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*R&D Proposal to NSF*

**Collaborative Research: Feasibility Study of NNbar Experiment at DUSEL**

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**(a) Intellectual merit of the proposed activity**

The goal of the collaborative research proposed here is to demonstrate the feasibility of a new experiment that would search for transitions of neutrons to antineutrons in a 1-km long vertical shaft at the Deep Underground Science and Engineering Laboratory (DUSEL). An observation of neutron to antineutron transitions in a vacuum or the transformation of baryonic matter to antimatter will be a momentous discovery of a new force of nature that might help to provide an explanation of the matter-antimatter asymmetry in the universe. The same interactions that are responsible for the small masses of neutrinos can cause the  $n \rightarrow \bar{n}$  transitions at possibly observable rates. Existence of  $n \rightarrow \bar{n}$  transitions (free neutron oscillations, or simply NNbar oscillations) might also be a manifestation of low quantum gravity scale effects and could provide the first experimental signature of extra-dimensions in nature. Thus, the NNbar could be a “transformative type” of experiment for the fields of particle physics and cosmology. The proposed NNbar experiment will require a source of cold neutrons from a 3.5 MW TRIGA reactor, installed on top of a 1-km vertical mine shaft. The antineutron detector will be located at the bottom of the shaft. One of the vertical shafts currently available at the Homestake mine could be used for this experiment or a new shaft might be constructed at DUSEL. To keep the neutron and antineutron states degenerate (as required for unsuppressed transition) good vacuum in the flight tube is required and the Earth’s magnetic field should be canceled by a shielding system down to a residual value of  $\sim 1$  nT. The sensitivity of this experiment will be significantly enhanced by a large neutron focusing reflector. A vertical layout compensates for the disturbing effect of the Earth’s gravity. Although all the components of the proposed technique are well known and tested at small scales, the construction of an experiment in a long vertical shaft at DUSEL with a good vacuum, a high intensity cold neutron beam, and with a low residual magnetic field, may be a challenging task. The purpose of the proposal is to address safety, regulatory, and legal issues for the neutron source, perform engineering and technical studies, identify and address possible project showstoppers, estimate the cost, and formulate a pre-conceptual scheme for the experiment that could prove the feasibility of an NNbar search at DUSEL.

**(b) Broader impacts resulting from the proposed activity**

Our project will benefit other DUSEL physics proposals, especially those that require a “Vertical Facility” (a long vertical path with a good vacuum and shielding of the Earth’s magnetic field). The reactor and vertical facility at DUSEL would be available for multiple purposes such as the production of radioisotopes for detector calibration and for neutron activation analysis. The results of our research would be disseminated to the scientific community through peer-reviewed publications and by presentations at physics and engineering professional meetings.

This project includes educational outreach activities that will provide opportunities for disseminating knowledge about DUSEL, improving scientific literacy, and by developing networks with target audiences of (1) undergraduate students and (2) members of the general public. The goals of our educational plan for undergraduate engineering and physics students is to (1) increase their knowledge base and understanding of how large scale design and feasibility studies are done, (2) expand their knowledge and communications skills regarding the cross disciplinary nature of this project, and (3) provide opportunities to interact with scientists and to develop an international network of scientific collaborators. This plan will include genuine research experiences related to this project, College curriculum enhancement, and direct interaction and networking of undergraduate students with scientists and professionals through an engineering and physics workshop that will be held near the DUSEL facility. The goals of the educational plan for the public will be to initiate interest in science at DUSEL, to provide encouragement to pursue career paths in science, and to develop the invaluable contacts for public involvement and future educational advancement. Local public outreach will be achieved through four seminars or lectures that will be associated with project meetings. Seminar materials will consist of presentation slides on energy resources, the role of nuclear technology in the future, and how these topics relate to scientific research at DUSEL. Additional materials and information will be provided concerning research in other scientific disciplines at DUSEL and on how DUSEL plans to enhance educational training of students for scientific and technical employment. Summative assessment of the outcomes of educational and outreach activities will be conducted using pre and post-activity questionnaires to evaluate changes in the level of scientific knowledge, and in acquired technical and communication skills.

## Physics motivation

Recent theoretical, as well as experimental, developments in the field of neutrino physics have provided very compelling reasons for the existence of neutron-antineutron oscillations ( $n \rightarrow \bar{n}$ , or NNbar) at some level. Indeed, there are now new neutrino models, very different from conventional grand unified theories, which predict an observable NNbar oscillation rate. The situation is not unlike that of proton decay in the late seventies, when the emergence of SU(5) theory, despite its shortcomings, had a prediction for the proton lifetime that was within experimental reach and which led to a host of experimental searches for proton decay. Although these experiments failed to observe proton decay, they nonetheless considerably enhanced our understanding of possible Grand Unification Theories (GUT). NNbar oscillation is similarly predicted in interesting models for neutrino masses and an improved experimental precision will be very illuminating in the search for B-L (baryon number minus lepton number) symmetry scale and quark-lepton unification. An explicit discovery will of course be a major step towards an understanding of physics beyond the standard model and will fundamentally alter our thinking about new physics.

There are several arguments that lead to the new search for NNbar transitions:

(i) There are ample indications that baryon number is not a perfect symmetry of nature; the most profound being that it is an essential ingredient in our understanding of the microscopic origin of matter in the universe [1]; another is the fact [2] that not only the Standard Model but also many of its extensions that break baryon number.

(ii) Recent discoveries in neutrino physics seem to strongly point towards B-L as a new symmetry of nature which is likely an essential part of any new physics scenario. It must be broken by two units in order to provide an understanding of the small neutrino masses via the seesaw mechanism [3]. This raises several questions: (a) is B-L a global or local symmetry? (b) what is the scale at which the new symmetry is broken? Note that the seesaw mechanism does not determine this scale due to the presence of unknown parameters; and (c) what new physics is associated with B-L breaking?

(iii) If neutrinos are Majorana particles as is widely believed (and double beta decay experiments are going to test this hypothesis), then lepton number must be broken by two units. Since the true symmetry of the standard model is B-L (and not L by itself due to triangle anomalies), Majorana neutrinos imply  $\Delta(B-L)=2$ . The implication of this selection rule for purely nonleptonic processes, is that baryon number can also break by two units  $\Delta B=2$ . A spectacular manifestation of this selection rule would be neutron-anti-neutron oscillation. It was shown explicitly in 1980 [4] that in seesaw models for neutrinos with quark-lepton unification as in the Pati-Salam model, the Majorana mass of the neutrino implies that NNbar oscillations occur if one wants to understand the matter-antimatter asymmetry. Thus, cosmology plus neutrino physics in a unified quark-lepton framework would predict the existence of NNbar oscillations [4]. Since there is no proton decay in such models, the scale of new physics can be considerably lower and NNbar oscillations can determine this scale.

