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USE OF COLD SOURCE AND LARGE REFLECTOR MIRROR GUIDE FOR NEUTRON–ANTINEUTRON OSCILLATION SEARCH (PROPOSAL)

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ABSTRACT

An ORNL-UTK-UW-Harvard group is exploring the possibility of performing a new experiment to search for neutron-antineutron oscillations either at the ORNL HFIR reactor or at the proposed neutron spallation source. The advanced layout, based on a large mirror focusing reflector, proposed for this experiment should allow improving the discovery potential of an $n \rightarrow \bar{n}$ transition search by 3-4 orders of magnitude, as compared to the most recent similar experiment at ILL-Grenoble, and to reach the limit of the characteristic transition time of $\tau_{n\bar{n}} > 10^{10}$ seconds. Use of a cold neutron moderator operating at temperatures lower than conventional moderators can further enhance the discovery potential of an $n \rightarrow \bar{n}$ search provided that neutrons can be thermalized at these lower temperatures. The latter assumption is an open question.

1. $n - \bar{n}$ Experiment

Experiments which search for neutron-antineutron oscillations can provide important information on the "baryon asymmetry" of the universe [1] and on baryon number nonconservation expected in some GUT models [2]. The most recent review of theoretical models related to neutron-antineutron transitions can be found in reference [3]. Present lower limit on characteristic $n \rightarrow \bar{n}$ transition time of $\tau_{n\bar{n}} > 8.6 \cdot 10^7$s is set by an experiment [4] performed at ILL-Grenoble with free-flying neutrons. Although the limit for $\tau_{n\bar{n}}$ extracted from baryon-number-violating intranuclear transition searches [5] (including uncertainties of nuclear model calculations [6]) is higher ($\tau_{n\bar{n}} > 1.2 \cdot 10^8$s), experiments with free neutrons have a higher potential for improvement. The ORNL-UTK-UW- Harvard [7] group is exploring the possibility to perform an experiment either at the HFIR reactor at ORNL or at a newly-proposed, powerful spallation neutron source [8], with the goal of improving the discovery potential for an $n \rightarrow \bar{n}$ search by 3–4 orders of magnitude or of setting a new limit of $\tau_{n\bar{n}} > 3 \cdot 10^9 - 1 \cdot 10^{10}$ s. Earlier we proposed an $n \rightarrow \bar{n}$ search experiment for the proposed ANS reactor in which, due to the larger flux of neutrons, the discovery potential could have been even higher. Unfortunately, the ANS project was discontinued.

Keywords: Focusing, Moderator, Oscillation, Experiment

Since the transition probability of $n \rightarrow \bar{n}$ in vacuum in the absence of external fields (earth magnetic field can be compensated for down to a sufficient level of few nanotesla [4]) is

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

where t is the neutron flight time; the discovery potential (D.P.) is proportional to $N \cdot t^2$, where N is the number of neutrons per second crossing the target at the end of the flight path. (Antineutrons would be observed via their annihilation in the target.) To maximize the discovery potential for an experiment with a given geometry, the highest flux of neutrons with the coldest possible spectrum (large t) is required at the target. If no focusing device is used between the source of neutrons and the annihilation target, the discovery potential will not be dependent on the distance L between source and target. Indeed, the neutron flux will decrease in proportion to the solid angle which decreases with increasing L. This decrease will be compensated by an increase of neutron flight time with increasing L. (We assume that the size of the neutron source and the size of the annihilation target are sufficiently large and fixed by practical constraints.) Use of a focusing reflector which concentrates neutrons on the target is an efficient way that can dramatically improve the discovery potential.

