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# PROSPECTS FOR NEUTRON–ANTINEUTRON TRANSITION SEARCH

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## ABSTRACT

Presently-available sources of free neutrons can allow an improvement in the discovery potential of a neutron-antineutron transition search by four orders of magnitude as compared to that of the most recent reactor-based search experiment performed at ILL in Grenoble [1]. This would be equivalent to a characteristic neutron-antineutron transition time limit of $>10^{10}$ seconds. With future dedicated neutron-source facilities, with further progress in cold-neutron-moderator techniques, and with a vertical experiment layout, the discovery potential could ultimately be pushed by another factor of ~100 corresponding to a characteristic transition time limit of $\sim 10^{11}$ seconds. Prospects for, and relative merits of, a neutron-antineutron oscillation search in intranuclear transitions are also discussed.

## 1. Introduction

Experimental search for baryon instability [2] discussed at this workshop is motivated by two major physics concepts: (a) "baryon asymmetry of the universe" [3] based on the observation that matter is more abundant in the universe than antimatter although both are believed to have been formed in equal amounts at the time of origin, and (b) the idea of unification of particles and their interactions [4, 5]. Both of these concepts involve the nonconservation of baryon number, B, either in the form of proton decay ( $\Delta B=1$ transition) or as a neutron-antineutron oscillation ($\Delta B=2$ transition). In different versions of unification models either $\Delta B=1$, or $\Delta B=2$ transitions, or both, are expected to take place. Since the original simplest SU(5) model [5], which predicted unification at an energy scale of $\sim 10^{15}$ GeV and a proton life time of $\sim 10^{29\pm2}$ years, was ruled out by experiments [6], other unification schemes have been advanced in which certain new physics related to baryon instability may prevail at the scale of $\sim 10^{5}$–$10^{6}$ GeV which is intermediate between electroweak and unification scales (for most recent review of these schemes see Refs. 7, 8, and 9). The neutron-antineutron transition is one of the processes which might belong to such new intermediate-energy-scale physics. There are no conservation laws of nature which would forbid the transition of n → $\bar{n}$ except the conservation of baryon number [10].

The possibility of neutron-antineutron oscillations was first considered in [11] and used as a mechanism for explanation of baryon asymmetry of the universe. In the context of unification models, n → $\bar{n}$ oscillations were first discussed in [12]. The most recent theoretical review of neutron-antineutron oscillations in the framework of unification and supersymmetric models is given in [9].

Since the $n \rightarrow \bar{n}$ transition at the quark level is described by a 6-fermion operator, the corresponding amplitude (for dimensional reasons) should be proportional to $m^{-5}$, where $m$ is the characteristic energy scale which cannot be very large in order to produce any observable rates of $n \rightarrow \bar{n}$ [9]. Thus, the experimental observation of $n \rightarrow \bar{n}$ oscillations would indicate a $\Delta B=2$ baryon instability and point to the new physics energy scale of $\sim 10^5$–$10^6$ GeV.

An interesting possibility which might lead to an alternative mechanism of $n \rightarrow \bar{n}$ transitions has been discussed by V. Kuzmin [13]. He assumed that the interaction of quarks inside baryons consisting of quarks of different generations (for example *bus*) can be mediated by the color-triplet scalar field coupled to the right components of the quarks. For neutral *bus*-type baryons such a scalar field might result in baryon-antibaryon oscillations with a characteristic time of $\sim 10^{-12}$ s. Neutron-antineutron oscillations, according to V. Kuzmin, will then arise from this interaction, being additionally suppressed by ~20 orders of magnitude by CKM-matrix quark-mixing probabilities, with a characteristic transition time of $\sim 10^8$ s.

There are two complementary experimental methods which can be used for an $n \rightarrow \bar{n}$ search: (a) utilizing free neutrons from reactors or neutron spallation sources and (b) with neutrons bound inside nuclei. The results of the most recent experiment [1] performed by method (a) are presented in [14] in these proceedings. The future prospects of $n \rightarrow \bar{n}$ search in intranuclear transitions — method (b) — were addressed in [15,16] at this workshop. In this paper we discuss the present status of both methods and their relative merits for the prospects of future experimental searches. In the conclusion arguments are presented for why experimental searches by both methods are necessary.