(iv) With available technologies, the reach of an  $n \rightarrow \bar{n}$  oscillation time search can go as far as  $10^{10}$  seconds, at least two orders of magnitude beyond the present lower limit [5] (and four orders of magnitude in appearance probability). The goal of the present proposal is to study the feasibility of such a new NNbar experiment based on the available technologies at the Deep Underground Science and Engineering Laboratory (DUSEL). A key question then is: are there plausible models where the NNbar oscillation time is predicted to be close to or below this observable limit? The answer to this question is **yes** and the model is the Pati-Salam extension of the Standard Model with a completion to generate the baryon asymmetry of the universe. In its non-supersymmetric version, NNbar probes the B-L breaking scale up to  $3 \times 10^5$  GeV [4] whereas it has recently been shown [6] that in its supersymmetric version, it can probe scales all the way up to  $10^{12}$  GeV. This is due to the presence of new operators that appear in supersymmetric (SUSY) models, a familiar phenomenon that also occurs in proton decay. The discovery of NNbar oscillations would therefore not only establish the scale of B-L symmetry somewhere between  $10^5$  to  $10^{12}$  GeV (to be compared with typical values in GUT theories of  $10^{16}$  GeV), but would also reveal that the same interactions that generate neutrino mass are also responsible for baryon number violation and the matter anti-matter asymmetry thus providing a unified (single) explanation of several important questions in particle physics and cosmology.

The existence of NNbar might also be a manifestation of other kinds of physics such as extra dimensional low quantum gravity scale effects [7, 8] or low-mass right handed neutrinos [9]. In the former case, it will provide the first experimental indication of the presence of extra-dimensions in nature. The NNbar

process also arises in other attempts to understand the origin of matter [10]. Thus, searches for NNbar oscillations can shed light on a wide variety of physics topics that go beyond the Standard Model. Since the right-handed component of the neutron is a singlet in the Standard Model it makes the neutron a unique object to reveal new interactions beyond the Standard Model, as mentioned above in our discussion of low quantum gravity scale effects.

It is worth noting that the classes of models described above are based on a totally different path to unification compared to the conventional SUSY GUT scenarios [11]. The key prediction of SUSY GUT models is proton decay. The mode  $p \rightarrow e^+ + \pi^0$  which arises via gauge exchange with a life time of  $10^{36}$  years is fairly model-independent whereas the mode  $p \rightarrow \bar{\nu} + K^+$  which can arise with a lower lifetime of  $10^{34}$  years is very model dependent. Such modes are however disconnected from neutrino mass physics and therefore probe fundamentally different physics from NNbar oscillation.

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. In general, searches for rare processes like  $n \rightarrow \bar{n}$ ,  $\mu \rightarrow e\gamma$ ,  $\nu \leftrightarrow \bar{\nu}$  etc. provide access to the highest energy scale  $> 100$  TeV. This energy scale presently is not attainable by LHC and ILC colliders.

Probability of  $n \rightarrow \bar{n}$  oscillations in vacuum [4] is proportional to the square of  $t$  neutron observation time:  $(t/\tau_{free})^2$ , where  $\tau_{free}$  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  $\sim 1$  second 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 limit on the  $n \rightarrow \bar{n}$  oscillation time in vacuum  $\tau > 8.6 \times 10^7$  s was established in experiment [5] at ILL/Grenoble research reactor. This limit is essentially larger than a free neutron lifetime. Therefore it is more appropriate to discuss  $n \rightarrow \bar{n}$  transitions rather than oscillations.

Transitions  $n \rightarrow \bar{n}$  have been also sought inside nuclei for bound neutrons. Highest published limit was obtained by Soudan-II collaboration [12]. Intranuclear transitions are heavily suppressed due to large difference of nuclear potential for neutron and antineutrons [13] with probability of transition reduced down to usual  $t/\tau_A$  (exponential law) where  $\tau_A$  is a nuclide A lifetime in respect to intranuclear  $n \rightarrow \bar{n}$  transition. This,  $\tau_A$  is related to  $\tau_{free}$  as  $\tau_A = R \cdot \tau_{free}^2$ , where R is intranuclear suppression factor of the order of  $10^{23} \text{ s}^{-1}$  known from nuclear theory with the accuracy about factor of 2 [13]. Thus, for example, the limit of Soudan-II [12] 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. Recent preliminary result of Super-Kamiokande collaboration [14] was reported as  $\tau_{Free} > 1.25 \times 10^8$  s at 90% CL although their nuclear lifetime limit is  $\tau_O > 1.8 \times 10^{32}$  years. To date, both free-vacuum and intranuclear transition search experiments produced very similar limits on  $\tau_{Free}$ . Sensitivity in case of intranuclear transitions is limited by the presence of atmospheric neutrino background and further improvement of NNbar limit, even for a megaton detector, will be very difficult, and the discovery of the effect impossible due to irreducible background. The advantage of free vacuum neutron transition for the exploration of the stability of matter would be clearly seen in case when the increase of sensitivity of free neutron transition time in vacuum, say, by two orders of magnitude provides an equivalent limit on the NNbar intranuclear lifetime  $\tau_A > 10^{36}$  years. Clear signature of antineutron annihilation for vacuum transition will allow observation of the effect without background.

In 1994-1995 a new high-sensitivity approach to an  $n \rightarrow \bar{n}$  experimental search was proposed using a horizontal cold neutron beam from the high-flux research reactor HFIR at Oak Ridge National Laboratory [15]. A high sensitivity of  $n \rightarrow \bar{n}$  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 [16] concentrating cold neutrons onto the target. However, this most powerful research reactor, which is operated in the US by BES office of DOE, was not available for fundamental particle physics experiments. Recently authors of the current proposal studied the availability of horizontal cold neutron beams [17] by contacting several existing research reactors. Common reply [17] from the management of the reactors was that the horizontal cold neutron beams for various reasons cannot be available for NNbar search.

Several workshops have been organized or participated in by the authors of this proposal where the physics of  $n \rightarrow \bar{n}$  was discussed and different methods of  $n \rightarrow \bar{n}$  transition search were addressed. Oak Ridge workshop in 1996 [18] was focused on geo-chemical methods and HFIR-based experiment with horizontal layout. At workshops in 2002 at Indiana University [19], and in 2003 at PNPI [20] the possibility of  $n \rightarrow \bar{n}$  search with ultracold neutrons was explored. At South Carolina Workshop in 2005 [21] the possibility of vertical layout of NNbar experiment was discussed with the fundamental physics neutron community. In 2005-2006 in the context of US Deep Underground Science and Engineering Laboratory (DUSEL) development program we have proposed [22] a high-sensitivity NNbar experiment for one of the vertical shafts of Homestake mine. At the recent International Workshop "Search for Baryon and Lepton Number Violations" at Lawrence Berkeley National Laboratory in September 20-22, 2007 [23] the idea of DUSEL-based NNbar experiment was discussed as complementary to the search for Majorana neutrinos.

To increase the time of observation of the neutron one needs to slow down the neutrons and to increase their flight path. For the case of a horizontal beam of neutrons the gravity becomes an important perturbation to non-monochromatic cold beam motion that limits the sensitivity to NNbar transitions per neutron. We therefore proposed [22] for DUSEL a vertical layout for the NNbar experiment that would eliminate the defocusing effect of gravity. The experiment requires a small dedicated research reactor with cryogenic moderator as a high-brightness source of cold neutrons with lowest average velocity. The low power of the reactor is compensated by the vertical layout of the experiment. Such vertical layout at DUSEL provides a sensitivity exceeding the sensitivity of the experiment originally proposed for HFIR. The sensitivity to NNbar appearance probability here can be a factor of >1,000 higher than in the previous best  $n \rightarrow \bar{n}$  search experiment [5], which established a limit for  $n \rightarrow \bar{n}$  oscillation time of  $\tau_{free} > 8.6 \times 10^7$  s. The possibility of a large increase in sensitivity of the experimental search for  $n \rightarrow \bar{n}$  transitions is the central motivation for this Proposal.

