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Prospects of a baryon instability search in neutron-antineutron oscillations

Yu. Efremenko, Yu. Kamyshkov

Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831, USA

ABSTRACT

The purpose of this article is to review the current status and the future prospects for an experimental neutron-antineutron transition search. Traditional and new experimental techniques are discussed here. In the $n \rightarrow \bar{n}$ search in experiments at existing reactors, it would be possible to increase the discovery potential up to four orders of magnitude for vacuum $n \rightarrow \bar{n}$ transitions relative to the existing experimental level or to achieve the limit of $\tau_{n\text{-}nbar} \sim 10^{10}$s. With dedicated future reactors and an ultimate experimental layout, it might be possible to reach the limit of 10^{11}s. Significant progress in an intranuclear $n \rightarrow \bar{n}$ transition search expected to be made during the next decade by the SuperKamiokande and Icarus detectors. It can be matched, or even exceeded, in a new alternative approach, where unstable long-lived isotopes of technetium are searched in non radioactive deep-mined ores.

I. INTRODUCTION

The transition of neutral matter into antimatter is known to occur in the K^0 and B^0 meson oscillations. It results from nonconservation of, respectively, strange and beauty quantum numbers by weak interactions. The only law which would forbid the $n \rightarrow \bar{n}$ transitions is the conservation of the baryon number [1]. There are two reasons to question the inevitability of this law.

The first reason refers to "baryon asymmetry" of the Universe [2]. The inflationary model and nonobservation of antimatter in the Universe imply that the baryon number was not conserved at the early stages of creation of the Universe. Neutron-antineutron oscillation as a possible mechanism of explanation of baryon asymmetry of the Universe was first proposed and discussed in [3].

The second reason is related to the contemporary theoretical unification models where baryon instability appears as two complementary or alternative processes: the baryon decay with $\Delta B = 1$ and/or the baryon-antibaryon oscillation with $\Delta B = 2$. In the context of unification models, $n \rightarrow \bar{n}$ oscillations were first considered in [4-6]. The most recent theoretical discussion of neutron-antineutron oscillations in the framework of unification and supersymmetric models can be found in [7].

The amplitude of an $n \rightarrow \bar{n}$ transition (as a six-fermion operator) for dimensional reasons should be proportional to the m^{-5}, where m is a characteristic mass scale of the mechanism responsible for the $n \rightarrow \bar{n}$ transition. The observable rate of an $n \rightarrow \bar{n}$ transition should then correspond to the mass scale $m \sim 10^5$-10^6 GeV [8]. Therefore, the search for an $n \rightarrow \bar{n}$ oscillation explores new physics at an energy scale beyond that of the modern existing or future planned accelerators [9].

An interesting alternative mechanism of $n \rightarrow \bar{n}$ transitions has been discussed recently by V. Kuzmin [10]. He assumed that interaction of quarks inside baryons consisting of quarks of the different generations (*bus*, for example) might be mediated by the color-triplet scalar field coupled to the right components of the quarks. For neutral baryons (of *bus* type) this scalar field will result in baryon-antibaryon oscillations with a characteristic time $\sim 10^{-12}$s. Neutron-antineutron oscillations then would arise from this interaction, being additionally suppressed by ~20 orders of magnitude by CKM matrix quark-mixing probabilities, with a characteristic time of an $n \rightarrow \bar{n}$ transition of $\tau \sim 10^8$ s.

There are two complementary experimental methods for an $n \rightarrow \bar{n}$ search: (a) utilizing free neutrons from reactors or neutron spallation sources and (b) with neutrons bound inside the nuclei. In this paper we discuss the present status, future prospects, and relative merits of these two methods.

II. FREE NEUTRONS

The yield of antineutrons N_{nbar} in a beam of free neutrons in a vacuum (in the absence of external fields and neutron scattering) due to $n \rightarrow \bar{n}$ transitions depends on the observation time t as $N_{nbar} \sim N_n \cdot (t/\tau_{n\text{-}nbar})^2$, where N_n is the number of neutrons used in an experiment and $\tau_{n\text{-}nbar}$ is the characteristic $n \rightarrow \bar{n}$ transition time [5]. 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 antineutrons. In this way, the discovery potential of an $n \rightarrow \bar{n}$ search experiment is proportional to the number of neutrons used in the experiment and to the square of the neutron time-of-flight. The most appropriate for an $n \rightarrow \bar{n}$ search would be research reactors or accelerator-based neutron spallation sources with high average neutron fluxes [11], equipped with cold neutron moderators. The general scheme of such an experiment includes; the neutron source (cold moderator), the flight path where neutrons are propagating, and antineutron detector. The flight path is a big vacuum volume, shielded against the earth's magnetic field down to the level of few nanotesla, where an $n \rightarrow \bar{n}$ transition can occur The detection of antineutrons is based on observation of a few-meson star with total energy release of about 1.8 GeV

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resulting from annihilation in the thin target, placed at the end of the flight path.