2. Large Focusing Mirror Reflector

The large focusing mirror reflector proposed for our experiment is a further development of the idea of neutron beam focusing used in an experiment [4 and 9] at ILL-Grenoble, which allows the optimization of both N and t. Indeed, if the neutrons emitted from the source within a fixed solid angle around the beam axis can be focused onto the target, the solid angle reduction with increase of L is eliminated and L in the experiment can be chosen as large as practically possible, thus enhancing the discovery potential via the increase of $t^2 = L^2 / V^2$ (V is the neutron velocity). Since the unperturbed coherence of n and $\bar{n}$ wave functions is required [10] for the unsuppressed transition, any scattering, including focusing scattering in the mirror reflector, will "reset the clock" which counts t^2. Therefore, the focusing scattering should occur as close to the source of neutrons as possible. Qualitatively the discovery potential can be expressed as

$$\text{D.P.} \sim A_{\text{mod}} \cdot \Delta\Omega \cdot L^2 / T_n , \qquad (2)$$

where A_{mod} is the effective luminous area of the cold moderator, $\Delta\Omega$ is the solid angle effectively intercepted by the focusing reflector, and T_n is the temperature corresponding to the average energy of the neutron spectrum. Only those neutrons within $\Delta\Omega$ with transverse velocity components at reflection point $< V_{\text{crit}}$ are reflected. Practically, V_{crit} can be in range of ~5–7 m/s [11]. This fraction will increase when the neutron spectrum temperature T_n is lowered. In addition, when T_n is lowered, the solid angle $\Delta\Omega$ can be increased by reoptimization of the shape of the focusing mirror to accept larger incident angles for reflection. Thus, the distance L and the neutron spectrum temperature T_n are the most effective parameters to increase the discovery potential of the experiment. A_{mod} will be maximized if the focusing reflector installed close to a cold moderator and is of the type similar to the one with a large luminous area proposed for the ANS reactor [12]. The proposed experimental setup for HFIR is shown schematically in Figure 1.

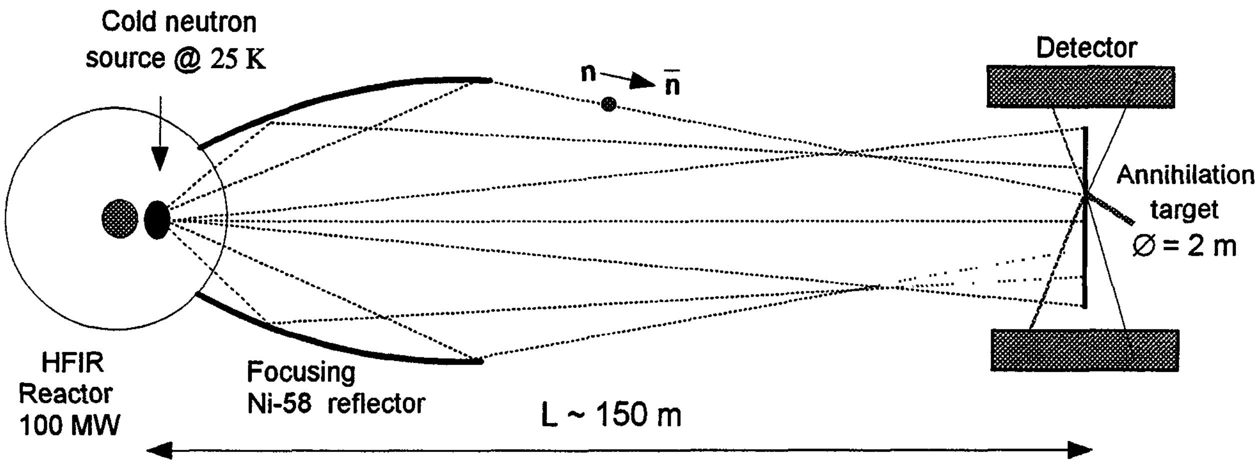

Fig. 1 Conceptual layout of nn̄ - search experiment proposed for Oak Ridge HFIR reactor (not to scale)

