the most spectacular manifestation of the new physics, if such physics exists, indicating (B–L) non-conservation at the energy scale of 10^5–10^6 GeV. The experimental signature of appearance of antineutron in the thermal-energy neutron beam would be unambiguous and background free as was demonstrated by the previous state-of-the-art $n \rightarrow \overline{n}$ experimental search performed with free cold neutrons by the Heidelberg-ILL-Padova-Pavia Collaboration [27] at ILL/RHF reactor in Grenoble. Transition probability $n \rightarrow \overline{n}$ for free neutrons can be found [17] from the solution of time-dependent Schrödinger equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\overline{n}} \end{pmatrix}\psi,$$

where ψ describes a 2-component neutron-antineutron state and α is a transition amplitude of $n \rightarrow \overline{n}$ mixing determined by (B–L) non-conservation scale. Probability of neutron to antineutron transition in the absence of external fields different for neutrons and anti-neutrons can be found as $P_{n\overline{n}} = (t/\tau_{n\overline{n}})^2$ where $\tau_{n\overline{n}} = \hbar/\alpha$ is a characteristic transition time. Experimental limit on free-neutron transition time of $\tau_{n\overline{n}} \geq 8.6 \cdot 10^7$ seconds obtained in $n \rightarrow \overline{n}$ search experiment [27] corresponds to the limit of $\sim 6.5 \cdot 10^{31}$ years obtained in the searches of intranuclear $n \rightarrow \overline{n}$ transitions in nucleon-decay experiments [7, 28]. The correspondence of these two limits is explained by the nuclear dimensional suppression factor R in intranuclear transitions such that $\tau(intranuclear) = R \cdot \tau^2_{n\overline{n}}(free)$ with $R \sim 2 \cdot 10^{23}\,\mathrm{sec}^{-1}$ [28] where τ (*intranuclear*) is a regular exponential lifetime. The factor R is known theoretically with an accuracy of $\sim \pm(20$–$25)\%$ [28]. This correspondence clearly demonstrates the potential of the reactor-based search with free neutrons in vacuum.

Another reason that makes $n \rightarrow \overline{n}$ transition attractive for new experiments is that with the present technology (focusing neutron reflector and cold neutron moderator) and with existing sources of neutrons (e.g., HFIR reactor at ORNL with the world highest thermal flux of $\sim 1.5 \cdot 10^{15}\ \mathrm{n} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$) it is possible [10] to increase the sensitivity of $n \rightarrow \overline{n}$ search by factor of $\sim 1{,}000$ and thus explore the stability of matter at the level $\sim 10^{35}$ years in terms of intranuclear $n \rightarrow \overline{n}$ transitions. The Super-Kamiokande detector after ~10 years of running can potentially reach corresponding intranuclear $n \to \overline{n}$ transition limit of τ (*intranuclear*) $\sim 1 \cdot 10^{33}$ years [29]. Comparison of two methods of $n \to \overline{n}$ search in intranuclear transitions and in transition of free neutrons from the reactors is shown in Figure 1.

Discovery potential (*D.P.*) of the $n \to \overline{n}$ search experiment is defined as a product of a number of neutrons per second in the beam and the square of the neutron flight time to the annihilation target. Discovery potential in a new $n \to \overline{n}$ search experiment proposed for 100-MW HFIR reactor at Oak Ridge National Laboratory [30] can be improved by using neutron-focusing reflector of optimized shape coated with ^{58}Ni layer [10]. The conceptual layer of such an experiment is shown in Figure 1. Large focusing reflector intercepts slow neutrons emitted from the source in a large solid angle and concentrates them on the annihilation-detector target situated at an optimized distance of 200–500 m from the source.