## 2. Experiments with Free Neutrons

The discovery potential of an $n \rightarrow \bar{n}$ transition search experiment can be characterized by the probability of production of antineutrons in the beam of neutrons. This probability (in vacuum, in the absence of external fields) depends on the observation time $t$ as [12]

$$P_{n\bar{n}} = (t / \tau_{n\bar{n}})^2 , \qquad (1)$$

where $\tau_{n\bar{n}}$ is the characteristic $n \rightarrow \bar{n}$ transition time. It is assumed in this expression that neutrons and antineutrons have equal masses (as required by CPT conservation) and that the gravitational interaction with the earth is the same for neutrons and antineutrons. Thus, we can define the *discovery potential* of an $n \rightarrow \bar{n}$ search experiment as the product of the number of neutrons per second, $N_n$, used in the experiment and the square of the averaged neutron time-of-flight $\bar{t}$ through the experimental volume,

$$D.P. \; = \; N_n \cdot \bar{t}^2 \;\; \text{[neutrons·seconds]} \qquad (2)$$

The most recent experimental search for $n \rightarrow \bar{n}$ with free neutrons [1] was performed at the 58-MW research reactor at the Institute Laue-Langevin (ILL) in

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Grenoble. The experiment had a discovery potential ~$1.5 \cdot 10^9$ n·s, and, for approximately one year of operation, set a limit of $\tau_{n\bar{n}} \geq 8.6 \cdot 10^7$ s. This experiment is described in detail in a talk [14] at this workshop. Some of the major features of this experiment are also listed in Table 1 below. This state-of-the-art experiment has improved the $n \rightarrow \bar{n}$ transition discovery potential relative to that of the best previous reactor experiment [17] by a factor of ~7,000. In the rest of this paper we will define the discovery potential of the ILL-experiment as 1 and we will express the discovery potentials of other different possible experimental options relative to it.

It is clear from equation (2) that for a larger discovery potential, a higher flux of neutrons from the reactor is desirable. Since the discovery potential is proportional to $t^2$, it is also desirable to increase the "neutron observation time" $t$. The latter requires the use of low-velocity neutrons, i.e., neutrons thermalized in a cold moderator to the lowest possible temperature.

The general scheme of an $n \rightarrow \bar{n}$ search experiment is as follows: neutrons emitted from the cold moderator are propagated in the vacuum in a volume (shielded against earth's magnetic field down to the level of few $nT$) where the $n \rightarrow \bar{n}$ transitions can occur. Produced antineutrons propagating along the initial neutron path would be detected as a few-meson star with a total energy release of ~1.8 GeV resulting from the annihilation with a thin carbon target. In the simplest configuration, the $n \rightarrow \bar{n}$ search experiment would consist of a neutron source (cold neutron moderator) with area $A_s$, a flight path of the length $L$, and an antineutron annihilation detector with area $A_d$. The areas $A_s$ and $A_d$ should be chosen as large as possible to intercept the maximum number of neutrons from the reactor, but they are limited by practical constraints. For a fixed detector area the intercepted solid angle of neutron emittance (number of neutrons used by the detector) will be proportional to $L^{-2}$, and for a given spectrum of neutron velocities the square of the neutron time of flight is

$$\bar{t}^2 = L^2 / \bar{V}^2 . \qquad (3)$$

Thus, in such an experimental configuration, the discovery potential (2) does not depend on the distance $L$ between the source and the target. An example of this kind of experimental approach is given in a 1982 proposal by a Harvard-ORNL-UT group [18]. Major parameters of the experiment proposed in [18] and the expected discovery potential are listed in Table 1 below.

A new approach proposed by an ORNL-UT-Harvard-UW group [19] for reactor or spallation source experiments is based on the property of neutrons to be focused by means of reflection from surfaces of certain materials. In this approach [20-22] the *elliptically-shaped reflector* intercepts neutrons emitted from the source within a large solid angle and focuses them onto the annihilation target. Since the intercepted solid angle is now determined by the acceptance of the focusing reflector and does not depend on the distance, the overall discovery potential (2) will be proportional to $L^2$ which provides an additional means by which the experiment can be improved. A possible layout for such a reactor experiment is illustrated schematically in Figure 1.

