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Short version of 2006 NSF DUSEL R&D Proposal for

Feasibility Study of NNbar Experiment at DUSEL

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Summary

This proposal by the group of several Universities and ORNL addresses the feasibility of a new "NNbar" experiment to search for transitions of neutrons to antineutrons at the Deep Underground Science and Engineering Laboratory (DUSEL). Observation of neutron to antineutron transitions in vacuum or the transformation of baryonic matter to antimatter will be a momentous discovery of a new force of Nature with fundamental impact on particle physics and cosmology, providing contribution to the possible explanation of matter-antimatter asymmetry of the universe. The same interactions that are responsible for the small masses of neutrinos can cause the $n \to \overline{n}$ transitions. Existence of $n \to \overline{n}$ might be also a manifestation of low quantum gravity scale effects and, thus, can provide a first experimental indication of the presence of extra-dimensions in Nature. The N-Nbar experiment will require a source of cold neutrons from a 3.5 MW TRIGA reactor, installed on top of a vertical shaft of ~1-km depth. The antineutron detector will be located at the bottom of the shaft. One of the vertical shafts available at DUSEL sites can be used for this experiment or a new shaft can be constructed. To keep the neutron and antineutron states degenerate (as required for unsuppressed transition) good vacuum should be provided in the flight tube and the Earth magnetic field should be canceled by the shielding system down to residual field of ~ 1 nT. Sensitivity of experiment will be essentially enhanced by the large neutron focusing reflector and the vertical layout; the latter compensates for the disturbing effect of Earth gravity. Although all the components of the proposed technique are known and tested at the small scales, the construction of experiment in a long vertical shaft at DUSEL in combination with the requirements for good vacuum, high intensity of cold neutrons, and the absence of magnetic field might be a challenging engineering task. The goal of the proposal is to perform engineering and technical studies, identify and address possible showstoppers, and estimate the cost in the proposed scheme of experiment that could prove the feasibility of NNbar search at DUSEL.

Proposed DUSEL facility with vertical km-long magnetically-shielded and evacuated tube can be also used for other fundamental physics experiments: (a) for search of matter to mirror matter transitions ($n \to n'$) and (b) for gravitational atomic interferometry for general relativity tests and detection of gravitational waves. Also, the reactor at DUESL site will be available for multiple purpose uses such as production of radioisotopes for detector calibration. The results of this R&D work will be disseminated through peer-reviewed publications and a physics community workshop.

Physics motivation

A major focus of research in particle physics is the search for new laws of nature that govern physics beyond the Standard Model. The discovery of neutrino mass has provided the first evidence for new laws since the Standard Model predicts that neutrinos are massless. While much remains to be discovered concerning the nature of the neutrinos, it now seems clear that the masses of all the neutrinos are in the sub-eV range. These values for the neutrino masses are considerably smaller than the masses of the quarks and the charged leptons. The simplest and most elegant way to understand such a tiny neutrino mass scale is to assume that it is its own anti-particle (a Majorana fermion), a possibility that is allowed since the neutrino is electrically neutral. This possibility is incorporated in the seesaw mechanism [1] postulates the existence of a right-handed neutrino with a large Majorana mass. This causes the light neutrino to have a tiny mass. A sub-eV neutrino mass requires that the mass of the right-handed neutrino be in the range of 10^{11} to 10^{15} GeV. The Majorana mass of the right-handed neutrino breaks the B–L (baryon number minus lepton number) symmetry of the Standard Model. The breaking of this B–L symmetry causes the neutrino to be its own anti-particle. As noted, this symmetry breaking would occur at an extremely high energy scale. Both the size of this new scale and the additional physics associated with this symmetry breaking then become important questions. Since B–L also involves baryon number a search for baryon number non-conserving processes would provide a sensitive probe of this new physics.

Two key baryon number violating processes are proton decay and neutron-antineutron (N-Nbar) oscillations. The first one probes the grand unified theories which can embed the seesaw mechanism if the seesaw scale is around 10^{15} GeV and generically conserves B–L symmetry. On the other hand, if the seesaw scale is around 10^{11} GeV or lower, the neutron-antineutron oscillation becomes the key signature. To see the connection between neutrino mass and N-Nbar oscillation, note that if the neutrino is indeed a Majorana fermion, it would be an indication of a violation of B–L by 2 units, which for neutrinos is simply ΔL=2. It also implies that there ought to exist processes that correspond to the other part of this selection rule i.e. ΔB=2, which is the process of N-Nbar oscillation. Thus, a search for N-Nbar oscillation will complement proton decay searches in the attempt to understand the high-energy scale physics connected with neutrino mass.

Another powerful argument for N-Nbar oscillations comes from the attempts to understand the origin of matter in the universe. It has long been realized since the classic work of Sakharov [2] that a key requirement for understanding the dominance of matter over anti-matter in the universe is the presence of baryon violating interactions. Sakharov's scenario does not specify the mechanism of baryon number violation or shed any light on the question whether this violation would produce proton decay or N-Nbar oscillations. However, it was pointed out in the early 80's [3] that in the hot universe at temperatures above ~10 TeV the Standard Model electroweak interactions conserving B–L at thermal equilibrium (sphaleron transitions) would violate baryon, lepton, and B+L numbers with the rates exceeding the rate of inflation. Therefore any baryon asymmetry that would be generated at earlier epochs (T >> 10 TeV) by B–L conserving interactions would be erased by the sphalerons. Thus, in order to understand the baryon asymmetry, the physics in the early universe must break B–L symmetry. This adds additional credibility to the seesaw models that provide such interactions. N-Nbar transitions violating B–L therefore have also additional strong potential to throw light on the question of the origin of the matter-antimatter asymmetry in the universe.

Despite an intense experimental effort in the last three decades, proton decay has not been observed, thus ruling out the original SU(5)-based Grand Unification model (GUT) [4] and severely restricting SUSY-extended GUT models [5]. Since the SU(5) model conserves B–L symmetry, it also cannot explain the baryon asymmetry of the Universe (BAU). Searches for baryon-lepton instability with the violation of (B–L) should be more directly related to the possible explanation of BAU. These include searches for (a) non-traditional (B–L) violating nucleon decay (for example, $n \to \nu\nu\bar{\nu}$) with Δ(B–L) = 2, (b) neutrinoless double-beta decays with ΔL = 2, and (c) a most spectacular process of neutron to anti-neutron transition with ΔB = 2. The last process has an unambiguous signature (a star pattern of pions with ~2 GeV total energy) and can be searched for in an experimentally controlled environment with zero background. With existing techniques the sensitivity of $n \to \bar{n}$ search can in principle be increased by a factor of $\gtrsim$1,000 compared to previous $n \to \bar{n}$ searches (the latter with

cold neutrons at ILL/Grenoble reactor [6] and with neutrons bound inside nuclei in Soudan-II experiment [7]). This proposal addresses the possibility of a new experiment for $n \to \bar{n}$ search at the DUSEL laboratory.