The recent most advanced experimental search for $n \to \bar{n}$ with free neutrons was performed [12] at the 58 MW research reactor at the Institute Laue-Langevin (ILL) in Grenoble. The experiment had a discovery potential of D.P. = $N_n \cdot t^2 \sim 1.5 \cdot 10^9$ seconds. After one year of operation, the collaboration achieved a limit of $\tau_{n\text{-}nbar} \geq 8.6 \cdot 10^7$s.

A new approach proposed by an ORNL-UT group [13-15] for the reactor or the spallation source experiments is based on the properties of neutrons to be focused by means of reflection from the surfaces of certain materials. In this approach an elliptical shape reflector intercepts the neutrons emitted from the source within large solid angle and focuses them on the annihilation target. Possible layout of such an experiment is illustrated schematically in Figure 1.

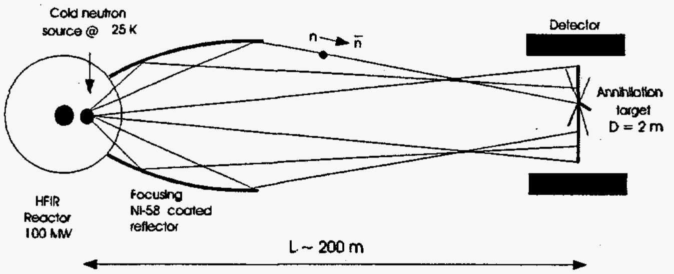

Fig. 1 Conceptual layout of the $n \to \bar{n}$ search experiment proposed for the HFIR (Oak Ridge High Flux Isotope Reactor), shown not in scale.

This approach has been developed within the proposal of a new experiment at the 100 MW High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. The gain in discovery potential (relative to the ILL/Grenoble experiment) in such new experiment can result from the following factors: higher reactor power, larger area of the cold neutron emitting source, larger area of the detector target, and, most essentially, from the use of a large-solid angle elliptical focusing reflector. The latter factor provides an opportunity of increasing the neutron flight path (from 70 m at ILL/Grenoble to 150-200 at HIFR) without reducing the intercepted solid angle of cold neutrons. Depending on the neutron beam line available at HFIR for such an experiment and also on the performance upgrade scenario of HFIR, it will be possible to increase the discovery potential relative to the ILL experiment by factors from ~50 to ~5,000. The lower factor assumes no reactor upgrade and represents the advantages of the focusing reflector layout for one of the existing neutron beams without use of cold moderator. The higher factor corresponds to the full upgrade option of the HFIR reactor [16] in which the beryllium reflector would be replaced by a heavy water reflector, and the large-size cold liquid deuterium moderator would be built at the HFIR radial beam. For two to three years of experimental operation, an overall discovery potential relative to the ILL experiment as high as 10^4 could be achieved. The latter would correspond to an increase in the limit of $n \to \bar{n}$ characteristic transition time of up to $\tau_{n\text{-}nbar} \geq 10^{10}$s.

For the next generation of experiments, several possibilities can be considered in order to stretch the discovery potential level beyond the feasibility limits of HFIR. In a new high-flux research reactor of the ANS (Advanced Neutron Source) [17] type, thermal neutron fluxes could be higher by an additional factor of ~5. It is also important to mention that the development of a new reactor would allow optimizing the layout of the cold moderator and of the focusing reflector in a way which would maximize the discovery potential of an $n \to \bar{n}$ search. Once a focusing reflector is used, the discovery potential can be improved by increasing the distance between the neutron source and the annihilation target. In the horizontal layout this increase, unfortunately, is limited by the spread of neutrons with different velocity due to earth's gravity effect. This results in an optimum length of the experiment. There would be no gravity effect limitation in an experiment with a vertical layout, although a vertical layout does not seem to be practical in a reactor environment where various services are usually located beneath the reactor vessel. In an experiment at the neutron spallation source, a vertical layout would be more appropriate. Here it can partially compensate for the lower [11] average neutron flux of the spallation source. Another way to enhance the discovery potential would be to use neutrons thermalized to a spectrum with lower temperatures than in the conventional liquid hydrogen and deuterium cold moderators. This possibility is discussed in [15,18]. A palletized solid methane moderator [19] cooled by liquid or superfluid helium can, hopefully, thermalize the neutron spectrum to temperatures below ~10K. This option will require extensive R&D work. The combination of all improvement factors mentioned above employed in the next generation of future experiments should allow a gain of an additional factor of ~100 in the discovery potential or establish a transition time limit of $\tau_{n\text{-}nbar} \geq 10^{11}$s.