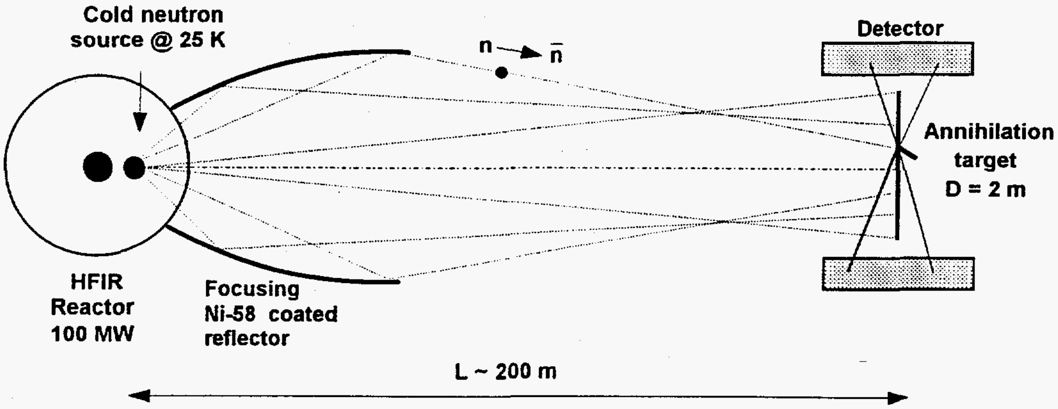

Figure 1. Conceptual layout of an experiment with a large elliptical focusing reflector for an n → n̄ transition search at a reactor (not to scale).

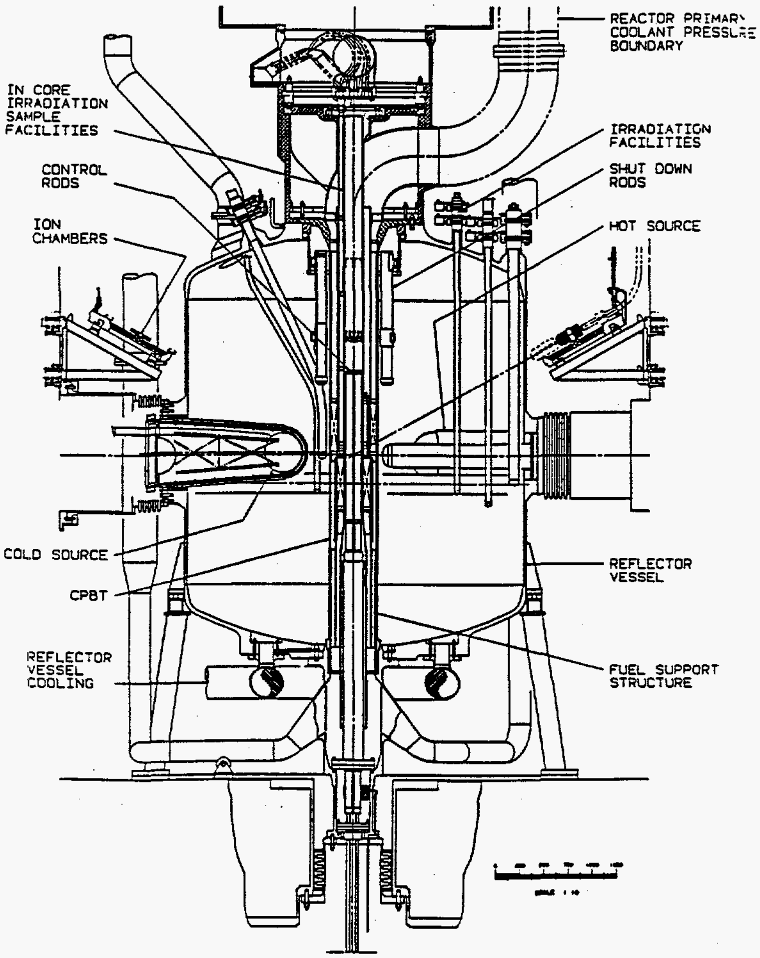

Figure 2. ANS reactor with compact core, heavy water reflector, and 40 cm diameter liquid deuterium moderator. The ANS project at ORNL was discontinued in 1995.

Originally this approach was developed for an $n \rightarrow \bar{n}$ search experiment proposed for the 330-MW Advanced Neutron Source (ANS) research reactor which had been planned for construction at ORNL. The high neutron flux, the availability of a large-area liquid-deuterium cold neutron moderator, and the possibility of modifying the reactor shield in an optimum way would have allowed, for one year of operation, an increase in the discovery potential of a factor ~13,000 relative to that of the ILL experiment. Figure 2 shows the large liquid-deuterium cold neutron moderator layout of the ANS reactor which would have been the best contemplated source of neutrons for an $n \rightarrow \bar{n}$ search experiment. Unfortunately, the ANS project was discontinued in the development phase [23]. Some features and the discovery potential of the ANS-based experiment are given for comparison in Table 1 below.