The concept of $n \to \bar{n}$ transitions was first proposed [8] as a possible explanation of BAU and was developed within the framework of the unification models in [9]. In ref. [9], it was pointed out that there is an intimate connection between the seesaw scale and $n \to \bar{n}$ oscillations in the context of Pati-Salam type models. In non-supersymmetric versions of these models $\tau_{NNbar} \propto M_{Seesaw}^5$, where τ_{NNbar} is the characteristic transition time for $n \to \bar{n}$ oscillation, and only for $M_{Seesaw} \sim 10^5 GeV$ or below does the oscillation time fall into an experimentally observable range. Clearly if the seesaw scale in such models is around 10^{11} GeV then $n \to \bar{n}$ oscillations would be unobservable. A major recent theoretical development in this area is that once the above model becomes supersymmetric, despite the fact that the seesaw scale is high, there are two factors that lead to a much weaker dependence of τ_{NNbar} on M_{Seesaw} i.e. like a square rather the 5th power: (i) first are the accidental symmetries brought on by supersymmetry and (ii) new Feynman diagrams involving super-partners of particles [10]. This weakening dependence on M_{Seesaw} makes $n \to \bar{n}$ transitions in such models observable at the level of sensitivity achievable in the next generation of experiments. Furthermore, it has also been shown that one can then completely understand the baryogenesis using only the $n \to \bar{n}$ generating interactions [11,12] without the need for sphalerons.

There is also a possibility to understand $n \to \bar{n}$ transitions in other theoretical contexts such as extra dimensional models [13,14] where new physics emerges from lower energy scales. An example is the class of models with a low quantum gravity scale where unification occurs at ~100 TeV. In these models additional theoretical mechanisms must be introduced to suppress proton decay that otherwise occur at an unacceptable rate. Most of the suppression mechanisms proposed so far leave $n \to \bar{n}$ transitions unaffected. In particular, authors of Ref. [13] considered a general mechanism of non-conservation of global charges in a brane universe with large extra dimensions. Baryon or lepton number conservation can be violated inside the "baby-branes" (black holes) created by quantum fluctuations of 3-dimensional vacuum into an extra dimension. Since all Standard Model interactions live in a 3+1 dimensional brane, only iso-singlets of the Standard Model (like n_R or ν_R) can be taken away from the brane into the black hole where global charge (baryon or lepton number) can be violated. In this model baryon number violation cannot occur via proton decay and the only particles that practically can contribute to the violation of baryon or lepton charges are n_R and ν_R. While the question of the existence of a neutral right-handed particle, Majorana neutrino, is still a subject of intensive experimental search, the right-handed component of the neutron n_R is a part of the Standard Model and ready available for experiments. From this point of view the observation of $n \to \bar{n}$ transition could be used as a probe of the nature of extra dimensions. It is interesting to note that the lowest order observable $n \to \bar{n}$ operators would exist at an energy scale of ~ 100 TeV (close to unification scale in low quantum gravity models). Observable transitions $n \to \bar{n}$ are also discussed in other recent theoretical papers [15,16] within the context of extra-dimensional models.

Oscillations are known to occur in nature with other neutral particles: neutrinos and neutral mesons (e.g. K^0, B^0). The observation of oscillations in these systems has yielded information on aspects of physics (lepton flavor violation, CP and T-invariance violation, neutrino mass) that are not accessible using less sensitive techniques. It is reasonable to hope that a search for oscillations with the neutron, the only neutral baryon sufficiently long-lived to conduct a practical experiment, may uncover new processes in nature.

Previous studies and developments

Probability of free $n \to \bar{n}$ oscillations in vacuum is proportional to the square of t neutron observation time: $(t/\tau_{free})^2$, where τ_{free} is the characteristic free neutron oscillation time. Oscillation probability is also a sensitive function of the ambient magnetic field and density of the residual gas, each leading to the oscillation damping. For the neutron observation time of 1 s the Earth magnetic field must be screened down to nanoTesla level and the residual gas pressure in the vacuum volume should be better than 10^{-4} Pa in order to keep damping negligible. The best experimentally established [6] limit on the $n \to \bar{n}$ oscillation time in vacuum is $\tau > 8.6 \times 10^7 s$, which is essentially

larger than a free neutron lifetime. Therefore it is more appropriate to discuss $n \to \bar{n}$ appearance transitions rather than oscillations.

Transitions $n \to \bar{n}$ have been also sought inside nuclei for bound neutrons. Highest limit is obtained here by Soudan-II collaboration [7]. Intranuclear transitions are heavily suppressed due to large difference of nuclear potential for neutron and antineutrons [17] with probability of transition reduced down to usual t/τ_A (exponential law) where τ_A is a nuclide A lifetime in respect to intranuclear $n \to \bar{n}$ transition. This τ_A is related to τ_{free} as $\tau_A = R \cdot \tau_{free}^2$, where R is intranuclear suppression factor of the order of 10^{23} s^{-1} known from nuclear theory with the accuracy about factor of 2 [17]. Thus, for example, the limit of Soudan-II [7] experiment $\tau_{Fe} > 7.2 \times 10^{31}$ years is equivalent to free vacuum transition oscillation time $\tau_{Free} > 1.3 \times 10^8 s$. This clearly demonstrates the advantage of free neutron transition compared to intranuclear search in the exploration of the stability of matter where increase of sensitivity of free neutron transition in vacuum, say, by two orders of magnitude would provide an increase in the probability of appearance of the transition by factor of 10,000.

There was an extensive discussion of the possibility for a new $n \to \bar{n}$ search in the Physics Study group at Snowmass in July 2001. The idea of a new $n \to \bar{n}$ experiment was also favorably mentioned by the NP NSAC Long Range Plan Committee Study in the White Paper of "Astrophysics, Neutrinos and Symmetries" town meeting at Oakland in November 2000 (pp. 41-42). These and other documents related to $n \to \bar{n}$ searches can be found at [18].

In the HEPAP Subpanel Report on the Long-Range Planning for US HEP (January, 2002, page 21) the idea of an $n \to \bar{n}$ experiment was mentioned in the following way:

"Very rare processes provide additional probes of quarks and lepton flavor physics. They can offer important insight into the nature of physics at the unification scale, far beyond the reach of accelerators. For example, the observation of proton decay or neutron-antineutron oscillations would point toward grand unification, with profound implications for our understanding of matter, energy, space and time. Proposals for both types of experiments are being prepared."

In 1994-1995 a new high-sensitivity approach to a $n \to \bar{n}$ experimental search was proposed using a horizontal cold neutron beam from the high-flux research reactor HFIR at Oak Ridge National Laboratory [19]. A high sensitivity $n \to \bar{n}$ search could be achieved at HFIR by a combination of its high thermal flux, a cold neutron moderator, in combination with an elliptical focusing reflector [20] concentrating cold neutrons onto the target. However the HFIR reactor, which is operated in the US by BES office of DOE, is not available for fundamental physics experiments.

Several workshops have been organized by the authors of this proposal or with their participations where the physics of $n \to \bar{n}$ was discussed and different methods of $n \to \bar{n}$ transition search were addressed. Oak Ridge workshop in 1996 [21] was focused on HFIR-based experiment with horizontal layout and geo-chemical methods. At 2002 workshops at Indiana University [22], and in 2003 at PNPI [23] the possibility of $n \to \bar{n}$ search with ultracold neutrons was explored. At workshop at South Carolina in 2005 [24] possibility of vertical layout of NNbar experiment was discussed with the fundamental physics neutron community.