The possibility of an $n \to \bar{n}$ transition search with ultra cold neutrons (UCN) trapped in a bottle with reflecting walls was discussed in a number of papers, but no practical experimental efforts have been made so far. Although a storage time of the order of free-neutron life time can be achieved with the neutrons contained in the bottle, the gain in the discovery potential will be only linearly proportional to the storage time. As was shown in [20], the reason for this is the neutron reflection off the wall. Each reflection destroys the coherence of the transition amplitude and resets the time square accumulated in between the collisions. With presently achieved UCN densities of ~50 n/cm^3 for a practical-size storage vessel and annihilation detector, the discovery potential would be a factor of ~75 lower than that in the ILL experiment. High-peak flux neutron spallation sources are most efficient for the production of UCN of high density. In a rather optimistic scenario of UCN production described in [18], a density of up to ~$2.5 \cdot 10^5$ n/cm^3 should be obtained. Even at this density the discovery potential can surpass that of the ILL experiment by only a factor of ~30.

III. INTRANUCLEAR TRANSITIONS

Since the potentials of neutrons and antineutrons inside the nucleus are different, the intranuclear $n \rightarrow \bar{n}$ transition is strongly suppressed. The lifetime of a nucleus for an $n \rightarrow \bar{n}$ transition T_A is related to free-neutron oscillation time $\tau_{n\text{-}nbar}$ as $T_A = T_R \cdot \tau_{n\text{-}nbar}^2$, where T_R is the nuclear suppression factor. This factor has been evaluated by several authors during the last two decades. Most recent discussions and new reevaluations, as well as references to the previous works, can be found in [21-24]. According to [21], for oxygen, argon, and iron the suppression factor has a value $T_R \sim 2 \cdot 10^{23} sec^{-1}$.

Experimentally, the intranuclear $n \rightarrow \bar{n}$ transitions have been searched in the nucleon stability experiments IMB, Kamiokande, and Frejus [25-27]. The best limit for the intranuclear $n \rightarrow \bar{n}$ transition lifetime is set for the iron nuclei by tht Frejus collaboration. The result is $T_{Iron} \geq 6.5 \cdot 10^{31}$ years which, according to the suppression factor from [21], corresponds to $\tau_{n\text{-}nbar} \geq (0.8\text{-}1.0) \cdot 10^8$sec.

During the next decade, the large next generation nucleon stability experiments SuperKamiokande and Icarus will improve the $n \rightarrow \bar{n}$ transition limit. After a few years of operation the SuperKamiokande detector [28] (it was commissioned in April 1996) will be able to set an $n \rightarrow \bar{n}$ transition limit of $T_{Oxygen} \geq 10^{33}$years [29]. This will correspond to a free-neutron transition limit of $\tau_{n\text{-}nbar} \geq (4\text{-}5) \cdot 10^8$sec.

A new approach to an $n \rightarrow \bar{n}$ intranuclear transition search has been recently proposed by an ORNL-UTK group [30]. This approach is based on the measurement of the concentration of the long-lived isotopes (with a lifetime in the range of million years) which may be the remnants of $n \rightarrow \bar{n}$ intranuclear transitions. These isotopes might be accumulated among the parent nuclides in the nonradioactive deep-mined ore. For these reasons the search for technetium isotopes ^{97}Tc, ^{98}Tc, and ^{99}Tc in tin ore looks very attractive. Since the technetium has no stable isotopes, the chemical extraction of "useful" isotopes should be very efficient. In addition, the background contamination with these isotopes in the nonradioactive deep-mined ore is expected to be much smaller than for stable nuclides. Detailed discussion of this method is found in [30]. The extraction of technetium from the large volumes of tin ore is envisaged as a by-process of the industrial manufacturing of tin [31]. Final separation and count of technetium atoms can be made by a combination of chemical [31] and selective laser photoionization spectroscopy methods [32-33]. Major sources of background are (a) the admixture of or the contamination with spontaneously fissionable nuclides and (b) nuclear transmutations caused by inelastic interactions of cosmic muons in ore deposits. The discovery potential in this approach is determined by the background processes and can be varied for different ore deposits. It is summarized in Figure 2 with optimistic and pessimistic assumptions made there. In the optimistic case the concentration of uranium in the ore is assumed to be 10 ppb, and the depth of ore deposits is 2 miles of rock. In the pessimistic case the concentration of uranium in the ore is 1 ppm, and the depth of deposits is 1 mile of rock. Calculations for ^{97}Tc are represented by solid lines and for ^{98}Tc by dotted lines, respectively. Detection of ^{99}Tc, according to [30], is less attractive due to larger background, thought it might be extremely useful for complimentary background and contamination measurements.