**Brief description of proposed experimental method**

One of the existing or new-constructed vertical shafts at Homestake/DUSEL can be used for NNbar experiment. A reactor installed on the top of this shaft can be typically 2 km away from the main underground DUSEL campus. The conceptual plan for a vertical NNbar experiment proposed for the DUSEL (Figure 1) includes a dedicated 3.4 MW standard research reactor (Figure 2) of TRIGA type [24] (commercially available from General Atomic Company) as a neutron source. The reactor will be configured to have an annular core with a vertical central tube for convenient insertion of a cold neutron moderator from the top and extraction of the cold neutrons from the bottom.

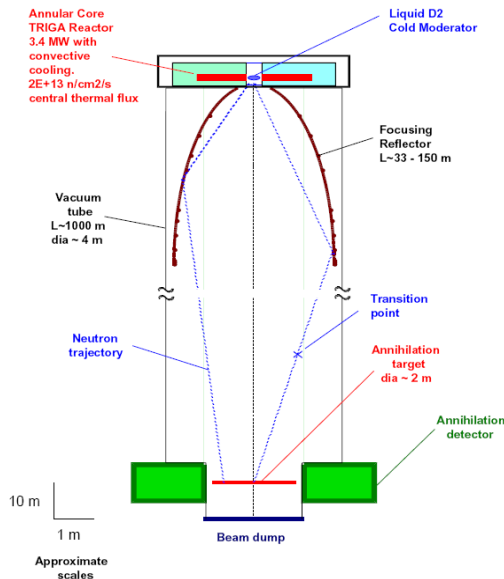


Figure 1. Schematic view of the vertical NNbar experiment.

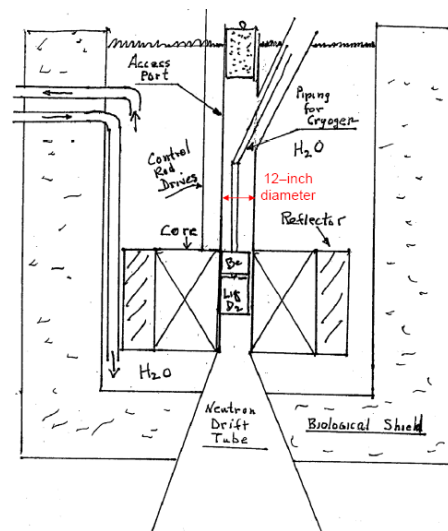


Figure 2. Schematic drawing of the 3.4 MW TRIGA reactor with thermal water convection, annular core and 12-inch throughout vertical tube (courtesy of W. Whittemore, General Atomics, 2003).

The unperturbed thermal flux in the central plane of this reactor will be  $\sim 10^{13}$  n/cm<sup>2</sup>/s yielding a fluence of cold neutrons at the annihilation target  $\geq 10^{11}$  n/s. To reach maximum sensitivity for  $n \rightarrow \bar{n}$  search, the neutrons must 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 ( $\geq 1$ s). The reactor should be installed at the top of a vertical mineshaft of  $\geq 1$  km depth with a diameter of a several meters. The experiment requires a large elliptical focusing reflector [16] with the cold source at one focus to 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 the ellipse. Since cold neutron source is not a point-like source it is not possible to achieve exact point-to-point focusing but rather an effective enhancement of the neutron flux at the large-diameter target. The vertical layout of the flight path preserves the most valuable slowest neutrons (falling on the walls in the horizontal tube) and thus yields a dramatic improvement of sensitivity to  $n \rightarrow \bar{n}$ .

The 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 minimized along the flight path by active and passive magnetic shields to be less than a few nano-Tesla. Requirements similar to these were achieved in the previous NNbar ILL/Grenoble-based experiment [5] and even better shielding factors have been achieved in small-scale experiments, e.g. in [25]. 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 <sup>3</sup>He gas near the moderator and then measuring the precession angle of the neutrons in the magnetic field using a polarized <sup>3</sup>He polarization analyzer close the bottom of vacuum path. 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) would be similar to one used in the experiment [5] at the ILL/Grenoble reactor with a thin 130 $\mu$ m carbon foil with diameter  $\sim 2$  m serving 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 tracks of annihilation pions to the z-position of the carbon-film target, thus providing excellent discrimination against background events (primarily due to cosmic ray interactions). The tracker is surrounded by a calorimeter, a cylindrical detecting layer to measure the energies of the annihilation products (typically 5 pions per annihilation) and provides a trigger signal for readout. If necessary the calorimeter can be surrounded by a scintillator veto system against cosmic ray-induced events.

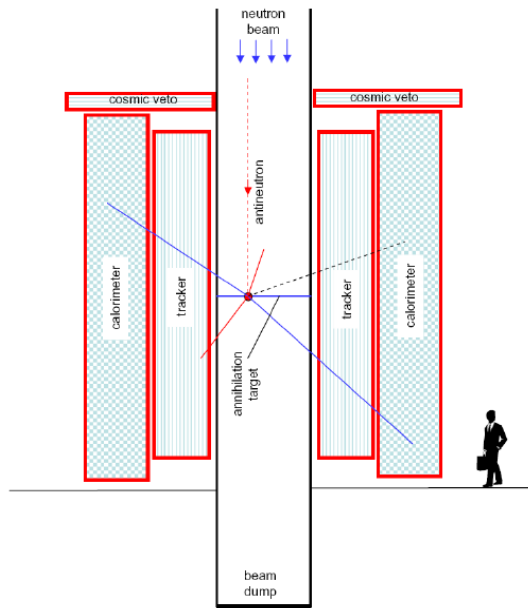


Figure 3. View of generic antineutron annihilation detector similar to one used in ILL/Grenoble experiment [5].

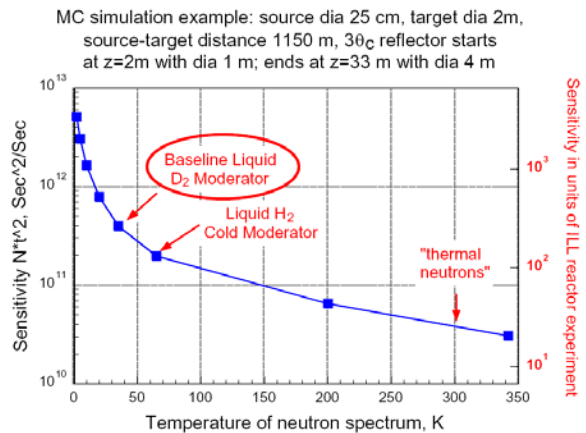


Figure 4. Monte Carlo simulation of the sensitivity of NNbar search experiment in terms of  $N \cdot t^2$  (flux of cold neutrons through annihilation target times average time square of the free time-of-flight in vacuum) vs temperature of the neutron spectrum. Sensitivity is also shown in the units of sensitivity of the previous ILL/Grenoble-based NNbar search experiment [5] where sensitivity  $N \cdot t^2$  was  $1.5 \times 10^9$  n·sec<sup>2</sup>/sec and the experimental running time was  $\sim 1$  year.