To increase the time of observation of the neutron one needs to slow down the neutrons. For the case of a horizontal beam of neutrons gravity becomes an important perturbation to the motion of cold neutrons. We therefore propose a vertical layout for the NNbar experiment (compensating for the defocusing effect of gravity) with a small dedicated research reactor and a liquid deuterium moderator as the source of cold neutrons. The low power density of the smaller reactor may also allow in the future the use of new types of very cold neutron moderators, which could further reduce the average neutron speed. Such vertical layout at DUSEL can provide a sensitivity exceeding the sensitivity of the horizontal experiment proposed for HFIR. The sensitivity here can be a factor of >1,000 higher than in the previous best $n \to \bar{n}$ search experiment [6], which established a limit for $n \to \bar{n}$ oscillation time of τ_{free} > 8.6×10^7s. The possibility of a large increase in sensitivity of the experimental search for $n \to \bar{n}$ transitions is a central motivation for this Proposal.

Brief description of proposed experimental method

The conceptual idea of a vertical N-Nbar experiment proposed for the DUSEL (Figure 1) includes a dedicated 3.4 MW standard research reactor (Figure 2) of TRIGA type [25] (to be purchased from

General Atomic Company) as a neutron source. This unique reactor possesses an annular core with a vertical through tube for convenient insertion of a cold neutron moderator and extraction of the cold neutrons. To reach maximum sensitivity in an $n \to \bar{n}$ search, the neutrons should be cooled to the lowest possible temperature (average velocities < 1,000 m/s) using a cold moderator and maintained in free flight as long as possible ($\gtrsim$1s). The reactor should be installed at the top of a vertical mineshaft of $\gtrsim$ 1 km depth with a diameter of a few meters. The experiment requires a large elliptical focusing reflector [20] with the cold source at one focus that intercepts neutrons in a wide solid angle and directs them along 1-km vacuum flight path onto the annihilation detector located in the second focus of ellipsis. Since cold neutron source is not a point-like source one cannot talk about exact point-to-point focusing in this case but rather about broad enhancement of neutron flux at the large-diameter target. The vertical layout of the flight path is a solution of the problem of gravity effect on the most valuable slow neutrons that keeps the latter from striking the vacuum walls during the observation time and yielding dramatic improvement of sensitivity of $n \to \bar{n}$ search.

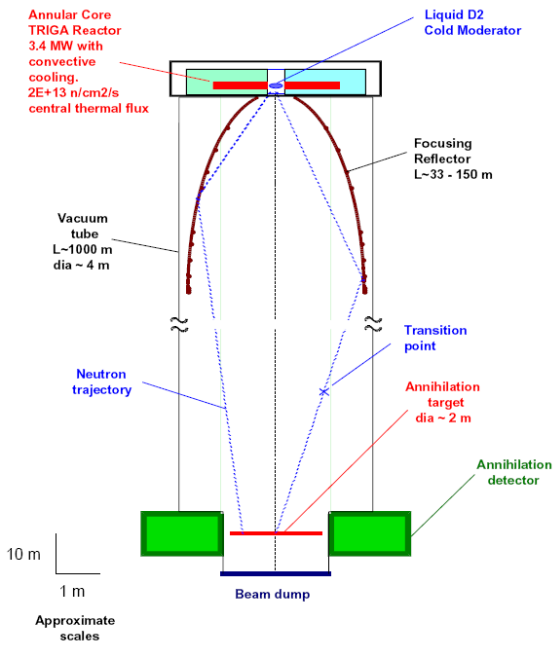

Figure 1. Schematic view of the vertical N-Nbar experiment.

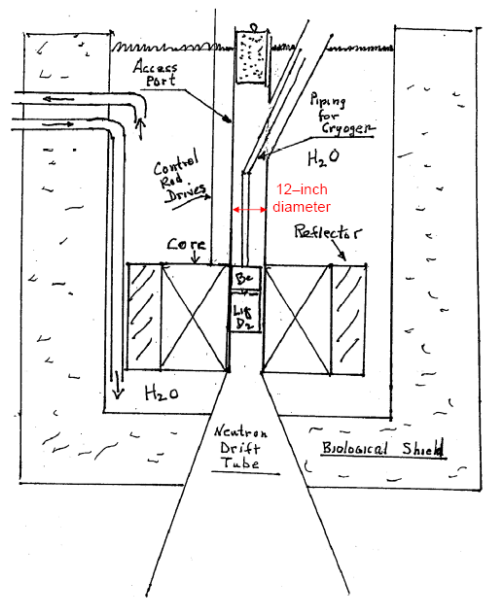

Figure 2. Schematic drawing of the TRIGA reactor with thermal water convection, annular core and 12-inch throughout vertical tube (courtesy of General Atomics, W. Whittemore).

A focusing neutron reflector will be installed inside the vertical vacuum chamber. The vacuum chamber should have a vacuum better than 10^{-4} Pa. The Earth's magnetic field inside the vacuum chamber needs to be shielded along the 1- km flight path by active and passive magnetic shields down to the level of a few nano-Tesla. Requirements similar to these have been achieved in the previous ILL/Grenoble-based experiment [6]. The magnetic field seen by the neutrons in the apparatus could be periodically checked in situ when necessary by polarizing the neutrons via transmission through polarized ^{3}He gas near the moderator and then measuring the precession angle of the neutrons in the magnetic field using a polarized ^{3}He polarization analyzer at the conversion foil. Antineutrons will be detected by an antineutron annihilation detector located in the experimental hole at the bottom of the mineshaft. The proposed antineutron detector (Figure 3) could be similar to one used in the experiment [6] at the ILL/Grenoble reactor: a thin 130μm carbon foil with diameter ~ 2 m can serve as the antineutron annihilation target. This target is viewed through the cylindrical walls of the 2.2-m diameter vacuum chamber by a tracking detector that reconstructs the annihilation star of several pions to the position of the carbon-film target, thus providing excellent discrimination against background events (which are mostly due to cosmic ray interactions). The tracker would be surrounded by a calorimeter, a cylindrical detecting layer that measures the energies of the annihilation products (these are in the form of a stars of 5 pions per annihilation) and provides a

trigger signal for readout. The calorimeter can be surrounded by a scintillator veto system against cosmic ray-induced events.

The sensitivity of the $n \to \bar{n}$ search experiment is proportional to the flux of neutrons through the annihilation target and the square of the time-of-flight through the vacuum path without magnetic field from the location of last scattering in matter (source or reflector) to the target. According to our simulations (Figure 4) in the proposed experimental scheme after ~3 years of operation the sensitivity of the $n \to \bar{n}$ search can be a factor of > 1,000 higher than in the previous experimental search at ILL/Grenoble reactor [6] due to the very long flight path and the focusing neutron reflector. Focusing reflector allows taking the advantage of sensitivity increase proportional to the square of the flight distance and further increases the sensitivity when neutron beam temperature is lowered. With a "zero-background" detector and with the very distinctive signature of $\bar{n}$ annihilation, <u>even one observed event would constitute a discovery.</u> If no events were observed after three years of measurements it would correspond to a new limit on the stability of matter, $\gtrsim 10^{35}$ years a goal that cannot be obtained in the intranuclear search with large underground detectors. To our knowledge, no other practical schemes or approaches for $n \to \bar{n}$ search exist with a comparable sensitivity.