Table 1. Comparison of neutron-antineutron search experiments.

| Neutron source | ILL' 94 | ORR' 82 | ANS | HFIR (upgraded with $D_2O$ reflector) |
|---|---|---|---|---|
| Status | Completed experiment | Rejected proposal | Discontinued project | Possible option |
| Power (MW) | 58 | 30 | 330 | 100 |
| Reactor's max. thermal neutron flux (n/cm²/s) | $1.5 \cdot 10^{15}$ | $1.5 \cdot 10^{14}$ | $7 \cdot 10^{15}$ | $2 \cdot 10^{15}$ |
| Moderator | Liq. $D_2$ @ 25 | $D_2O$ @ 300 K | Liq. $D_2$ @ 25 K | Liq. $D_2$ @ 25 K |
| Source area | 6×12 cm² | ∅ 42 cm | ∅ 40 cm | ∅ 40 cm |
| $\varnothing_{det}$ (m) | 1.1 m | 1.0 m | 2.0 m | 2.0 m |
| $L_{free}$ (m) | 76 | 20 | ~300 | ~150 |
| n/s @ target | $1.25 \cdot 10^{11}$ | $2 \cdot 10^{13}$ | $4.4 \cdot 10^{13}$ | $5.1 \cdot 10^{13}$ |
| $\sqrt{<t^2>}$ (s) | 0.109 | 0.01 | 0.672 | 0.384 |
| Detector efficiency | 0.48 | ~ 0.5 | ~ 0.5 | ~ 0.5 |
| Operation time (s) | $2.4 \cdot 10^7$ | $3 \cdot 10^7$ | $3 \cdot 10^7$ | $9 \cdot 10^7$ |
| Discovery potential $N \cdot \langle t^2 \rangle$ (n·s) | $1.5 \cdot 10^9$ | $2 \cdot 10^9$ | $2 \cdot 10^{13}$ | $0.75 \cdot 10^{13}$ |
| $\tau_{n\bar{n}}$ limit, s (90% CL) | $8.6 \cdot 10^7$ | $1.1 \cdot 10^8$ | $1.1 \cdot 10^{10}$ | $1.0 \cdot 10^{10}$ |

The high-flux neutron sources available at the present time and in the foreseeable future are reviewed by C. West [24] in these proceedings. The Oak Ridge 100-MW High Flux Isotope Reactor (HFIR) has the highest steady thermal-neutron flux among the research reactors. This reactor has a compact highly enriched fuel core, a beryllium reflector, a pressure vessel with a diameter of 8', and four horizontal beam openings: three with 8" diameter and one with 12" diameter (Figure 3). At the present time it is not equipped with cold neutron moderators. In one of the upgrade options of the HFIR reactor a heavy-water reflector and a large liquid-deuterium moderator of the ANS-type [25] would be installed. The openings in the reactor vessel in this case could be enlarged to accommodate the thimbles of the large cold moderators. This option is shown schematically in Figure 4. If implemented, such an upgrade would not only provide an excellent opportunity for the $n \rightarrow \bar{n}$ search but at the same time would also make available (similar to the ANS cold-source design) several cold-neutron beams for neutron scattering experiments. The discovery potential of an $n \rightarrow \bar{n}$ search experiment performed at the upgraded HFIR facilities could be a factor of ~5,000 higher than that of the ILL experiment. The gain in the discovery potential results from the following factors: higher reactor power, larger area of the cold-neutron emitting source, larger area of the annihilation detector, and, most importantly, from the use of a large-acceptance elliptical focusing reflector. This would be the most preferred option of implementation of a new reactor experiment. For 2-3 years of operation a discovery-potential gain (relative to the ILL experiment) of more than 10,000 can be envisaged which, if $n \rightarrow \bar{n}$ transitions are not found, would result in a new transition limit of $10^{10}$ seconds. The essential features of the upgraded HFIR option are shown in Table 1 for comparison with other experiments.