The sensitivity of the  $n \rightarrow \bar{n}$  search experiment is proportional to the flux of neutrons through the annihilation target and the square of the time-of-flight of these neutrons through the vacuum path without magnetic field from the location of last scattering in matter (source or reflector) to the target. Figure 4 shows results of Monte Carlo simulation for the proposed experimental scheme. After ~3 years of operation the sensitivity of the  $n \rightarrow \bar{n}$  search is a factor of > 1,000 higher than in the previous experimental search at ILL/Grenoble reactor [5] due to the very long vertical flight path, the cold moderator, and the focusing neutron reflector. Focusing reflector allows advantage of sensitivity increase proportional to the square of the flight distance and further increases the sensitivity when neutron beam temperature is lowered. The ILL/Grenoble experiment [5] demonstrated the possibility of constructing a zero-background detector due to the distinctive signature of antineutron annihilation. With a “zero-background” detector, even one observed event would constitute a discovery. If no events were observed after three years of measurements it would correspond to a new limit on the stability of matter,  $\geq 10^{35}$  years, a goal that cannot be obtained in the intranuclear search with large underground detectors. To our knowledge, no other practical schemes for  $n \rightarrow \bar{n}$  search exist with a comparable sensitivity [26].

### **Global Plan and Goals of the Proposed Studies**

In the Letter of Interest presented to the Homestake DUSEL [22] we emphasized that DUSEL infrastructure and facilities provide a unique possibility for NNbar experiment, a new search that could lead to a momentous discovery in science with substantial impact on the high-energy particle physics and cosmology. All conventional and neutron related technologies required for NNbar-experiment exist or have been proven at the smaller scale of applications. The previous  $n \rightarrow \bar{n}$  search with free neutrons in a vacuum, performed with a horizontal layout at the ILL/Grenoble reactor [5] can be considered as a prototype of the proposed NNbar experiment. However, there are several aspects of the proposed scheme that require additional study for the DUSEL implementation. The Program Advisory Committee of the Homestake Collaboration expressed [27] 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 closely with DUSEL Laboratory to address these questions.

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

We consider this proposed 2-year feasibility study program as a part of the preparation of the “Conceptual Design” for the NNbar experiment for DUSEL. Our global roadmap for project development is:

2007-2008: Scientific and Technical Review of the NNbar physics and experimental method;  
2008-2009: Feasibility study R&D; preparation of CDR, project schedule and cost estimate;  
2009-2010: Included in DUSEL S4: Preparation of PDR;  
2011-2012: Preparation of the Final Design Report;  
2012-2013: Separate MREFC Proposal for NNbar Construction at DUSEL;  
2014-2016: Experiment Construction at DUSEL;  
2016-2020: NNbar Operation at DUSEL

We have also realized that other physics experimental ideas that are currently being prepared as LOIs for Homestake/DUSEL program [28,29] have significant synergy with the requirements of NNbar experiment, i.e. a long vertical shaft shielded from Earth magnetic field, good vacuum and [28] source of cold neutrons. In the proposed study we plan to look at requirements of these experiments within the concept of DUSEL Vertical Facility [30] and address their space and time compatibility with NNbar configuration.

### ***Project participants***

The NNbar collaboration is a multidisciplinary group of scientists and educators from universities and Oak Ridge National Laboratory with substantial experience and record of participation in high-energy physics experiments, neutron science, neutron interactions, underground physics, reactor physics, and long-term studies of various aspects of the NNbar search. Our group includes: from North Carolina State University (NCSU): Hawari, the director of the campus university research reactor (URR) and a recognized expert in the areas of Generation IV power reactors, neutronics simulations, and the design and implementation of radiation beam experiments at URRs; Young is a nuclear physicist with extensive experience in ultracold neutron (UCN) experiments. He helped to develop the first spallation-driven SD2 ultracold neutron source at Los Alamos, and is involved in the UCNA project, the first measurement of beta-decay angular correlations using ultracold neutrons as well as in the development of the ultracold neutron source at NCSU reactor; Wehring is a Research Professor having retired from the University of Texas at Austin in 2000. For 11 years in Austin, he was Coordinator of the Nuclear Engineering Program and Director of the Mark II TRIGA reactor, newly licensed for operation in 1992. He was responsible for installing a cold neutron source (CNS) at the UT TRIGA, the only operating CNS at a URR in the U.S. He was director of the NCSU reactor from 1984 to 1989. Before 1984 he was Professor of Nuclear Engineering at the University of Illinois, where he used the Illinois TRIGA Mark II URR for research. He participated in amending the reactor license for upgrading the Illinois TRIGA from 250 kW to 1.5 MW; Snow from Indiana University (IU), particle physicist with experience in neutron measurements in nuclear, particle, and condensed matter physics. He has measured the Bose condensate fraction in superfluid  $^4\text{He}$ , the neutron lifetime, coherent neutron scattering lengths of H, D, and  $^3\text{He}$ , and parity-odd correlations in neutron reactions with nuclei (n-p and n- $^4\text{He}$  in progress). Has developed neutron polarizers and analyzers based on transmission through polarized  $^3\text{He}$  gas. Conceived and developed the initial ideas for neutron spin echo spectroscopy and neutron cooling for the LENS neutron source at Indiana/IUCF; Greene, particle physicist from the University of Tennessee (UT), Project leader of Fundamental Neutron Physics beam at SNS, has more than 30 years of experience in precision measurements with low energy neutrons; he has an extensive experience in the design, construction, and operation of experimental apparatus as well as in the management of medium scale federally funded projects and programs; Kamyshkov from 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 for study of calorimeter options for SSC/LHC hadron colliders at ITEP/Moscow in 1990, in underground physics at KamLAND, with 13 years experience of studying NNbar transitions for implementation at ANS and HFIR reactors at ORNL and at DUSEL; Efremenko is joint UT/ORNL faculty with broad experience in detector design and participation in KamLAND, Majorana,  $\nu\text{SNS}$  and other big projects; Bugg, UT Emeritus Professor, high-energy physicist and long-time enthusiast of NNbar search; Dodds, UT Nuclear Engineering, with experience in nuclear reactor analysis, design, safety, and in nuclear engineering education; Ganezer from California State University at Dominguez Hills (CSUDH), particle physicist with experience of participation in Super-K experiments and search for intranuclear  $n \rightarrow \bar{n}$  transitions, Hill (CSUDH), particle physicist with experience of participation in neutrino experiments LSND, SNO, Super-K, K2K; and Pfiffner from UT Microbiology, with experience in education and outreach.

NNbar Collaboration also includes a group of nuclear scientists from Nuclear Science and Technology Division of ORNL: Flanagan, has extensive experience with research reactor operation, safety compliance, design, risk assessment, and cold source interfaces having been the engineering and safety manager for the HFIR for 15 years and having interaction with both the DOE and the NRC programs on reactors licensing and Environmental Impact Assessment; Johnson is a recognized expert in the development and application of radiation transport and shielding analysis methods for unique nuclear facilities such as the SNS target, space nuclear propulsion, and several defense-related programs; Williams has extensive experience providing cost estimates for the AFCI, Gen IV, GNEP, and space nuclear fission power and propulsion programs. ORNL group is applying to the Department of Energy for funding their activities in the proposed project. These activities will be joint and complementary to the activities of Nuclear Engineering groups of NCSU and UT. We also plan to use partially paid services of General Atomics Company (manufacturers of TRIGA reactors) for defining the configuration of the TRIGA

reactor and for help in the understanding of reactor infrastructure, operation, refueling, licensing, environmental impact, etc. (see Supplementary section of the proposal.)