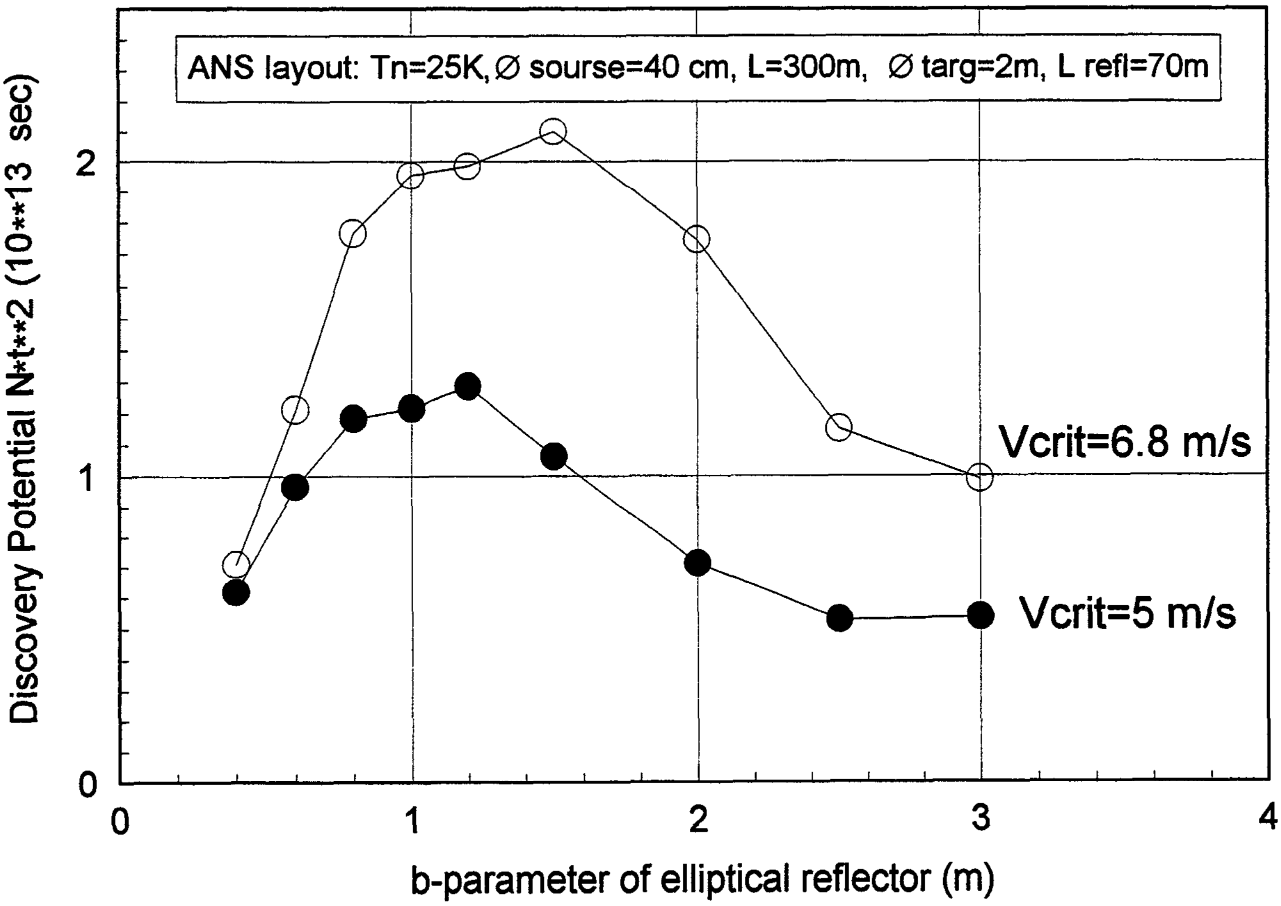

Fig. 2 Monte Carlo optimization of b-parameter of elliptical reflector

When large L and low T_n values are used, the effects of gravity play an important role in neutron propagation. To simulate accurately all of the above-mentioned effects and parameters, we have developed a Monte Carlo code for the neutron transport. In the Monte Carlo procedure, neutrons originated in a cold moderator with spectra deduced from more detailed simulations [13]. The radial variation of the effective temperature of neutrons produced in the cold moderator was taken into account. Neutrons emitted from the surface of the cold moderator were propagated in the gravitational field through the focusing mirror reflector, experiencing reflections when appropriate conditions were satisfied. Various focusing reflector shapes were tried (conical, parabolic, cylindrical). The best results were obtained with an ellipsoidal reflector where the cold moderator was positioned at one focus of the ellipsoid and the annihilation target was placed at the other focus. In the simulations the reflector typically started at ~3 m from the center of the cold moderator and extended to a distance of 50-100 m, while the distance to the annihilation target was in the range of 150-300 m. Simulated data were normalized to the expected flux of cold neutrons obtained from more detailed simulations of the reactor-cold moderator system [13]. Figure 2 shows the discovery potential versus parameter b (b is the small half-axis of the ellipsoid) simulated by the Monte Carlo program for two different assumptions of reflector coating in the scenario of the ANS experiment. At the optimum, the discovery potential of $D.P. = N \cdot t^2 \sim 2 \cdot 10^{13}$ s corresponds to the maximum diameter of the ellipsoid tube of 2–2.4 m. Similar calculations were performed for different possible options of a HFIR-based experiment, depending