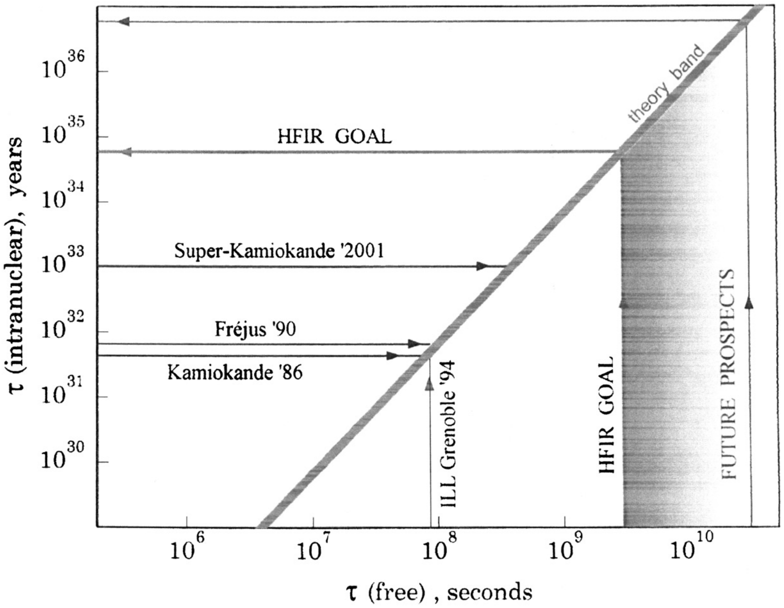

FIGURE 1. Two search methods for $n \to \overline{n}$ transitions. Horizontal scale: limits for characteristic transition time in experiments with free neutrons from the reactors. Vertical scale: limits for lifetime for intranuclear $n \to \overline{n}$ transition in nucleon decay experiments. Two methods are related by theoretical “nuclear suppression” dependence [28] as explained in the text.

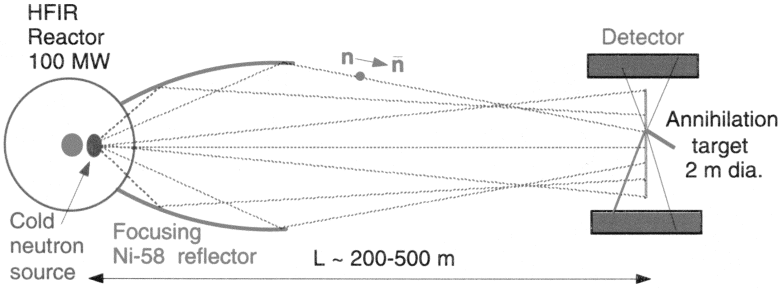

FIGURE 2. Conceptual layout of $n \to \overline{n}$ search experiment with focusing reflector (not to scale).

Figure 3 shows cross-section of the HFIR reactor at ORNL where $n \to \overline{n}$ search experiment can be implemented at HB-3 beam line equipped with a new cold neutron moderator.

One can show, neglecting the effect of gravity, that the probability of observation of antineutron in the experiment with optimized focusing reflector is proportional to $D.P. \sim L^2/T^{3/2}$, where L is the distance between the point of reflection and the annihilation detector and T is an effective temperature of the thermalized neutron spectrum. This should be compared with the discovery potential for the layout without the focusing reflector where $D.P. \sim 1/T^{1/2}$. Thus, with the advanced layout the large length of the experiment and the low temperature of neutrons would result in substantial increase of the discovery potential. More comprehensive Monte-Carlo simulations including gravity effect [10] show that discovery potential of HFIR-based experiment with cold supercritical hydrogen moderator [31] in HB-3 beam pipe (see Figure 3) can be factor of ~ 400 higher than in ILL/RHF-based experiment [27]. Thus, *one day* of operation at HFIR in the new proposed $n \to \overline{n}$ search [30] is equivalent to *one year* in the previous ILL/RHF-based experiment. Table 1 compares essential features of the new-proposed HFIR experiment [30] in HB-3 beam port with the previous ILL/RHF-based experiment [27].