Since experiment feasibility depends upon engineering of the vertical shaft facility, large-scale implementation, and cost; the participation of high-quality specialized engineers is crucial for our project. We plan to use the services of a team led by CNA Consulting Engineers for pre-conceptual design and underground engineering related to project feasibility (see Supplementary section). Engineers and experts will work closely with project scientists who will define the major parameters of the proposed experiment and provide corresponding physics simulations of expected performance. The CNA team will address the feasibility and cost of the proposed scheme of experiment and identify potential technical and cost showstoppers.

Feasibility issues relating to conceptual design and cost estimate of the focusing reflector, magnetic shielding, vacuum, and annihilation detector, will be studied mostly in the second year of the project, using engineering expertise available at the National Laboratories. Our current plan is in the first year of the project to establish collaboration with Lawrence Berkeley National Laboratory, who then will provide high-quality engineering for these technological issues during the second year of our studies (see LBL Letter of Interest in the Supplemental section of the proposal).

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), 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). We also plan to use paid consulting services of Martovetsky (ORNL) for magnetic shielding system calculations. Supplemental section of the proposal contains Letters of Interest and other information pertaining to these participants.

#### ***Deliverables and Time Scale of Proposed Work***

The result of proposed studies will be a report with conceptual and system description of the Vertical Facility for DUSEL and vertical NNbar experimental scheme and subsystems. It will provide a list of identified resolved and unresolved showstoppers with proposed options for their resolution and corresponding project cost variation implied by these options, as well as 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 in preparation of CDR and in following steps outlined by NNbar project development plan [31]. 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 and cost 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 24 months starting from June 1, 2008. First year will be devoted to the demonstration of feasibility of the reactor implementation at DUSEL (with participation of General Atomics Company) and to development of pre-conceptual design of the vertical facility (with participation of DUSEL and CNA Consulting Engineers Company). In the second year, continuing our studies with GA and CNA, we will address detailed feasibility study and cost of focusing reflector, passive magnetic shielding, vacuum system, and pre-conceptual design of annihilation detector. We assume that collaboration with a National Laboratory (LBL) will be built during the first year to address these engineering issues.

We have made a preliminary assessment of the possible cost [32] of the proposed NNbar experiment at DUSEL as to be in the range between \$169M and \$342M. Without a conceptual design and with insufficient construction engineering information this cost range cannot be considered as reliable. One of the major goals of our proposal is to produce an accurate cost estimate based on conceptual design, engineering studies, and parametric cost model.

We see the developments of this project as an opportunity to bring our scientific research ideas to the community of the state of South Dakota, to our local communities in the states and cities where our universities are located, and to the students in our Universities. These opportunities are discussed in the section below "Broader impact of the proposed activities".

### **Organization and detailed scope of the proposed studies**

Some of the feasibility issues and potential showstoppers are identified in the current proposal; others no doubt will arise and will be addressed in the course of the study. For the proposed initial studies we identified several most controversial issues with the potential to be showstoppers: (a) reactor at the DUSEL including issues of safety, security, ownership, licensing, and public relations to the local community; (b) large-volume vacuum tube failure mode safety; (c) potential reactor neutrino and neutron backgrounds for other DUSEL experiments; (d) identifying suitable vertical shaft at DUSEL and pre-conceptual design of the vertical flight path, parametric cost model and overall project cost estimate; (e) pre-conceptual design of large neutron reflector and magnetic shielding systems. Four universities in NNbar Collaboration (NCSU, IU, CSUDH, and UT) and the Reactor group at ORNL will perform these tasks with overall coordination provided by UT (Kamyshkov) who will act as the primary source of contact between the scientists, DUSEL site, and the engineering teams.

#### **(a) Feasibility issues and Detailed Scope for Reactor and Cold Source**

Nuclear Reactor Facility. Sub-thermal energy (cold) neutrons will be used for the  $n \rightarrow \bar{n}$  search. These neutrons will come from a liquid-deuterium cold neutron source (CNS) driven by a small university-type nuclear research reactor (NNbar reactor). It is anticipated that an annular core TRIGA reactor, operating at steady state with the CNS in the central void section, will serve as the NNbar reactor. With the assistance of North Carolina State University (NCSU) and Oak Ridge National Laboratory (ORNL), General Atomics (GA), as prime contractor, will oversee and direct all facets of the construction and licensing of this TRIGA reactor. Personnel at NCSU have had experience in licensing, operating, and using university research reactors at NCSU, The University of Texas (TRIGA), University of Illinois (TRIGA), and The University of Michigan. Personnel at ORNL have had experience in licensing, operating, and using large liquid-hydrogen cold sources and large neutron flight tubes at ORNL.

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 [33].

TRIGA's "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, a reactor power excursion is terminated quickly and safely by physics laws. This phenomenon, referred to as pulsing, is used in routine operation, and also serves to guarantee the safety of the reactor, independent of engineered mechanical safety systems. The history of safety and the conservative design of TRIGA reactors have permitted TRIGA's 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.

GA with the assistance of NCSU and ORNL will design a building to contain the NNbar reactor and support facilities 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.

Cold Neutron Source. NCSU with the assistance of ORNL and GA will design a CNS for the NNbar experiment. At this time, a thermosiphon-type CNS with liquid deuterium (LD) as moderator and coolant is thought to be optimum for operation in the relatively high radiation field at the center of a nuclear reactor. A reasonable size for such a LD cold source is 20 liters. A cold source at the Institute Laue-Langevin has a volume of 27 liters of D<sub>2</sub>; the cold source at the Technische Universität München (FRM-II), 15 liters of D<sub>2</sub> + 5 % H<sub>2</sub>; the cold source at Australian Nuclear Science & Technology Organization, 15 liters of D<sub>2</sub>. Using a calculated heat load of 5000 W, a conceptual design for a CNS for the NNbar experiment has been developed by NCSU based on the liquid hydrogen cold source operating at the NBS reactor at the National Institute of Standards and Technology (NIST) [34].

ORNL has just finished with the design and initiated operation of four cold source systems in large nuclear facilities: a cold source for the HFIR and three cold sources for the SNS. In particular, ORNL will apply its recent experience in the construction, design, and operation of the HFIR and its associated cold source to address the safety, licensing and compliance, operations, reactor modifications, integrated (reactor/cold source) instrumentation and control systems, training, siting, and environmental impact issues which will complement the studies being done by NCSU and GA described above. As an example, in addition to the reactor issues associated with having a cold source located within or immediately adjacent to a reactor core, ORNL experience indicates that other issues related to the location and sizing of support facilities, such as the refrigerator and storage tanks, building layout, piping layout and lengths, emergency power, hydrogen venting and waste disposal, have been identified as having significant impact on reliability, efficiency, cost, and licensing issues.