on various scenarios of reactor upgrade. These options with corresponding discovery potential gains are described in Table 1. The maximum discovery potential gain at HFIR can be obtained when cold neutron moderators are used. We assumed that either the solid methane moderator (pellet technique as was discussed in [14] at this meeting) or a large-size liquid deuterium moderator (design developed for the ANS [12]) can be implemented at HFIR.

Table 1. Experimental Options for Neutron-Antineutron Transition Search. The discovery potential of ILL-Grenoble reactor experiment was taken as 1. All HFIR-based experiment options are assumed to have a horizontal layout. SCNM stands for super-cold neutron moderator as explained below in the text.

1	Neutron source	Neutron moderator	Discovery potential gain for one year of operation
2	ILL'94 *completed experiment*	Liq D_2 @ 25 K	× 1
3	ANS *discontinued project*	Large Liq D_2 @ 25 K	× 13,000
4	HFIR *present*	Be @ 342 K	× 50
5	HFIR *present*	Small CH_4 @ 20 K	× 300
6	HFIR modified *with new Be reflector*	Large CH_4 @ 20 K	× 1000
7	HFIR upgraded *with D_2O reflector*	Large Liq D_2 @ 25 K	× 5,000
8	HFIR upgraded *with D_2O reflector*	SCNM @ 1 K	× 23,000
9	5-MW spallation source *horizontal layout*	SCNM @ 1 K	× 10,000
10	5-MW spallation source *vertical layout*	SCNM @ 1 K	× 80,000

In Table 2 a more detailed comparisons of the parameters of one of the HFIR-based experiment options (HFIR upgraded with a D_2O reflector and with a large liquid-deuterium source of the ANS type) with those of the experiment [4] performed at ILL-Grenoble are given. Also shown in the table are the parameters of an experiment proposed for the discontinued ANS project and those of an experiment proposed at ORNL in 1982 for the ORR reactor [15].

Table 2. Comparison of neutron-antineutron search experiments. The upgraded HFIR configuration shown in this table corresponds to the option of row 7 in Table 1.