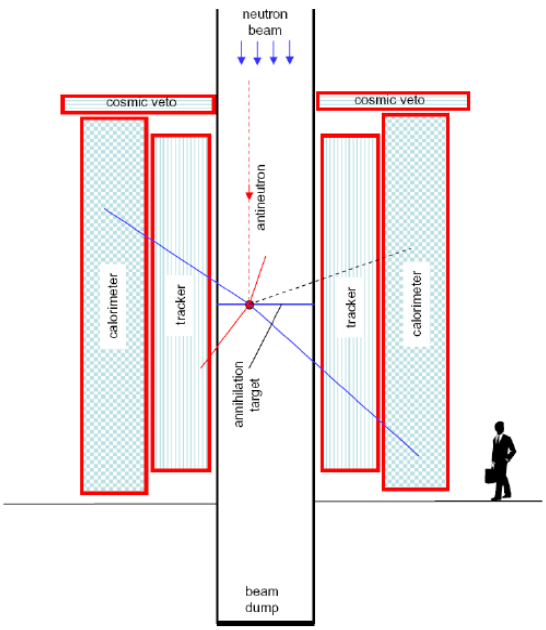

Figure 3. View of generic antineutron annihilation detector similar to one used in ILL/Grenoble experiment [6].

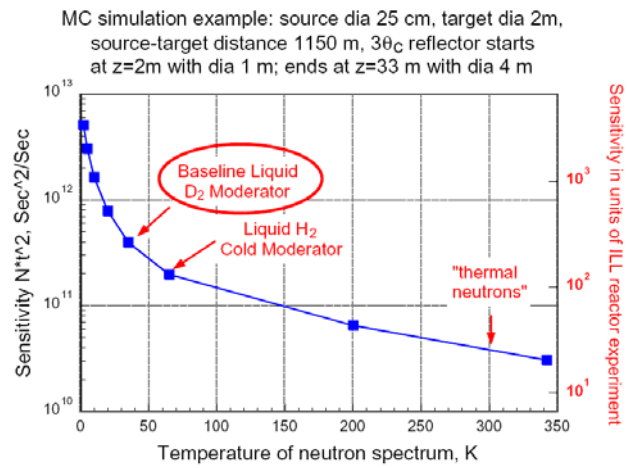

Figure 4. Monte Carlo simulation of the sensitivity of N-Nbar search experiment in terms of $N{\cdot}t^2$ (flux of cold neutrons through annihilation target times average time square of the free time-of-flight in vacuum) vs temperature of the neutron spectrum. Sensitivity is also shown in the units of sensitivity of the previous ILL/Grenoble-based N-Nbar search experiment [6] where sensitivity $N{\cdot}t^2$ was $1.5{\times}10^9$ n·sec^2/sec and experiment running time was ~1 year.

Table 1 compares the different sensitivities for $n \to \bar{n}$ search by known experimental methods [26]. The sensitivity of the previous cold neutron beam experiment [6] (at ILL/Grenoble) and the approximately equivalent sensitivity of intranuclear search in the Soudan-II experiment [7] correspond here to unity.

Goal of proposed studies

In our Letter of Interest presented to the DUSEL collaborations [27] we emphasized that DUSEL infrastructure and facilities provide a unique possibility to realize the NNbar experiment and to conduct a new search that can lead to a momentous discovery in science with substantial impact on the high-energy particle physics and cosmology. All conventional and neutron research technologies required for NNbar-experiment exist or have been proven at the small scale of applications. Previous $n \to \bar{n}$ search with free neutron in vacuum performed with horizontal layout at the ILL/Grenoble reactor [6] can be considered as a prototype of the proposed NNbar experiment with flight tube of ~ 10% scale. However, there are several aspects of the proposed scheme that require additional study for the

DUSEL implementation. Program Advisory Committee of the Homestake Collaboration expressed [28] such considerations in the following way:

"The Program Advisory Committee finds this proposal of significant scientific merit, and endorses consideration as a long-range possibility for DUSEL. For the Early Implementation Program, the PAC recommends the engineering and feasibility studies needed to develop a full proposal and technical design in approximately 5 years. In particular, the PAC agrees with the proponents that serious infrastructure questions must be addressed: identifying a suitable vertical shaft (or costing the construction of a new one), engineering km-long magnetic shielding to the level of nanoTesla, vacuum to 10^{-4} Pa, and numerous additional considerations related to locating a 3MW research reactor on the surface at Homestake. Issues like safety, licensing, security, and backgrounds to other experiments need to be considered." The PAC also encouraged us to work with DUSEL Laboratory to address these serious questions.

This is the goal of the current proposal to perform recommended engineering and feasibility studies, identify and address possible showstoppers, and estimate the cost in the proposed scheme of experiment at DUSEL. Detailed description of the proposed activities is given below.

Table 1. Present and possible future sensitivities of different methods of $n \to \bar{n}$ transition search

Method	Present limit	Possible future limit	Possible sensitivity increase factor
Intranuclear [7, 22] (N-decay expts)	$7.2 \cdot 10^{31}$ yr ≈ 1unit Soudan II	$7.5 \cdot 10^{32}$ yr (Super-K) $4.8 \cdot 10^{32}$ yr (SNO)	× 16
Geo-chemical method [21]	None	$4 \cdot 10^{8} \div 1 \cdot 10^{9}$ s (Tc in Sn ore)	× 20 –100
UCN trap [22,23] (6×10^{7} ucn/sec)	None	~ $1 \cdot 10^{9}$ s	× 100
Cold horizontal beam [19, 26]	$8.6 \cdot 10^{7}$ s = 1unit @ILL/Grenoble	$1 \cdot 10^{9}$ – $3 \cdot 10^{9}$ s (e.g. @HFIR/ORNL)	× 100 –1,000
Cold Vertical beam [24,27]	none	$3 \cdot 10^{9}$ – $1 \cdot 10^{10}$ s (DUSEL)	× 1,000 –10,000

Multiple use of vertical tube facility at DUSEL

Proposed DUSEL facility with vertical km-long magnetically-shielded and evacuated tube can be also used for other fundamental physics experiments: (a) for search of matter to mirror matter transitions ($n \to n'$) [29] and (b) for gravitational atomic interferometry used for general relativity tests and detection of gravitational waves [30].