Reactor Licensing, Ownership and Public Outreach. The design, construction, and operation of the annular core TRIGA reactor proposed for the  $n \rightarrow \bar{n}$  search is a major undertaking needing a great deal of work. However, as mentioned above, similar reactor facilities have been successfully built and operated in this country and abroad. Thus, we anticipate that GA with the assistance of NCSU and ORNL will resolved all reactor specific questions about reactor safety and protection, licensing and liability, environmental impact, primary and secondary cooling systems, staffing, decommissioning, etc. The Nuclear Regulatory Commission (NRC) regulates TRIGAs under the “non-power reactor” classification. The licensing of non-power reactors is described in NUREG-1537 [35], and is much less work than the licensing of power reactors.

The proposed DUSEL experiment introduces unique interfaces between the reactor and a number of subsystems, such as the magnetic field reduction system, the vacuum systems, the refrigerator and cryogenic storage systems, the experiment detection system, and emergency power systems. In order to obtain a license for reactor operation with these subsystems, it must be assured that these interfaces cannot have adverse effects on the safety and performance of the reactor. ORNL experience in addressing such system interaction problems and application of risk analysis techniques to similar systems interactions experienced with the HFIR cold source and SNS complement the work proposed by NCSU and GA. In addition ORNL has been working with the NRC on application of risk-based licensing which takes into account such interactions. ORNL will work closely with NCSU and GA to address the nuclear subsystem feasibility issues called out by the Homestake DUSEL program advisory committee.

There is one reactor-related crucial feasibility issue, viz., who will take responsibility for (i.e., own and operate) the annular core TRIGA reactor? To resolve this reactor-related feasibility issue, NCSU and The University of Tennessee (UT) will study this issue with respect to the local acceptance of siting a reactor at DUSEL and the cost of the reactor and fuel. Then they will initiate pursuit of ownership by (a) South Dakota, (b) an agency of South Dakota such as a University, (c) the DUSEL laboratory at the mine site, or (d) any other legitimate federal or state organization. ORNL will explore the safety implications of the options for NNbar reactor ownership.

NCSU, UT, GA, and ORNL will provide technical information and address public concerns regarding the safety, security, licensing, and ownership of the reactor. This will be done as part of the outreach and education process as described in this proposal using DUSEL local community contacts through public lectures, question and answer forums, presentations at educational institution, and the public media. This will be carried out in a way similar to the procedure used by NRC for assessment of public concerns in development of Environmental Impact Statement during power reactor licensing [36].

Cost and Performance of Reactor and Cold Source. There are two system-feasibility issues: (a) total costs for the annular core TRIGA reactor operating for 5 years, and for 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? First cut answers to both of these issues have been obtained with some arbitrary assumptions.

The total cost for the annular core TRIGA reactor operating for 5 years, determined from estimates of reactor related costs provided by General Atomics for a single purpose reactor, is \$46M to \$75M [32]. St. Petersburg Nuclear Physics Institute (PNPI) provided a quote for construction of a thermosiphon LD cold source at a total cost of \$5M to \$7M [32].

A better estimate 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 vs single

purpose design, which is related to the ownership issue. ORNL is involved with cost estimation of unique DOE nuclear facilities such as those associated with the Advanced Fuel Cycle Initiative, the Generation IV reactor program, the Global Nuclear Energy Partnership (GNEP) facilities, and the space nuclear fission power and propulsion program. ORNL will apply these same techniques to the nuclear subsystem of the DUSEL experiment and review the costs provided by GA, and PNPI to assure consistency.

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 require operating, fuel, and decommissioning costs to be included in the cost of experiment. Our initial cost assessments [32] are based on the latter option.

The performance of a 19-L LD cold neutron source located in the central void of a TRIGA annular core reactor was calculated by NCSU using MCNP. Because of the conservatism of the MCNP model used, the results of this simulation indicate that, at a reasonable power (3.4 MW), such a cold source can produce the sufficiently large number of cold neutrons (moderator CN flux  $> 10^{13}$  n/cm<sup>2</sup>-s) required to give the sensitivity quoted earlier in this proposal [37]. Thus, the first cut at cost and performance indicates that the proposed TRIGA reactor with cold-source can produce the sufficiently large CN flux at a reasonable cost. NCSU will work with General Atomics to finalize these results. In addition, NCSU will do MCNP calculations with more detailed MCNP models independent of General Atomics to verify their results. NCSU will also calculate the position, angle, and energy dependences of the cold neutrons entering the vertical flight tube.

Radiation Transport, Shielding, Materials Irradiation, and Background. ORNL is a recognized leader in the development and application of radiation transport methods to unique issues. Using the MCNP results obtained by NCSU above and other source estimates ORNL proposes to apply its expertise to the unique issues associated with the proposed NNbar experiment. These involve the optimization of the transport of a focused cold neutron beam from the cold source to the detector system within a large evacuated tube containing magnetic isolation equipment over distances of 1 km. Issues that need to be addressed are materials activation, cold source beam intensity losses, fast neutron and, gamma attenuation, optimization of detector location, shielding of sensitive detection equipment and electronics, and irradiated materials behavior. Experience gained from similar analysis associated with the HFIR and SNS cold beams will be applied to the DUSEL experiment. This will complement the work proposed by NCSU and GA in being able to optimize cold neutron beam strengths, the choice of materials, special shielding requirements for detectors and monitors, system maintenance, and interaction with adjacent experimental facilities. It will also address disposal issues at the completion of the experiment.

Another issue for the use of reactor at DUSEL, as was mentioned by Homestake PAC [27], is the reactor as a potential source of neutron background for other DUSEL experiments. With anticipated distance of ~ 2 km between the reactor and the main DUSEL experimental underground campus the shielding for fast and thermal neutrons can be achieved with relatively small amounts of bulk materials. Although we do not see neutron background as a serious showstopper issue, ORNL plans to continue studying neutron backgrounds in the course of our proposed project. Not-expensive passive neutron shielding can be designed to eliminate reactor-induced neutron background to the level of underground environmental neutron background.

***(b) Large-volume vacuum tube failure mode safety***

The NNbar experiment employs a large vertical vacuum chamber ~1 km long and ~4-5 m diameter with the total vacuum volume up to 30,000 m<sup>3</sup>. The vacuum chamber will have large entrance window for the neutrons. Failure of the window clearly represents a serious potential safety hazard. A detailed engineering safety analysis will be performed (Snow/IU, LBNL/second year).

***(c) Potential reactor backgrounds for other DUSEL experiments***

Proposed 3.5 MW TRIGA reactor at a distance of ~ 2 km from the main underground DUSEL campus is a source of antineutrinos and thermal neutrons that can be a potential background for other experiments planned for DUSEL. In spite of controlled nature of this background detailed studies are required to

demonstrate the feasibility of the reactor. Shielding for fast and thermal neutrons can be easily achieved with relatively small amount of the bulk materials. One can also calculate (see supplemental section) that the flux of reactor antineutrinos at the distance of  $\sim 2$  km is substantially smaller than irreducible flux of solar neutrinos of similar energy, that have to be coped with in the proposed  $2\beta 0\nu$  and dark matter search experiments at DUSEL. TRIGA reactor antineutrino flux will be certainly a substantial background for geo-neutrino detection experiment, provided that the schedule of the latter at DUSEL will coincide with the schedule of running of NNbar experiment. Although with present estimates we do not see neutron or neutrino background as a serious showstopper issue, we plan to continue studying these backgrounds in the course of our proposed project (CSUDH and ORNL groups).