The conceptual scheme of the antineutron annihilation detector (Figure 4) can be similar to that used in the previous Hidelberg-ILL-Padova-Pavia experiment [27] at ILL/RHF in Grenoble. Annihilation target is a thin carbon-film membrane with almost 100% efficiency for antineutron detection and low efficiency for (n,γ) conversion. Final states of nucleon-antinucleon annihilation are well understood mainly due to the LEAR

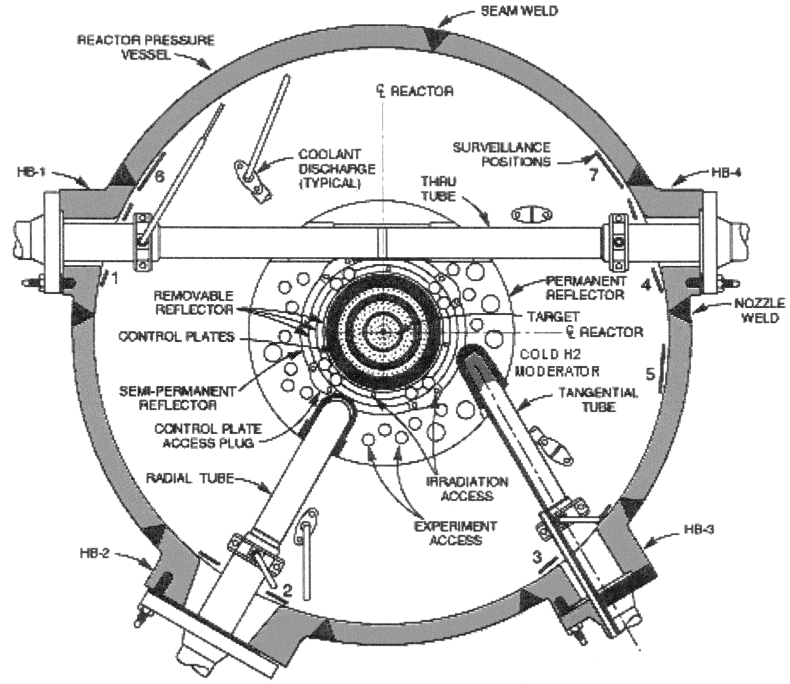

FIGURE 3. Section view of ORNL/HFIR reactor core. In the $n \rightarrow \overline{n}$ search experiment the cold supercritical hydrogen moderator should be installed in the HB-3 beam tube.

TABLE 1. Comparison of the major parameters of a new $n \rightarrow \overline{n}$ search experiment proposed for HB–3 beam line at High Flux Isotope Reactor at Oak Ridge National Laboratory with the previous $n \rightarrow \overline{n}$ search experiment performed in 1989–91 at RHF Reactor at ILL/Grenoble

Neutron source	*RHF/Grenoble*	*HFIR/ORNL*
Reference	[27]	[30]
Status of experiment	Completed	Proposed (HB–3 beam)
Reactor power, MW	58	(85) 100
Reactor's peak thermal n-flux	$1.4 \cdot 10^{15}$ (n/cm^2/s)	$1.5 \cdot 10^{15}$ (n/cm^2/s)
Moderator	Liquid D_2	Supercritical H_2
Source area	6×12 cm^2	~11 cm diameter
Target diameter	1.1 m	2.0 m
Flight path	76 m	300 m
Neutron fluence @ target	$1.25 \cdot 10^{11}$ n/s	$\sim 8.5 \cdot 10^{12}$ n/s
Average time of flight	0.109 s	0.27 s
Detector efficiency	0.48	~ 0.5
Operation time (s)	$2.4 \cdot 10^7$	$7 \cdot 10^7$ (~3 years)
Discovery potential per sec	$1.5 \cdot 10^9$ n $\cdot$ s^2	$6.2 \cdot 10^{11}$ n $\cdot$ s^2
$\tau_{n\overline{n}}$ limit (90% CL)	$8.6 \cdot 10^7$ s	$3.0 \cdot 10^9$ s