Neutron source	ILL' 94	ORR' 82	ANS	HFIR (upgraded)
Status	Completed experiment	Rejected proposal	Discontinued project	New proposal
Power (MW)	57	30	330	100
Max. thermal neutron flux (n/cm2/s)	$1.5 \cdot 10^{15}$	$(7 \cdot 10^{13})$	$7 \cdot 10^{15}$	$2 \cdot 10^{15}$
Moderator	Liq. D_2 @ 25 K	D_2O @ 300 K	Liq. D_2 @ 25 K	Liq. D_2 @ 25 K
Source area	6x12 cm^2	Ø 42 cm	Ø 40 cm	Ø 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
Run time (s)	$2.4 \cdot 10^7$	$3 \cdot 10^7$	$3 \cdot 10^7$	$9 \cdot 10^7$
Discovery potential $N \cdot \langle t^2 \rangle$ (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 discovery potential for the HFIR-based option shown in Table 2, for three years of operation, would be a factor of ~10,000 higher than the discovery potential of the completed experiment at the ILL-Grenoble reactor [4]. This factor is made up of the following contributions: higher reactor power (x 1.75); larger cold source area (x 16); larger detector area (x 3.3); focusing reflector and optimized layout (x 50); and three years of running time (x 3). Advantages of the focusing reflector are clearly seen in Table 1, where a considerable gain is indicated even for the option without a cold moderator (row 4).

3. Colder Sources of Neutrons?

As we saw from formula (2) and from the discussion thereafter, a cold neutron moderator allowing the lowest possible temperature, T_n, of the neutron spectrum would be the most advantageous for an increase of the discovery potential of the $n \rightarrow \bar{n}$ search. In previous discussions we assumed that in large-size moderators, neutrons can be thermalized down to the temperature of the moderator substance (~25K). This assumption may not be valid, even for such well-studied systems as liquid deuterium moderators, and needs more careful comparisons of detailed Monte Carlo simulations with measured neutron spectra. The situation is even less clear if the temperature of the moderator is lowered to helium temperatures. All moderators of practical interest, except helium proper, (i.e., D_2, H_2, CH_4, and CD_4) are solid at these temperatures. Inelastic scattering of cold neutrons with excitation of translational and vibrational modes of the moderator media plays an important role in the moderation process, while elastic scattering becomes less efficient when the neutron wavelength exceeds interatomic distances in the moderator.

Although a considerable amount of experimental and theoretical information on cold moderators can be found in the literature, the following question remains unanswered both at an experimental level and at the level of simulations: *what is the lowest temperature that the neutron maxwellian spectrum can be moderated to?* The answer to this question can open new possibilities in the search for $n \rightarrow \bar{n}$ transitions. If we assume that a super-cold neutron moderator (SCNM) can be build (for example, based on deuterium or methane pellets [14] immersed in super-fluid helium-4) with neutron spectra thermalized down to 1K, a further gain in the discovery potential can be obtained as indicated in row 8 of Table 1. The average velocity of 1K neutrons is about 150 m/s and, in ~150-m-long horizontal layout of a possible experiment, the gravity effect would modify the trajectories of the neutrons and substantially destroy the focusing effect of the elliptical reflector. A vertical layout of the experiment would minimize the negative effects of gravity and would allow the use of the full advantage of a SCNM in the $n \rightarrow \bar{n}$ search. It is rather unlikely that a long vertical layout can be used in the reactor environment where many services and safety features are located in the lower part of the reactor. A vertical layout is, however, suitable for an experiment designed for the spallation neutron source (SNS). Table 1 shows the discovery potential gain for both a horizontal (row 9) and a vertical (row 10) layout of the experiment, based on 5-MW SNS. In the calculations it was assumed that the maximum thermal flux for a 5-MW SNS will be as high as ~ $1 \cdot 10^{15}$ n/cm2/s.

4. Conclusions

We have shown that with existing and future generation of neutron sources, it is possible to increase the discovery potential of the $n \rightarrow \bar{n}$ search by 3 to 4 orders of magnitude relative to present experiments. The key element of the proposed setup is a large focusing reflector installed close to the cold moderator. Further increases of the discovery potential will be possible if neutrons can be moderated down to lower temperatures (ultimately to 1K) with a super-cold neutron moderator. Whether this is a practical future option remains to be demonstrated both experimentally and via simulations.

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