***(d) Feasibility issues of vertical shaft availability and vertical construction***

All vertical shafts available at DUSEL will be evaluated to identify a candidate shaft. This will include study of available drawings, descriptions and dimensions, inspection of these shafts by local site experts. The candidate shaft will be surveyed for straightness, and the 3-component of geo-magnetic field along the length of the shaft, since the presence of local magnetic anomalies may severely complicate the design of magnetic shielding system. The most important engineering feasibility issue is overall cost of technically viable construction of the vertical experiment with proposed performance parameters that will comply with the requirements from mine infrastructure, operation, and safety. The use of an existing DUSEL shaft would significantly reduce the project cost. If no existing DUSEL shaft is available, we will estimate the cost of an option of construction of a new shaft at DUSEL. Difficulties and issues of the vertical construction to be addressed in our study are essentially generic for either option.

Studies at the Homestake mine will be coordinated by Kamyshkov/UT who will work with local mine engineers and consultants from South Dakota universities and with CNA, and will interact with DUSEL Lab and with South Dakota Science and Technology Authority (SDSTA) for technical and access issues. Scope of work of UT group will include: survey of existing vertical shafts at Homestake; measurements of dimensions and straightness of the candidate shaft; measurement of magnetic field in the shaft; simulation the muon-induced and neutron beam induced backgrounds in the NNbar detector.

The CNA Consulting Engineers team, lead by Lee Petersen, will be a sub-contractor to UT, providing conventional and underground engineering with following scope (more detailed description of CNA scope is given in supplemental section of the proposal): (1) Develop concept drawings of surface support spaces, underground layouts, cross sections and elevations, and revision of 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 based on information provided DUSEL and SDSTA; (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, and recommendations for future activities.

UT group together with CNA 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 the focusing reflector, reflecting quality of the mirror, acceptance of the detector, cold source brightness 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 UT and CSUDH groups who will also address the issue of backgrounds in the detector including cosmic muon interactions, fast spallation neutrons, and high-flux of low-energy  $\gamma$  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 [5], for mitigation of the flux of capture  $\gamma$ s.

We anticipate that the detector design for NNbar DUSEL experiment will follow that of the experiment performed at ILL/Grenoble [5] where strong background suppression (zero background expected) was provided by the virtue of its design. The NNbar detector at DUSEL located deep underground should be more robust with respect to background, thus, we expect that a single observed  $n \rightarrow \bar{n}$  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.

#### **(e) Pre-conceptual design of neutron focusing reflector and magnetic shielding systems**

Neutron Reflector: The experiment requires a focusing neutron reflector with the cold source at one focus and the annihilation detector at the other focus. The *vertical* flight path avoids defocusing of the neutrons due to gravity. The length of the reflector is  $\sim$  tens of meters (up to 150 m) and the maximum radius of the reflector is  $\sim$ 1-2m. The neutron reflector needs to be installed inside the vacuum chamber and magnetic shielding. The optical elements consist of multilayer neutron “supermirrors”. Although the elliptical shape could be approximated by a tiled set of flat supermirrors, curved neutron mirrors can now be made commercially [38, 39]. The neutron guide for the WISH diffractometer at ISIS [40] will employ a horizontal 40 m elliptical neutron guide enclosed in a large vacuum tank and will possess some technical with our proposed reflector.

We propose to investigate the neutron optics of 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. We will involve an IU undergraduate in simulations to explore within these constraints the sensitivity of the experiment to changes in the reflector geometry. Existing neutron optics simulation packages such as McStas and VITESSE will suffice.

The experiment may need to produce its own supermirror coating facility for more economical mass production. Since neutrons will bounce off of the reflector only once we are less sensitive to some types of mirror imperfections that concern manufacturers of supermirror neutron guides for neutron scattering beamlines. We will analyze the sensitivity of the reflectivity to the characteristic types of mirror non-uniformities to identify the relevant parameter space for a cost-effective production method. These studies will be conducted by our collaborator H. Shimizu/KEK, who directs a Japanese neutron optics project studying a number of cutting-edge neutron optical technologies (see Supplemental section). In addition we propose to consult with Swiss Neutronics on various aspects of the reflector.

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 the requirements for the vacuum tube.

Magnetic Shielding: The magnetic field inside the vacuum chamber needs to be reduced to a few nano-Tesla. This was achieved in the previous ILL experiment with a one-layer shield [41] of  $\sim$ 1m diameter 80 meters long. The dominant component of the residual magnetic field inside a long cylindrical shield is axial, and in the limit of an infinite shield and no transverse fields the residual longitudinal component becomes uniform. The strategy is therefore to suppress transverse components of the magnetic field and render the longitudinal component sufficiently uniform that it can be compensated by a solenoid. 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 required at ILL to maintain the quasi-free condition.

Members of our collaboration have employed a 2m long magnetic shield for a neutron spin rotation experiment consisting of two layers of  $\sim$ 1m diameter  $\mu$ -metal of 1.5 mm wall thickness and an external coil with an active compensation system. Even with 15 cm x 15 cm holes in the endcaps this system suppresses internal fields to  $<10$  nT over the central 1m length in passive operation and keeps local field

variations to less than 1nT in the presence of changes in the external field of ~0.5 Gauss. This system will be available for use on the timescale of this proposal as a test bed for magnetic shielding development. 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  $\mu$ -metal; (b) identification of a strategy for assembly and annealing of the shields: this will likely involve construction using a series of flat panels as demonstrated by PNPI in their magnetic shields developed for neutron EDM experiments; (c) 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;(d) Analysis of the loss of sensitivity of the oscillation measurement to various types of time and space-dependent residual magnetic fields; (e) Investigation of the compatibility of nonmagnetic 304L stainless steel for the vacuum chamber 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 ORNL) to explore these possibilities.

Neutron Polarimetry: Periodic in-situ measurements of the magnetic fields seen by the neutrons are important to verify that the quasifree condition for neutron-antineutron oscillations is maintained. 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 a typical cold neutron with a ~1 second flight time rotates 0.2 radians in a B=1 nT field.

The neutron cold source produces a broad spectrum of neutron velocities and this will lead to a distribution of rotation angles. With a second magnetic coil before the polarization analyzer with a known internal field and length, the measurement can be operated in "spin echo" mode [42]. 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. 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  $^3\text{He}$  gas. Such neutron spin filters have been developed over the last decade for neutron scattering applications [43].

Vacuum Chamber and Quality of Vacuum: The neutrons must travel in a vacuum of  $\sim 10^{-5}$  Pa so that the difference between the neutron and antineutron optical potential in the residual gas does not violate 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 (b) Analysis of the mechanical stability of the 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 the tube manufacture.

There is extensive experience with the 2 km long, 1.2 m diameter chambers for the LIGO gravitational wave observatory. The LIGO vacuum tubes are pumped to  $\sim 10^{-9}$  torr after 2 months of pumping with 9 pumps, each connected to a 25 cm diameter pumpout port and ar4 maintained with only pumping at the ends of the chamber. This was achieved through the use of nonmagnetic 304L stainless steel baked at 150C by electrical heating of the tube (using the tube as a resistor) with steel heat-treated during manufacture to reduce the hydrogen outgassing rate from the usual  $10^{-11}$  torr liters/sec/cm<sup>2</sup> to  $5 \times 10^{-14}$  torr liters/sec/cm<sup>2</sup>. 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 [44].