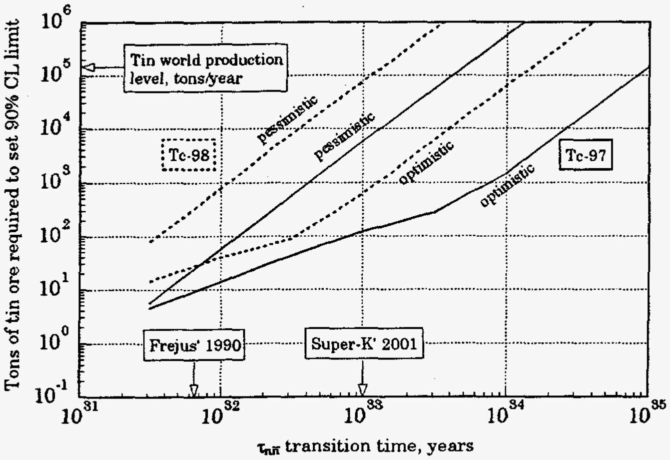

Fig 2. Discovery potential of an $n \rightarrow \bar{n}$ transition search by rare isotope method for the tin-technetium parent-daughter nuclides. For each isotope the discovery potential is shown with two optimistic and pessimistic assumptions for background (see text). Calculations for ^{97}Tc are represented by solid lines and for ^{98}Tc by dotted lines.

IV. CONCLUSIONS

The status and the prospects of an $n \rightarrow \bar{n}$ transition search with free neutrons in reactor experiments and with intranuclear nucleon stability search experiments discussed above are summarized in Table 1 and in Figure 3.

Table 1

Method	Present limits	Possible future limits
Free neutrons from reactor	$8.6 \cdot 10^7$ sec (ILL/Grenoble)	$\sim 10^{10}$sec (HFIR/ORNL proposal)
UCN trapped in the reflecting bottle	none	$\sim 5 \cdot 10^8$sec
Intranuclear search in nucleon stability experiments	$4\text{-}6 \cdot 10^{31}$years (IMB, Frejus, Kamiokande)	$\sim 10^{33}$years (Super-K)
Search for long-lived isotopes in intranuclear transition remnants	none	$\sim 10^{33}\text{-}10^{34}$sec (ORNL/UTK proposal)

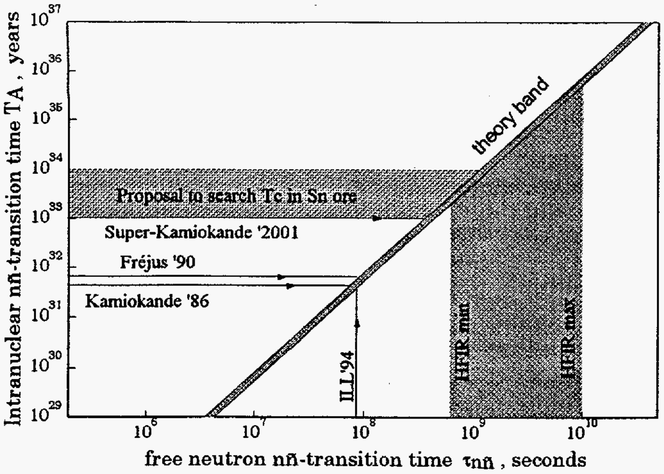

Fig 3. Comparison of $n \rightarrow \bar{n}$ searches in intranuclear transitions (τA) to those in free-flying neutron experiments ($\tau_{n\text{-nbar}}$). Shaded areas indicate possible improvement in HFIR-based experiment with free neutrons [13-15] and in a new proposed experiment with long-lived isotopes [30].

As was pointed out in [34], if $n \rightarrow \bar{n}$ transitions are found, the comparison of the results of two experiments with free and bonded neutrons might provide a precision test of CPT theorem by the measurement of Δm of neutrons and antineutrons. For free neutrons in a vacuum, the $n \rightarrow \bar{n}$ transition probability will be suppressed if there is a mass difference Δm between neutrons and antineutrons. On the other side, in intranuclear $n \rightarrow \bar{n}$ transitions Δm will not provide an additional suppression because it is much smaller than the binding energy of the neutron in the nucleus. Both measurements with free neutrons and intranuclear (if $n \rightarrow \bar{n}$ transition exists) are needed in order for a precise test of CPT theorem at the mass scale of $(m_{Plank})^{-1}$.

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