Participants

Our NNbar collaboration is a group of scientists and educators from Universities with substantial record of participation and experience in high-energy physics, neutron science, neutron interactions, underground physics, reactor physics, and long-tern studies of various aspects of NNbar search. Our group includes: Young, Hawari and Wehring from North Carolina State University (NCSU), with expertise and capabilities in the design and utilization of research reactors and cold neutron sources and the fundamental development of thermal neutron scattering kernels; Snow from Indiana University (IU), particle physicist with experience of neutron measurements in nuclear, particle, and condensed matter physics, including measurement of the Bose condensate fraction in superfluid ^{4}He using neutron scattering, measurement of the neutron lifetime using a Penning trap, development of neutron polarizers and analyzers based on transmission through polarized ^{3}He gas, measurements of neutron coherent scattering lengths of H, D, and ^{3}He using neutron interferometry; he conceived of and helped developed the initial ideas for the LENS neutron source at Indiana/IUCF and is involved in the design and construction of a neutron spin echo spectrometer at LENS and a test beam for investigation of new materials for neutron cooling; Kamyshkov from University of Tennessee (UT), high-energy

physicist with experience in integration of large systems: 300-t uranium calorimeter in experiment L3 at LEP, calorimeter system in GEM/SSC, in coordination of multi-directional R&D: calorimeter options studies for SSC/LHC hadron colliders at ITEP/Moscow in 1990, in underground physics at KamLAND, with more than a dozen of years experience of study NNbar transitions for possible implementation at ANS and HFIR reactors at Oak Ridge National Laboratory and at DUSEL; Bugg, UT Emeritus Professor, high-energy physicist and long-time enthusiast of $n \to \bar{n}$ search; Dodds from UT Nuclear Engineering, with experience in nuclear reactor analysis, design, safety, and nuclear engineering education; Ganezer from California State University at Dominguez Hills (CSUDH), with experience of participation in Super-Kamiokande experiments and search for intranuclear $n \to \bar{n}$ transitions; Mei young faculty from the University of South Dakota (USD), with experience of KamLAND participation and study of cosmic ray interactions and backgrounds in underground experiments, and Keller (USD) theoretical physicist and Pfiffner (UT) microbiologist, both with experience in education and outreach.

We propose to work with engineers and consultants at DUSEL sites, with engineers from LBNL, and with experts and engineers from participating Universities. Also, we will use services of two private companies: General Atomics (manufacturers of TRIGA reactors, with partially paid services) and CNA (paid services for conventional and underground engineering.) These engineers and experts will work in a close interaction with project scientists who will define the major parameters of the proposed experiment and provide corresponding physics simulations of the expected performance. Role of engineer and experts will be to address by technical studies the feasibility and cost of the scheme of experiment proposed by scientists and in defining potential technical and cost showstoppers. At this stage of the project engineering work will be concentrated on the studies of feasibility and showstoppers in various sub-systems. We anticipate that after the feasibility study at the following stages of the experiment development more detailed “system approach” will be needed for integration of engineering efforts together with comprehensive interactive optimization of expected performance of the experiment as function of all essential parameters and cost.

We also plan to use expertise and experience of the people who will work with us on this project as free participants and consultants: West (Former Director of ANS reactor project at ORNL and former Director of HFIR reactor upgrade program), Green (UT Professor, Project leader of Fundamental Neutron Physics beam at SNS), Serebrov (Head of Neutron Physics Division at St. Petersburg Nuclear Physics Institute, Russia), Weiss (MIT, vacuum expert of LIGO experiment), and Roggenthen (SDSMT South Dakota School of Mines and Technology). Supplemental section of the proposal contains Letter of Interest and other information describing activity of the participants.

Deliverables and Time Scale of Proposed Work

We anticipate that result of these studies will be a report containing conceptual and system description of the vertical NNbar experimental scheme and subsystems, list of identified resolved and unresolved showstoppers with proposed options for their resolution and corresponding project cost variation implied by these options, overall cost estimate of a viable optimized configuration of the NNbar experiment, list of technical recommendations and solutions that can be used for the next step of the project development in the preparation of Technical Design Report. Results and recommendations of our report will be available to and can be used by other DUSEL experiments and projects that may encounter similar problems in design and implementation of their experiments and who might benefit from our studies.

In view of the complexity of engineering issues to be resolved in the project and necessity of several iterations between engineers and physicists we plan the duration of this study to be 18 months. Before the grant resources are available to us, we plan to start preliminary studies between participating University groups and available engineers and experts in order to formulate the initial scheme of the experiment that will serve for the first iteration in our study. During this time we will prepare software tools for simulation of the performance of the experimental scheme and detector and will start to interact with undergraduate and graduate students we will attract to the project. These initial studies should also help in ramping up the engineering efforts after the start of the project funding that we plan for July 1, 2007.

Organization and detailed scope of the proposed studies

Some of the feasibility issues and potential showstoppers are identified in the current proposal; others we assume will arise and will be addressed in the course of the proposed study. One of the major issues to be addressed by the proposal work is the possible overall cost of the NNbar experimental facility at DUSEL. Crude estimate of the cost component includes: TRIGA reactor and cold neutron source ~ $15M (based on GA information), vertical vacuum tube with magnetic shielding ~ $20-40M (most uncertain component), annihilation detector ~ $20M (rescaled from previous ILL experiment [6]), new vertical shaft (if necessary) ~ $20-25M. Overall cost of experiment is expected to be in the range of $55 – 100 M and is the subject of more reliable estimate within the proposed project.

For the proposed studies we identified three major directions where feasibility needs to be demonstrated. These are: (a) vertical shaft availability and vertical construction issues, (b) reactor and cold source issues, and (c) feasibility and cost of required vacuum, magnetic screening and large neutron reflector. Three institutions in our Collaboration will be responsible for these directions: UT, NCSU, and IU with overall coordination provided by Yu. Kamyshkov (UT) who will act as a primary source of contact between the scientists, DUSEL sites, and the engineering teams.

(a) Feasibility issues of vertical shaft availability and vertical construction

Vertical shaft availability and construction issues, interaction with DUSEL sites, and detector performance simulations will be in the scope of studies for USD (Mei), CSUDH (Ganezer), and UT (Kamyshkov) with UT as the lead institution.

Most important feasibility issue in this part of the study is overall cost of technically viable construction in the vertical shaft of the NNbar experiment with proposed performance parameters that will comply with the requirements from mine infrastructure, operation, and safety. Large cost of the proposed experiment might be a major showstopper for the whole NNbar project at DUSEL. Possibility of use of existing DUSEL shaft can make a significant impact on the cost of the project. In case if no existing DISEL shafts can be used for NNbar experiment, we plan to study and cost estimate an option of construction of a new shaft at DUSEL. Difficulties and issues of the vertical tube construction in the shaft will be essentially common for existing or new shafts.

We plan to evaluate for suitability and availability the existing vertical shafts at Henderson and at Homestake mines. This will include study of available drawings, descriptions and dimensions, inspection of these shafts by local site experts, and measurements of straightness of the shafts. We will also measure the geo-magnetic field along the length of the shaft since the presence of local magnetic anomalies may severely complicate the magnetic shielding needed for the neutron flight path. These activities should also provide connection and input for the engineering studies by CAN Engineering of the possibility of a new vertical shaft construction at the DUSEL site. For identification of the possible location of a new shaft more detailed geo-magnetic survey of the DUSEL sites will be required from the surface as well as from inside the existing shaft.