In the case that the heavy-water reflector upgrade of the HFIR reactor will not be implemented, the next-best possibility would be to use the radial HFIR beam which has a 12"-diameter opening. A medium-size cold moderator would be required in this beam in order to enhance the discovery potential up to ~1,000 times relative to that of the ILL experiment. This and other options with their discovery potentials for various combinations of beams and cold moderators are shown in Table 2.

The calculations of the discovery potential for different options of the $n \rightarrow \bar{n}$ search experiment have been performed with a Monte-Carlo neutron-transport code which takes into account the brightness of the neutron source with appropriate normalization, the cold moderator and beam layout, beam collimation, reflection of the neutrons off the material of the focusing reflector, and the effects of gravity. The dimensions and parameters of the reflector have been optimized to maximize the discovery potential for the various options of experimental layout and of cold moderators.

Effects of gravity (more important at low neutron velocities) produce significant defocusing if the length of the horizontal experiment is too large. This effect limits the advantages of using a very cold neutron source. The defocusing gravity effect can be eliminated in a layout with a vertical neutron flight path. This layout would be most efficient if the neutrons were thermalized in the cold moderator to the lowest possible temperatures. At the present time the lowest experimentally achieved temperatures of thermalized neutron Maxwellian distributions are in the range of 20-40K. The possibility of thermalization of neutrons to temperatures as low as 1-10K has not been sufficiently studied either theoretically or experimentally. This situation is addressed in References 22 and 26. For some options in Table 2, a temperature for the neutron spectrum of 1K was assumed, which, in practice, might not be achievable.

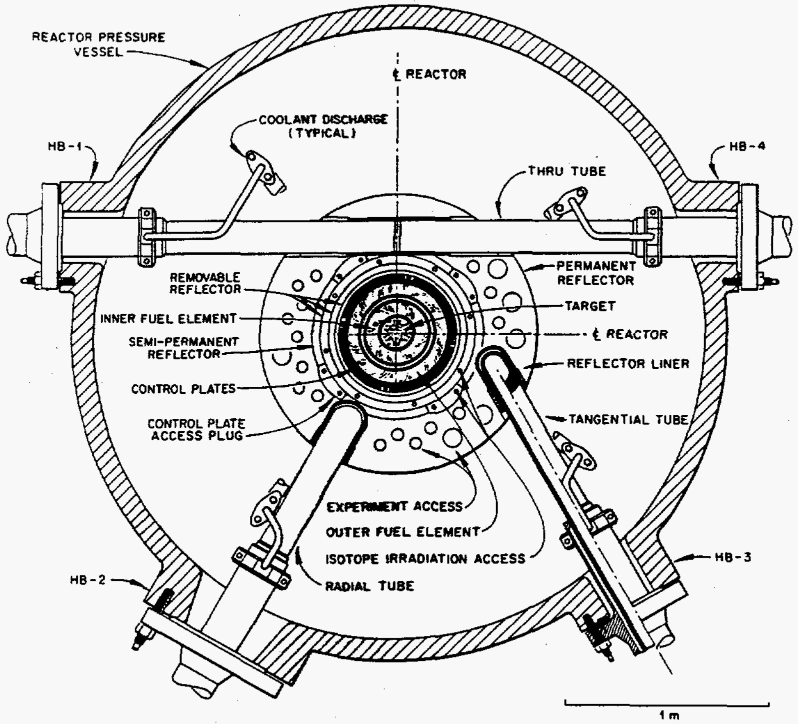

Figure 3. Current layout of neutron beams at the HFIR reactor in the present configuration.