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 larger 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 we expect will contribute engineering support and analysis of possibilities.

### ***Broader Intellectual Merit Impacts***

Other DUSEL experiments will benefit for the reasons that relevant scientific and design issues, i.e., availability of vertical shafts, shaft straightness, geo-magnetic measurements, will be addressed in this study. First of all these are the experiments [28-30] that rely on using Vertical Facility at DUSEL. The possibilities also exist for multiple purpose uses of the reactor and or facility (i.e., production of short-lived radioisotopes for detector calibration or Neutron Activation Analysis).

### ***Broader Educational and Outreach Impacts***

Science, Technology, Engineering, and Math (STEM) education has been identified by NSF and other national science organizations as a critical need to meet U.S. workforce needs and to sustain United States competitiveness internationally [45,46,47]. To address this need, the PIs will follow the recommendations in the Deep Science Report [48], as well as coordinate with Ben Sayler, the education and outreach lead for Homestake DUSEL. From an educational and outreach standpoint, this study provides opportunities for spreading knowledge about DUSEL, increasing science literacy and science content, and improving networks with target audiences of (1) graduate or undergraduate students, (2) visits to high school science classrooms, and (3) general public (via the web site).

The goals of the education plan for undergraduate and graduate students is (1) to increase their knowledge base and understanding of how large scale design and feasibility studies are done, (2) to expand their knowledge and communications skills regarding the cross disciplinary nature of this project, and (3) to interact with scientists and develop an international scientific network of collaborators. This plan will include authentic research experiences related to this project, college coursework enhancement, and direct interaction and networking of undergraduates with scientists and professionals. To accomplish these goals, undergraduate and graduate students will be involved in the design efforts and in performance and background simulation of experiment. PIs will visit and provide a lecture with discussion at various campuses (USD, DSU, SD State and SD School of Mines). The coursework enhancement will consist of adding a new topic within established System Design courses at UT and NCSU. This new topic will be based on the leading-edge efforts of reactor and CNS design for the NNbar experiment at DUSEL.

The goals of the education plan for high schools and the public are to spark interest in science at DUSEL, to highlight science career paths, and to address potential concerns of the public regarding the construction and operation of a small research reactor on the DUSEL site as part of the NNbar experiment. These audiences will have access to an NNbar web site that will contain information on the NNbar experiment, DUSEL science, associated presentation and hands' on activities and links to related web sites. Local public outreach will be achieved through four public seminars/lectures that will be associated with the project meetings. These seminars will reach out to these audiences at college campuses, in high school classrooms, and local community groups. Christina Keller (USD) in South Dakota will assist with advertising these activities and providing advice on presentation format and activity evaluations. Seminar material will be developed by the PIs for presentation to these audiences. Seminar material will consist of slides on research reactor design and inherent safety aspects of the TRIGA reactor, the licensing process, as well as, on energy resources, the role of nuclear technology in the future and how these issues relates to scientific research at DUSEL. Additional materials and information will be provided about other science discipline research at DUSEL and the future advantages for the state of educational training of students for scientific and technical employment (handouts and URLs). An example is the installation of TRIGA at the DUSEL site for use by Nuclear Engineering students as a means for both education and research training. Assessment of this plan will include questionnaires as well as interviews.

To extent the education and outreach efforts should this proposal be funded, a supplemental proposal will be requested to support two workshops. The year one workshop will target engineering and physics

undergraduates and will be held near the DUSEL facility. For this 2-3 day workshop, we will recruit several undergraduate students from universities located within the DUSEL region as well as from the pool of students involved directly with this research project at our respective institutions. In addition to providing travel and a stipend for the students, we will provide travel for four scientists or professionals. This workshop will overlap with a scientific meeting so that there will be direct contact and shared ideas between the students and science professionals. Due to the multi-disciplinary nature of this feasibility study, we plan to recruit undergraduates majoring in physics and engineering (nuclear, mechanical, electrical). Workshop topics include those controversial issues described above in the detailed scope of the proposed studies. Evaluations of the undergraduate activities will include pre and post questionnaires, final reports and oral presentations by undergraduates directly involved in NNbar research (with assistance from their advisors) and assessment of the workshop [49].

The year 2 workshop will target on high school physics teachers. This workshop would focus on the physics and other sciences at DUSEL to provide a scope of the interdisciplinary nature of DUSEL. This 2-day workshop would concentrate on increasing their knowledge base and understanding of physics experiments planned at DUSEL and how to bring this cutting-edge science into their classroom. Assessment of the teachers will involve pre and post questionnaires and a follow-up on what aspects or lesson plans were used in their classrooms.

### ***NSF Prior Support***

**Snow.** PHY-0100348, 0457219 Results: measurement of neutron lifetime and neutron interferometric measurements of n-p, n-D, and n-3He coherent scattering lengths, measurement of parity violation in polarized neutron capture on medium-mass nuclei. PHY-0242300 Results: conceptual design of LENS neutron source. PHY-0320627 Results: construction of LENS accelerator, target, moderator, measurement of cold neutron spectrum. PHY-0220560 Results: construction of SANS spectrometer and initial measurements. PHY-0116146, 8/01-8/03 Results: successful construction of CsI gamma array, used now in NPDGamma experiment. PHY-9501312 and Special Creativity Extension. Results: development of neutron polarizers based on polarized 3He gas, use in neutron reflectometry, measurement of absolute neutron polarization. PHY-0331217 Result: collaborative research agreements with SNS on neutron detectors.

**Young** received initial support for "Using the Princeton Cyclotron, Lasers, and Ultra-Cold Neutrons" from grant 9807133, and has carried on with ultracold neutron research in grants 0100689, 0354970 and MRI award 9977557. This research produced the first optically pumped Rb in 2K He vapor, results for the APEX experiment, the first solid deuterium ultracold neutron source coupled to a spallation target, the construction of the UCNA experiment at Los Alamos, and work on next generation UCN sources.

**Hawari** receives support on a current project "Development of an Intense Positron Annihilation Spectrometry System for Nanophase Characterization", through grant 0521270, for which there are no findings yet. A. R. Young and A. Hawari share support for "A Superthermal Ultracold Neutron Source at NCState University," through grant 0314114. The source is currently under construction.

**Pfiffner.** EAR-02441130, REU Site: Biogeochemical Education Experience-South Africa. A total of 82 undergraduate and graduate students, and science professionals represented 24 institutions of higher learning participated in the 2003-04 REU. US undergraduates with majors in geosciences, chemistry, and biology completed hands-on, hypothesis-driven research projects. The REU program had a positive impact on career decisions. Students are in graduate/medical school (13), in STEM occupation (2) and poised to graduate (2).

**Kamyshkov** shares with Snow and Young current grant PHY-0736996 for Workshop on the "Search for Baryon and Lepton Number Violations" that took place at LBNL, September 20-22, 2007.

**Ganezer** current grant PHY-0401139 for participation in Super-K experiment resulted in a new limit on intranuclear bound  $n \rightarrow \bar{n}$  transition along with many other physics results. Previously he was a PI on NSF research grants PHY-0071656 (08/1/00-07/31/04), PHY-9514150, PHY-9208472, and on instructional laboratory improvement grant PHY-9352746.

**Hill** shares current grant PHY-0401139 with Ganezer; his current grant 0227016 allows participation in LA education and outreach.

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