Study activities at the Homestake mine will be organized by Mei (USD) who will work with local mine engineers and consultants from South Dakota Universities and interact with South Dakota Science and Technology Authority (SDSTA) for technical and access issues. Scope of USD work includes: survey of existing vertical shafts at Homestake; measurements of straightness of the candidate shaft; measurement of magnetic field in the shaft; simulation the muon-induced background in the NNbar detector, and evaluation of the reactor antineutrino backgrounds for other experiments at DUSEL.

The LBNL agreed to provide to the project a lead mechanical engineer, (DiGennaro) and additional engineering support, to be paid as sub-contractor from the project and to be involved in the aspects of the feasibility study for vacuum system, mechanics of large neutron focusing reflector, and the magnetic shielding system. This study will include the development of concepts, the identification of the high-risk items, and preliminary cost study.

"CNA Consulting Engineers" group lead by Lee Petersen will be our sub-contractor providing conventional and underground engineering with following scope (more detailed description of scope is

given in supplemental section of the proposal): (1) Develop concept drawings of surface support spaces, underground layouts, cross sections and elevations, and revise these drawings as the feasibility study continues, (2) Develop project work breakdown structures (WBS) for capital and operating costs, (3) Prepare design criteria, using input from the scientists that will guide development and comparison of project alternatives, (4) Establish general guidelines for subsurface construction conditions, including practical limits and the cost of construction under these conditions, (5) Evaluate shaft construction, and outfitting for the experiment, including the vacuum control liner and magnetic field coils, (6) Conceptual design of tunnels, caverns and other project components. In this task a conceptual selection of tunnel and cavern rock support and lining will be provided, (7) Review suitability and feasibility of existing shafts and adjoining facilities at two selected sites, based on information provided by the sites, (8) Conceptual design of project systems. Systems include ventilation, exhaust, cooling systems, plumbing systems, electrical power, lighting, fire alarm, utility water systems, process utility systems, clean space systems, safety ventilation systems, fire protection, security, communications, etc., (9) Address fire and life safety aspects of project conventional facilities, excluding neutron source safety. Address site access restrictions, including reactor site protection, and (10) Develop project cost estimates, and design and construction schedules. Prepare a final report of findings, including: project concept drawings, WBS, discussion of project feasibility and potential showstoppers, estimated project cost and schedule, recommendations for future activities.

Together with LBNL and CNA, we will prepare an initial parametric model that will include both the NNbar sensitivity and estimated overall cost as functions of major parameters of the experiment including the length of the flight path, diameter of vacuum tube, length of focusing reflector, reflecting quality of the mirror, acceptance and efficiency of the annihilation detector, reactor power and diameter of annular core, temperature of cold moderator and other essential parameters that can be varied by the design. This will allow us to optimize the *performance to cost ratio* of the conceptual scheme of experiment.

Essential for such studies will be development of *cold source-neutron transport and annihilation detector* simulation tools that we will develop between CSUDH, USD, and UT groups. Simulation input for the cold source with reactor/moderator parameters variations will be provided by MCNP simulations of NCSU group. CSUDH with UT will provide generator of annihilation events, neutron transport in Earth gravitational field including focusing reflections, and detector model for evaluation of detector acceptance and trigger efficiency. CSUDH together with USD and ORNL will also address the issue of backgrounds in the detector including cosmic muon interactions, fast spallation neutrons, and high-flux of low-energy γ resulting from neutron captures. With these tools it will be possible to determine whether cosmic veto system will be required for annihilation detector and design the system of filters and shields in the vacuum tube, as in experiment [6], for mitigation of the flux of capture γs.

We anticipate that the detector design for NNbar DUSEL experiment will follow that of the experiment performed at ILL/Grenoble [6] where strong background suppression (zero background expected) was provided by the virtue of that design. The NNbar detector at DUSEL located deep underground should be more robust with respect to background, thus, we expect that a single observed $n \to \bar{n}$ event in this experiment will be a major discovery. Nevertheless, potential presence of background might be an essential performance showstopper for our detector and needs to be addressed in the proposed study.

(b) Feasibility issues for Reactor and Cold Source

Forty-eight TRIGA (Training Research Isotopes General Atomics) nuclear reactors are now in operation throughout the world, and, of these, 31 are licensed for routine pulsing to high reactor powers (1000's of MW) for short periods of time (10's of ms). More than 450 reactors-years of operating experience, over 30,000 power pulses, and more than 15,000 years of fuel-element use without accidents attest to the fact that TRIGA reactors are safe and reliable.

In these systems, "inherent safety" arises from a large prompt negative temperature coefficient characteristic of uranium zirconium hydride fuel elements used in TRIGA reactors. As the fuel temperature increases, this coefficient immediately compensates for the reactivity insertion. The result

is that a reactor power excursion is terminated quickly and safely by physics laws. This phenomenon, referred to as pulsing, is used in routine operation, and serves to guarantee the safety of the reactor, independent of the engineered safety features, which may be subject to failure.

The prompt shutdown mechanism has been studied extensively in many thousands of transient tests performed on two prototype TRIGA reactors at the GA Technologies laboratory in San Diego, California. These tests included reactivity insertions that produce peak reactor powers up to 8400 MW on TRIGA cores containing fuel elements similar to ones to be used in the proposed annular-core TRIGA reactor. The history of safety and the conservative design of the TRIGA reactors have permitted TRIGA systems to be sited in urban areas using buildings without pressure containment. Thus, the proposed annular-core TRIGA reactor can be designed, constructed, and operated safely at DUSEL, while posing no health or safety threat.

In general, design of a building to contain the annular-core TRIGA reactor (NNbar reactor operating in steady mode) and the support facilities will be based on protection requirements for the reactor fuel and on control of exposures to radioactive materials. At similar reactor facilities, standard structural-engineering practices have been used to provide physical protection of fuel elements and confinement of radioactive materials including airborne activation products from routine operation and fission-product materials from non-routine fuel element failures. Major engineering design features used are the reactor bay ventilation system, the reactor shield structure, fuel element storage, and a liquid waste system. General engineering safety features required for the NNbar reactor are typical of many other similar reactor installations.

Specific design features will be used to protect against building failures caused by site conditions with origin in climatology (winds, hailstones, floods, tornados, hurricanes), geology (faults), seismology (earthquakes), hydrology (ground water, aquifers), and history (burial of waste, toxic, or radioactive materials). These problems are common to all the structures of similar size near the site area. Following the best procedures for design, construction, and inspection used for other similar reactor installations and other similar structures near the site area will provide a building for the safe and reliable operation of the NNbar reactor.

For a cold neutron source operating in the relatively high radiation field that exists at the center of a nuclear reactor, the optimum moderating material is liquid deuterium (D_2). Twenty liters of liquid is representative of a reasonable volume for this moderator. A cold source at the Institute Laue-Langevin has a volume of 27 liters of D_2; the cold source at the Technische Universitat Munchen (FRM-II), 15 liters of D_2 + 5 % H_2; the cold source at Australian Nuclear Science & Technology Organization, 15 liters of D_2. The nuclear heating load for a 20-liter D_2 cold source at the center of the annular-core TRIGA reactor operating at 3.4 MW is estimated to be ~ 1000 W. Using these assumed values, a preliminary conceptual cold-source design for the NNbar experiment has been developed based on the hydrogen cold source operating at the NBS reactor at the National Institute of Standards and Technology (NIST).