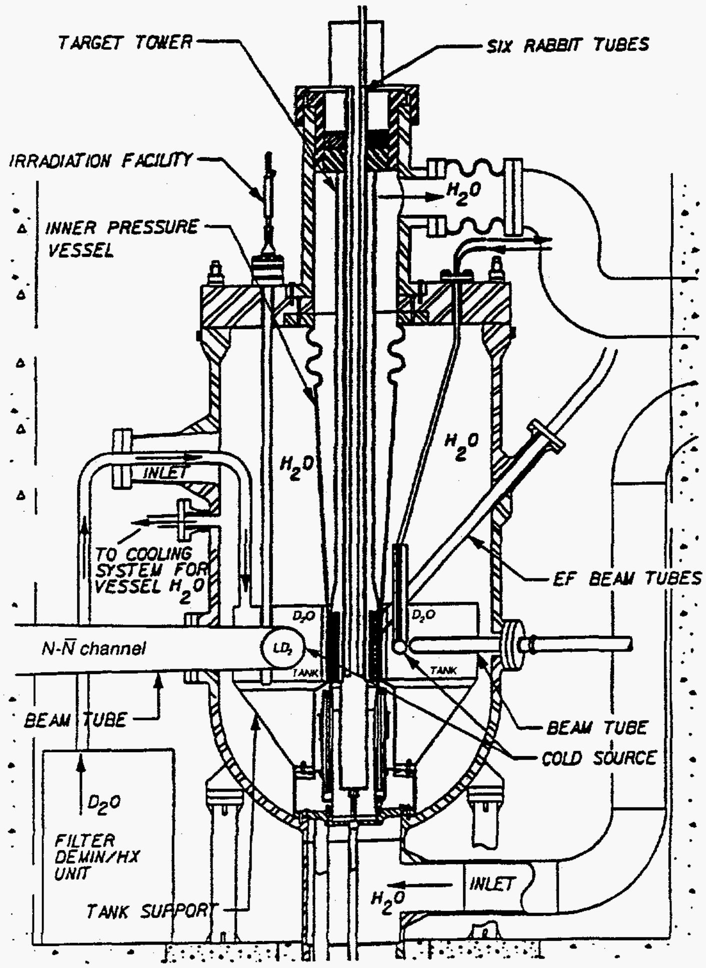

Figure 4. Upgrade option of HFIR reactor using a heavy-water reflector and a large cold moderator.

Table 2. Experimental options for neutron-antineutron transition search.

| Neutron source | Neutron moderator | Discovery potential gain for one year of operation |
|---|---|---|
| ILL (1991)<br>*completed experiment* | Large liquid $D_2$ | × 1 |
| ANS<br>*discontinued project* | Large liquid $D_2$ | × 13,000 |
| HFIR *with enlarged radial beam opening, upgraded to $D_2O$ reflector* | Large liquid $D_2$ or solid $CH_4$ | × 5,000 |
| HFIR *12" radial beam with modified Be reflector* | Liquid $H_2$ | × 1,000 |
| HFIR *8" tangential beam with modified Be reflector* | Small liquid $H_2$ | × 100–400 |
| HFIR *12" radial beam no modifications* | No cold moderator | × 50 |
| New ANS-type reactor<br>*vertical layout of experiment* | Super-cold moderator<br>*thermalizing neutrons @ 1K* | up to × 1,000,000 |
| Long pulse 1-MW neutron spallation source | Large-area liquid $H_2$<br>*coupled, not poisoned moderator* | × 500 |
| Long pulse 1-MW neutron spallation source, *vertical layout* | Super-cold moderator<br>*thermalizing neutrons @ 1K* | × 16,000 |

For the next generation of experiments, several improvement factors are essential in order to stretch the discovery potential level beyond the feasibility limits of HFIR. These factors are: (a) high flux neutron sources similar to ANS reactor, (b) newly developed super-cold neutron moderators, and (c) vertical experimental layouts combined with a focusing reflector. The combination of all of these factors in a next generation experiment should, hopefully, allow a total gain-factor of up to $10^6$ relative to the present ILL level, or, it should allow the establishment of a $n \rightarrow \bar{n}$ transition-time limit of $>10^{11}$ s.

Neutron spallation sources, although delivering very high neutron peak fluxes, cannot compete [24] with reactors when it comes to the average neutron flux, which is most important requirement for a progress of $n \rightarrow \bar{n}$ search. To enhance the advantages of pulse operation for neutron spectroscopy, moderators at spallation neutron sources are very often operated in the "decoupled" and "poisoned" modes which reduces substantially the average neutron flux. An experiment with a vertical layout is more likely to be built at the spallation source than at the reactor where the location of various reactor services and where safety regulations result in more restrictive environment. The combination of a vertical layout and a super-cold neutron moderator at the spallation neutron source could provide a discovery potential which is competitive with that of a midrange reactor experiment (see Table 2).

## 3. 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 $n \rightarrow \bar{n}$ intranuclear transition $T_A$ is related to free neutron oscillation time $\tau_{n\bar{n}}$ as

$$T_A = T_R \cdot \tau^2_{n\bar{n}} \ , \tag{4}$$

where $T_R$ is the nuclear suppression factor.