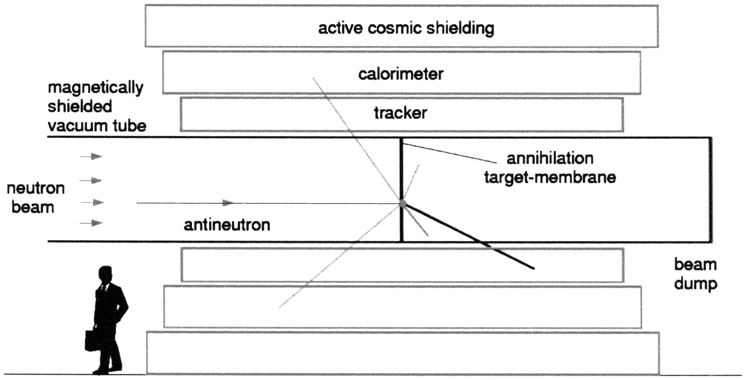

FIGURE 4. Conceptual view of the antineutron annihilation detector for $n \rightarrow \overline{n}$ search experiment.

studies and can be accurately modeled [32]. Average final state has five pions originating in the annihilation target. Tracking part of the detector should reconstruct the candidate event vertex and verify its position relative the annihilation target origin. A calorimeter is used for triggering and for the total energy deposit measurement (below ~1.8 GeV). Detector is surrounded by cosmic veto scintillator counter system to reduce trigger rate and to remove possible cosmic background.

Quality of the ^{58}Ni coating of the focusing reflector does not need to be as perfect as in the case of conventional neutron guide mirrors and supermirrors since neutrons undergo essentially only single reflection. Vacuum in the flight tube should be better than 10^{-4} Pa [27].

Earth magnetic field that would suppress the $n \rightarrow \overline{n}$ transition must be compensated down to a level of few nano-Tesla in the entire flight volume. Following the recommendation of [27] both active (compensating coils) and passive (permalloy) screens can be used to achieve required field compensation. An active magnetic field compensation system provides cross check by "switching off" the effect in the case if antineutron signature is observed.

It was pointed out in paper [33] that existence of $n \rightarrow \overline{n}$ transitions would provide a unique opportunity for testing CPT-theorem by looking at the mass difference Δm of neutron and antineutron. Such mass difference (or similarly a small gravitational non-equivalence of neutron and antineutron) will suppress the $n \rightarrow \overline{n}$ transition for free neutrons but will be too small to produce a sizable additional effect in intranuclear transitions where a very large suppression is already present due to significant difference of nuclear potentials for neutron and antineutron. Therefore, two measurements are required: one with free neutrons in the reactor experiment and the other with bound neutrons in intranucldear transitions [33]. The latter experiment can be replaced by a reactor-based measurement with a controllable variation of the magnetic field. Since the ultimate sensitivity to Δm of the reactor-based experiment is $\Delta m < \hbar/\Delta t$, with a neutron flight time $\Delta t \sim 0.3$ sec (for HFIR-based experiment), the smallest achievable value of $\Delta m/m$ can be few orders of magnitude lower than $m_{Nucleon}/m_{Plank}$.

4. CONCLUSION

Reactor search for $n \to \overline{n}$ transition is a very sensitive method of observation of (B–L) nonconserving processes. Proposed new experimental approach to search for $n \to \overline{n}$ transition at HFIR/ORNL reactor might result in an equivalent experimental limit of 10^{35} years for baryonic intranuclear stability. Such limit is not attainable by any other existing experimental method.

Physics at the energy scale of 10^5–10^6 GeV might be dominated by quantum gravity effects that could be manifested through $n \to \overline{n}$ transition. If $n \to \overline{n}$ transitions are observed, it will reveal a new phenomenon leading to a new physics at the energy scale beyond the range of colliders. New symmetry principles determining the history of the universe during the first moments of creation might be established; the left-right symmetry, broken in the Standard Model, may be found restored. The discovery of $n \to \overline{n}$ transition would provide a major constraint on unification models and contribute to the understanding of baryon asymmetry of the universe. If and when such phenomenon is established, the subsequent experiments with $n \to \overline{n}$ transition should allow a most precise test of CPT invariance and/or gravitational equivalence of baryonic matter and antimatter.

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