In our design, the heat generated by reactor neutrons and gamma rays in the liquid deuterium and in the moderator chamber is removed by boiling off the liquid deuterium. The D_2 vapor exits the moderator chamber and rises in the inner tube of a hydrogen transfer line to a hydrogen condenser where it is re-liquefied. The liquid returns to the moderator chamber through the outer portion of the hydrogen transfer line. During normal operation, the vapor and liquid are maintained at ~ 21 K and ~ 152 kPa. The cooling necessary to remove the heat, i.e., secondary side of the condenser, is supplied by a closed cycle helium gas refrigerator (>1000 W of cooling power with a final gas temperature of ~ 18 K). The driving force necessary to establish flow of liquid down to the moderator and vapor back to the condenser is supplied by the difference in density of liquid and vapor acting over the height difference between the condenser and moderator. This natural-circulation loop, called a thermosiphon, requires no moving parts to ensure flow of liquid to the moderator of the cold source for cooling purposes. Calculations at NIST of loop stability and loop friction indicated that > 20 cm head is adequate for the operation of the D_2 thermosiphon.

The design, construction, and operation of the annular-core TRIGA reactor proposed for the $n \to \bar{n}$ search is a major undertaking needing a great deal of work. However, as mentioned above, similar reactor installations have been successfully built and operated in this country and abroad.

Thus, there are no unresolved questions about reactor safety and protection, licensing and liability, environmental impact, primary and secondary cooling systems, staffing, decommissioning, etc. We will work with General Atomics as well as with TRIGA owners, NRC, etc. in order to optimize the effectiveness and reduce the cost of the NNbar reactor.

There is one reactor related feasibility issue, however, viz., who will take responsibility for (i.e., ownership and operate) the annular-core TRIGA reactor? As a solution to this reactor related feasibility issue, we will pursue ownership by (a) the State in which the mine is located, (b) an agency of this State such as a University, (c) the DUSEL laboratory at the mine site, or (d) any other legitimate federal or state organization.

A multipurpose annular-core TRIGA reactor would be a major educational asset for the training of nuclear science in chemistry, physics, and engineering. A multipurpose reactor design would also allow reactor use for other research and service activities such as neutron activation analysis, detector calibration, neutron radiography, etc. An alternative to the multipurpose concept is a single purpose design, which would provide only an intense neutron field at the bottom of the vertical shaft for the NNbar experiment and possibly other particle physics experiments. It is expected that the single purpose reactor would have smaller capital and operating costs, but would probably require operating costs to be covered by NSF and not some other organization.

The design, construction, and operation of the cold-neutron source proposed for the antineutron search requires state-of-the-art cryogenic technology. However, as given above, similar cold-neutron sources have been successfully built and operated in this country and abroad. Some of these are in large evacuated beam tubes similar to the NNbar experiment design. Thus, there are no unresolved questions about the design, operation, or safety related to the proposed cold-neutron source. Wee will work with General Atomics and will be in contact with facilities operating cold-neutron sources in order to optimize the effectiveness and reduce the cost of the liquid-deuterium cold-neutron source.

There are, however, two system feasibility issues. They are: (a) total cost of the annular-core TRIGA reactor and the liquid deuterium cold neutron source; (b) performance of the liquid deuterium cold neutron source, i.e., can a sufficiently large cold neutron flux be achieved with reasonable reactor power?

Estimation of the total cost of the annual-core TRIGA reactor and liquid-deuterium cold-neutron source requires resolution of the ownership issue given above and the question of multipurpose versus single purpose design, which is related to the ownership issue. We expect to provide a breakdown of costs that includes all options of ownership and designs.

The efficiency of moderating a thermal neutron into a cold neutron in the liquid-deuterium cold-neutron source can be enhanced by increasing its volume (~ 20 liters). However, a larger cold-neutron source requires a larger central void in the annular-core TRIGA reactor. A larger central void in turn requires a larger reactor core, reducing the flux of thermal neutrons incident on the cold source at constant power. Thus, there is an optimum design which delivers the maximum cold neutron flux to the vertical tube. Is this flux sufficient to justify the cost (a)? We will work with General Atomics to resolve this issue. In addition, we will do calculations (MCNP) independent of General Atomics to verify their results. Our calculations will also give the position, angle, and energy dependences of the cold neutrons entering the vertical tube. Using the MCNP results, cold neutron transport in the vertical tube will be performed to verify the preliminary results presented in this proposal.

(c) Feasibility issues of vacuum, focusing neutron reflector, and magnetic screening

Neutron Reflector: The proposed experiment requires a large elliptical focusing neutron reflector with the cold source at one focus that intercepts neutrons in a wide solid angle and directs them along ~ 1 km vacuum flight path onto the annihilation detector, placed at the other focus. The *vertical* layout of the flight path is needed to keep the most valuable slow neutrons from striking the vacuum walls during the observation time. The length of the reflector is of order tens of meters (up to 150 m) and the maximum radius of the reflector is on the order of 1-2m. The neutron reflector needs to be installed inside the vertical vacuum chamber and magnetic shielding. The optical elements of the mirror consist of multilayer neutron “supermirrors” with critical angles 3 times that of ^{58}Ni (so-called “m=3” neutron mirrors). Curved neutron guides can now be made commercially and are starting to find applications in

neutron scattering facilities [31]. Tests using a parabolically-shaped neutron guide coated with m=3 supermirrors showed excellent agreement between simulations and measurement [32]. The neutron guide proposed for the WISH diffractometer at the ISIS second target station [33] will require a horizontal 40 m elliptical neutron guide made of m=2 supermirrors which will be enclosed in a large vacuum tank. Although not a vertical arrangement, it is clear that this elliptical guide will possess significant technical overlap in the area of mechanical design and neutron optical tolerances with our proposed reflector. We propose to visit the ISIS WISH project team and consult with Swiss Neutronics to narrow the phase space of neutron optical possibilities for large elliptical mirrors, taking into account the required mechanical tolerances and acceptable nonmagnetic materials, vacuum compatibility, sensitivity to thermal and mechanical stress, long-term stability of the multilayer coatings, etc. After this initial exploration has narrowed the possibilities, we plan to involve an undergraduate student in further simulations to explore within these constraints the sensitivity of the experiment to changes in the reflector geometry. The agreement between neutron optics theory and measurement mentioned above supports our assumption that the existing neutron optics simulation packages such as McStas and VITESSE will suffice for these calculations.