The following simple speculation [27] allows obtaining a very approximate estimate of the nuclear suppression factor. The neutrons bound inside the nuclei can be considered "free" for a time $\Delta t$ given by:

$$\Delta t \sim 1 / E_{binding} \sim 1 / 10 MeV \sim 10^{-22} s \, , \tag{5}$$

and will "experience" this condition $N = 1/\Delta t$ times per second. The intranuclear $n \rightarrow \bar{n}$ transition probability per unit time, $1/T_A$, is then, according to (1):

$$\frac{1}{T_A} = \left(\frac{\Delta t}{\tau_{n\bar{n}}}\right)^2 \cdot \left(\frac{1}{\Delta t}\right) . \tag{6}$$

The comparison of (6) with (4) shows that $T_R \sim 1/\Delta t \sim 10^{22} \, s^{-1}$.

The nuclear suppression factor has been evaluated with different methods by several authors during the past two decades. Most recent theoretical discussions and new reevaluations, as well as references to the previous work, can be found in [28-31]. According to [28], for oxygen, argon, and iron, the suppression factor has a value of $T_R \sim 2 \cdot 10^{23} \, s^{-1}$.

Experimentally, intranuclear $n \rightarrow \bar{n}$ transitions have been searched for in nucleon stability experiments IMB, Kamiokande, and Fréjus [32]. For example, the limit for the intranuclear $n \rightarrow \bar{n}$ transition lifetime for iron nuclei set by the Fréjus experiment is $T_A \geq 6.5 \cdot 10^{31}$ years which, according to (4) and the suppression factor $T_R$ from [28], corresponds to a free $n \rightarrow \bar{n}$ transition time limit of $\tau_{n\bar{n}} \geq (8\text{-}10) \cdot 10^{7} s$.

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, commissioned in April this year, will be able to set an $n \rightarrow \bar{n}$ transition limit of $T_A \geq 10^{33}$ years [15] which will correspond, according to ( 4) and the suppression factor $T_R$ from [28], to a free $n \rightarrow \bar{n}$ transition limit of $\tau_{n\bar{n}} \geq 4 \cdot 10^{8} \, sec$.

A new possibility for an intranuclear $n \rightarrow \bar{n}$ transition search has been recently considered by an ORNL-UTK group [16]. The idea is based on the measurement of the concentration of long-lived isotopes (with a lifetime in the range of million years) which may be the remnants of $n \rightarrow \bar{n}$ intranuclear transitions accumulated among the parent nuclides contained in deeply-deposited nonradioactive ores. As an example, the search for technetium isotopes $^{97}$Tc, $^{98}$Tc, and $^{99}$Tc in deep-mined tin ore is discussed in [16]. In case of favorable backgrounds this approach can provide a limit for intranuclear $n \rightarrow \bar{n}$ transitions up to $T_A \approx 10^{34}$ years.