The sheer volume of required m=3 supermirrors for the reflector is likely to place an intolerable strain on the capacity of the world's commercial neutron guide manufacturers, and it is likely that the experiment will need to produce its own reflector and more economical mass production facilities for supermirrors. Since we have assumed in our intensity estimates that the neutrons will bounce off of the reflector only once (and thereby neglect the added neutrons that will be transported through garland reflections on the curved surface of the guide), we are much less sensitive to deviations away from perfect reflectivity than are the usual supermirror neutron guides produced for neutron scattering beamlines. This should simplify the requirements for surface quality of supermirrors and reduce the production cost. We propose to analyze the resulting sensitivity of the reflectivity to the characteristic types of non-uniformities in the multilayer structure that can occur in the coating process in order to help identify and specify the parameter space for a cost-effective production method.

One issue of potential concern is the effect of the adsorption of residual hydrogen gas on the performance of neutron optical components over an extended period of time (a few years). Neutron scattering facilities operate their supermirror neutron guides in vacuum and typically report no major time-dependent effects on neutron optical performance. We will survey and quantify this experience as further input to requirements for the vacuum tube.

Magnetic Shielding: The Earth's magnetic field inside the vacuum chamber needs to be shielded along the 1-km flight path by active and passive magnetic shields down to the level of a nanoTesla. Requirements similar to these were achieved in the previous ILL/Grenoble-based experiment with a two-layer shield [34] of ~1m diameter over a length of about 80 meters. For the magnetic shielding geometries of both the previous experiment and the proposed experiment, which use shields with cylindrical symmetry, the dominant component of the residual magnetic field inside the shield is the component along the axis of the shield. The internal shield for the previous ILL experiment suppressed transverse components of the magnetic field and rendered the longitudinal component sufficiently uniform that it could be compensated by a homogeneous external field generated by a coil wrapped on the outside of the shield. Current loops for shield demagnetization, an active compensation system for external magnetic field variations (including transverse fields), internal magnetometry, and removal of large external sources of magnetic field gradients were also required to maintain the quasi-free condition. Among the issues associated with the magnetic shielding are the following: (a) identification of a space-efficient scheme for sufficient suppression of both longitudinal and transverse magnetic fields in the presence of the μ-metal; (b) identification of a facility where sufficiently large-diameter μ-metal shields can be vacuum annealed in a furnace; (c) measurement of the ambient magnetic field in the shaft; (d) mechanical design of the vertical shield, including a mechanism for alignment and -mechanical support of the neutron reflector inside the shielding that is insensitive to effects such as thermal contraction;(e) Analysis of the loss of sensitivity of the oscillation measurement to various types of time and space-dependent residual magnetic fields; (f) Investigation of the compatibility of nonmagnetic 304L stainless steel for the vacuum chamber (preferable from the vacuum point of view) with the magnetic shielding system. We propose to consult with experts in low

magnetic field shielding and conduct 3D magnetic shielding simulations (Nicolai Martovetsky from LLNL) to explore these possibilities.

Neutron Polarimetry: No matter how effective the magnetic shielding should be theoretically, it is obvious that periodic in-situ measurements of the magnetic fields seen by the neutrons are essential to verify that the quasifree condition for neutron-antineutron oscillations is maintained during the measurement. In the previous oscillation experiment this was done by inserting a neutron polarizer and a neutron polarization analyzer before and after the magnetic field-free region and using the neutrons themselves to measure the magnetic field. If the neutrons are polarized transverse to this axis, then the presence of a magnetic field along the axis of the shield will rotate the neutron polarization direction by an angle $\phi = \gamma B t$ where γ is the neutron gyromagnetic ratio, B is the magnetic field, and t is the time that the neutron spends in the field. For cold neutrons, a ~1 second flight time, and B=1 nT this angle is about 0.2 radians.

The neutron cold source produces a broad spectrum of neutron velocities and this will lead to a distribution of rotation angles. One can chop the beam mechanically if necessary, but a more elegant solution, employed in the ILL experiment [35] is to employ a second magnetic coil before the polarization analyzer with a known internal field and length and operate the measurement in "spin echo" mode. In this case, when the echo condition $B_1 \cdot L_1 / v = B_2 \cdot L_2 / v$ is met the final neutron polarization is high and insensitive to the velocity distribution in the beam, and the decrease of the polarization away from this resonance condition depends on the shape of the velocity distribution. Furthermore, by changing the direction of the second magnetic coil in all 3 directions and using the spin echo detection method one can measure the line integral of all three magnetic field components in the shield as seen by the neutrons.

The neutron beam at the source and at the focus is large in cross sectional area and divergent. The only practical method for polarizing and analyzing such a neutron beam is to use transmission through polarized ^{3}He gas. Such neutron spin filters have been developed over the last decade for neutron scattering applications [36].

Vacuum Chamber and Quality of Vacuum: The experiment requires that the neutrons travel in a vacuum of ~ 10^{-5} Pa so that the difference between the neutron and antineutron optical potential in the residual gas does not cause a violation of the quasifree condition. Among the issues associated with the vacuum chamber are the following: (a) identification of a pumpout scheme to reach and maintain vacuum in the presence of outgassing from the tube walls which is consistent with all other aspects of the experiment; (b) Analysis of the mechanical stability of a 4-m diameter vacuum vessel using finite-element analysis for the wall thickness and size and spacing of external stiffening rings; (c) Investigation of cost-effective methods for 4m diameter tube manufacture.

Fortunately there is extensive experience with a vacuum chamber with nearly the same parameters: the 2 km long, 1.2 m diameter chambers for the LIGO gravitational wave observatory. The LIGO vacuum tubes are at the (much lower) pressure of ~10^{-9} torr, achieved after 2 months of pumping with 9 pumps, each connected to a 25 cm diameter pumpout port. Nevertheless they can be maintained at this pressure with only pumping at the ends of the chamber. In LIGO this relatively simple solution could be achieved through the use of nonmagnetic 304L stainless steel which was baked at 150C by electrical heating of the tube (using the tube as a resistor) and in addition the steel was heat-treated during manufacture to reduce the hydrogen outgassing rate from the usual 10^{-11} torr liters/sec/cm^2 to 5×10^{-14} torr liters/sec/cm^2. The required purity of the internal surface of the stainless steel was maintained during on-site welding assembly through the development of a continuous spiral welding process [37].

If it were possible to use nonmagnetic 304L stainless steel as the vacuum chamber for the NNbar experiment then a similar vacuum solution to LIGO could work. The 4m diameter makes the gas dynamics in this pressure regime 30 times faster than LIGO. Because of the larger diameter of the tube and the less stringent vacuum demands for the NNbar experiment even the outgassing rate from untreated stainless could be handled with a few hundred liters/sec pumping speed.

We propose to consult with Rainer Weiss of LIGO and visit Chicago Bridge and Iron in Plainfield, Illinois, the beam tube contractors for LIGO, to investigate possibilities. In addition we will investigate

the issues in constructing the tube out of aluminum. Typical in-service outgassing rates for long UHV aluminum vacuum cylinders of various surface treatments are well-documented from studies at accelerator facilities. The main issue to be investigated for aluminum tubes, in addition to the strength calculations, is the achievement of acceptable outgassing rates in aluminum tubes given the existing manufacturing processes at tube mills.

We intend to explore the parameter space of possibilities for the vacuum, magnetic shield, and neutron reflector early in the project in coordination with LBL, who will contribute engineering support and analysis of possibilities.

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