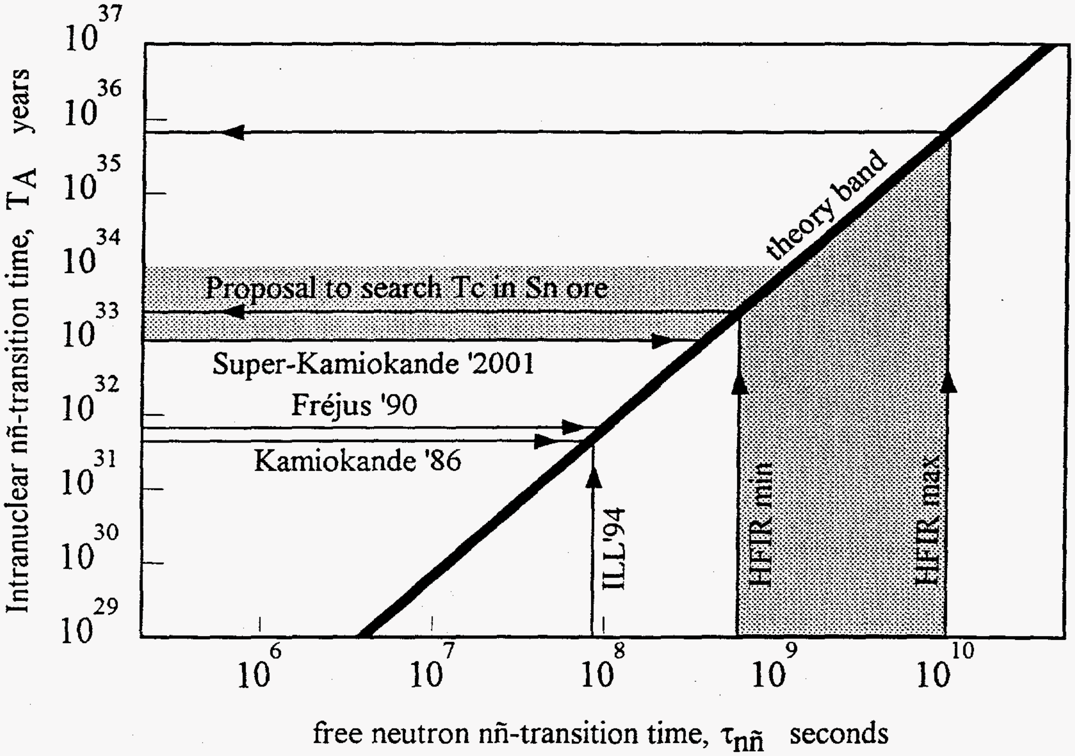

Figure 5. Comparison of $n \rightarrow \bar{n}$ searches in intranuclear transitions ($T_A$) to those in free neutron experiments ($\tau_{n\bar{n}}$). The slope and the width of the nuclear model band relating these two processes corresponds to $T_A = T_R \cdot \tau_{n\bar{n}}^2$, where $T_R$ is the nuclear suppression factor taken from [28].

## 4. Conclusions

Different methods for $n \rightarrow \bar{n}$ transition searches are compared in Figure 5. At the present time the experimental free-neutron transition limit and limits from intranuclear transition experiments are in agreement with each other as related by theoretical calculations [28] via the nuclear suppression factor $T_R$. If the experimental limits for an intranuclear $n \rightarrow \bar{n}$ transition will be improved to the level of $10^{33}$–$10^{34}$ years, this will correspond to an equivalent limit for the free-neutron transition time of ~$10^9$ s. Future reactor or spallation-source experiments with free neutrons have a much higher potential for $n \to \bar{n}$ discovery and can realistically set the limit for $n \to \bar{n}$ transitions as high as $10^{10}$ s (and ultimately at $10^{11}$ sec if all experimental possibilities will be stretched to their limits).

The current phenomenology of $n \to \bar{n}$ transitions is based on the assumption that neutrons and antineutrons have equal masses (as required by CPT conservation) and that the gravitational interaction with the earth is the same for neutrons and antineutrons. These assumptions, although perfectly acceptable by modern theories, require, in themselves, experimental confirmation. Strictly speaking, we do not know experimentally even whether antineutrons are attracted or repulsed by the gravitational field of the earth, and the neutron-antineutron mass difference is known with an accuracy of only ~ 100 KeV [6].

It was pointed out in [33] that a positive observation of $n \to \bar{n}$ transitions would allow a test of the CPT theorem (which predicts that the mass of a particle is equal to the mass of the antiparticle) with unprecedented accuracy. A similar conclusion can be drawn regarding the difference of gravitational interactions of neutrons and antineutrons.

The presence of, either a mass difference, $\Delta m$, or of a gravitational interaction difference of neutrons and antineutrons would result in the suppression of transitions of free neutrons to antineutrons. The intranuclear $n \to \bar{n}$ transitions, as was pointed out in [33], are not suppressed. This is correct provided that the mass difference, or the difference in the gravitational potentials of neutrons and antineutrons are considerably less than the difference of neutron and antineutron nuclear potentials (~ MeV range). The experimental observation of intranuclear $n \to \bar{n}$ transitions together with the suppression of the corresponding rate of transitions in experiments with free neutrons would indicate the presence of $\Delta m$ or a difference of gravitational interaction. If both types of experiments would measure matching $n \to \bar{n}$ transition rates, it will allow the setting of unprecedentedly low limits on $\Delta m$ or on the difference of gravitational interaction of particles and antiparticles. The $\Delta m$-sensitivity in such a case would be of the order of $1/t$, where $t$ is the time of neutron observation in the free-neutron experiment. In one of the HFIR-based free-neutron experiment options, $t \sim 0.4\ s$ and the corresponding $\Delta m/m$ sensitivity can be as low as ~$10^{-24}$. Both kinds of $n \to \bar{n}$ search experiments (intranuclear and with free neutrons) are necessary in order to address the question of the neutron and antineutron mass difference.

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