November 11, 2007

Working Group A3: New NNbar Experiment at DUSEL

1. Physics Motivation

Recent theoretical, as well as experimental, developments in the field of neutrinos have provided very compelling reasons for the existence of NNbar oscillation 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 the proton decay situation in the late seventies, when emergence of SU(5) theory, despite its shortcomings, had a prediction for proton lifetime that was within experimental reach and which led to a host of proton decay search experiments. While these experiments failed to observe proton decay, they nonetheless considerably enhanced our understanding of possible GUT theories. 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 minus lepton) symmetry scale and quark lepton unification. An explicit discovery will be of course a major step towards our 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 N-Nbar transitions:

(i) There are ample indications that baryon number is not a good symmetry of nature; the most profound being that it is an essential ingredient in microscopic understanding of origin of matter in the universe [1]; another being that not only the standard model [2] but also many of its simple extensions 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; (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 neutrino implies $\Delta(B-L)=2$. 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, Majorana mass of neutrino implies N-Nbar oscillation if one wants to understand matter-antimatter asymmetry. Thus, cosmology plus neutrino physics in a unified quark-lepton framework would predict the existence of N-Nbar oscillation [4]. Since there is no proton decay in such models, the scale of new physics can be considerably lower and N-Nbar oscillation can determine this scale.

(iv) With available technologies, the reach of the neutron-antineutron 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 for S4 is to study the feasibility of such a new N-Nbar DUSEL experiment based on the available technologies. A key question then is: are there plausible models where N-Nbar oscillation time is predicted to be close to or below this observable limit? The answer to this question is **yes** and the model is Pati-Salam extension of the Standard Model with a completion to generate baryon asymmetry of the universe. In its non-supersymmetric version, N-Nbar probes the B–L breaking scale up to 3×10^{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 SUSY models, a phenomenon familiar from the study of proton decay.

Discovery of N-Nbar oscillation will then 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 will also reveal that the same interactions that generate neutrino mass are also responsible for baryon violation and matter anti-matter asymmetry thus providing a unified description of several important issues in particle physics and cosmology.

Existence of N-Nbar might be also 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 a first experimental indication of the presence of extra-dimensions in Nature. The N-Nbar process also arises in other attempts to understand the origin of matter [10]. Thus search for NNbar oscillation can throw light on a wide variety of beyond Standard Model physics. Since the right component of neutron is a singlet of the Standard Model it makes the neutron a unique object to reveal new interactions beyond the Standard Model, such as mentioned above 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 $p \to e^+ + \pi^0$ which arises via gauge exchange with a life time of 10^{36} years is fairly model-independent whereas mode $p \to \bar{\nu} + K^+$ which can arise with 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 $n \to \bar{n}$, $\mu \to e\gamma$, $\nu \leftrightarrow \bar{\nu}$ etc. provide access to the highest energy scale > 100 TeV. This energy scale presently is not attainable by LHC and ILC colliders.

Probability of $n \to \bar{n}$ oscillations in vacuum [4] 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 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 experimentally established [5] 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 $n \to \bar{n}$ transitions rather than oscillations.

Transitions $n \to \bar{n}$ 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/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 [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 τ_{Free}. Sensitivity in case of intranuclear transitions is limited by the presence of atmospheric neutrino background. Further improvement of NNbar limit in intranuclear transition, 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. Physics of NNbar transitions was discussed e.g. at the recent International Workshop at LBL “Search for Baryon and Lepton Number Violations” in September 20-22, 2007 [15].

2. Description of the Proposed Experiment

The new, proposed high-sensitivity method of $n \to \overline{n}$ search is based on the use of combination of high flux of low energy neutrons from a cryogenic cold neutron source and an elliptical focusing reflector [16] concentrating cold neutrons onto the target. Sensitivity to observation of $n \to \overline{n}$ transitions is proportional to the product of available neutron flux and the square of neutron observation time in quasi-free state. In order to increase the time of observation of the neutron, it is necessary to slow down the neutrons and to increase their flight path. For the case of a horizontal beam of neutrons, gravity becomes an important perturbation for a non-monochromatic cold beam motion and limits the sensitivity to NNbar transitions per neutron. Therefore, we propose a vertical experiment for DUSEL [17] that eliminate the defocusing effect of gravity. The experiment requires a small dedicated research reactor with cryogenic moderator to provide a high-brightness source of cold neutrons. Such vertical layout at DUSEL allows an increase in sensitivity to $n \to \overline{n}$ oscillations by a factor of >1,000 with respect to the previous best experiment [5] which established the limit for $n \to \overline{n}$ oscillation time of $\tau_{free} > 8.6\times10^7$s.

The neutron source will be installed at DUSEL on the top of a dedicated (existing or new-constructed) vertical shaft with diameter ~ 5 m and the length of 1–1.5 km at the direct distance ~ 2 km from the main underground laboratory. A standard 3.4 MW research reactor of TRIGA type (commercially available from the General Atomic Company) with annular core equipped with cryogenic liquid deuterium moderator is proposed as the source of cold neutrons. The experiment will employ 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 km-long vacuum flight path onto and the annihilation detector located in the second focus of the ellipse. Such a neutron “optical” system provides a substantive increase in the useful source phase space. However, 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 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 $n \to \overline{n}$ transition.

The focusing neutron reflector will be installed inside the vertical vacuum chamber. The vacuum chamber should have a vacuum better than 10^{-4} Pa. In order to preserve the quasi-free condition, the Earth’s magnetic field inside the vacuum chamber must be reduced along the flight path to less than a few nano-Tesla. This will be accomplished by a combination of active and passive magnetic shields Requirements similar to these were achieved in the previous NNbar ILL/Grenoble-based experiment [5]. Antineutrons will be detected by an antineutron annihilation detector located in the experimental hole at the bottom of the mineshaft. The antineutron detector will be similar to one used in the experiment [5] at the ILL/Grenoble reactor with a thin 130μm carbon foil with diameter ~ 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, providing excellent discrimination against background events (primarily due to cosmic ray interactions). The tracker will be surrounded by a calorimeter, a cylindrical detecting layer that measures 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 the cosmic ray-induced events. We note that, in the previous best measurement, a similar sort of detector operating on the earths surface detected no background events in ~1 year of running. After ~3 years of experiment operation the sensitivity of the proposed $n \to \overline{n}$ search is estimated to be a factor of > 1,000 higher than in the previous search at ILL/Grenoble reactor [5]. The improvement is due to the very long vertical flight path, the cold moderator, and the focusing neutron reflector. The 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. 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 in respect to the $n \to \overline{n}$ intranuclear transitions, $\gtrsim 10^{35}$ years, a goal that cannot be obtained in the intranuclear search with large underground detectors.

A vertical NNbar experiment will be a unique experiment at DUSEL. No other underground laboratories provide the option for such an experiment. Due to significant increase of the sensitivity and clear signature, the experiment at DUSEL will have a potential to make a major physics discovery of fundamental importance.

3. Roadmap of the Proposed NNbar Experiment

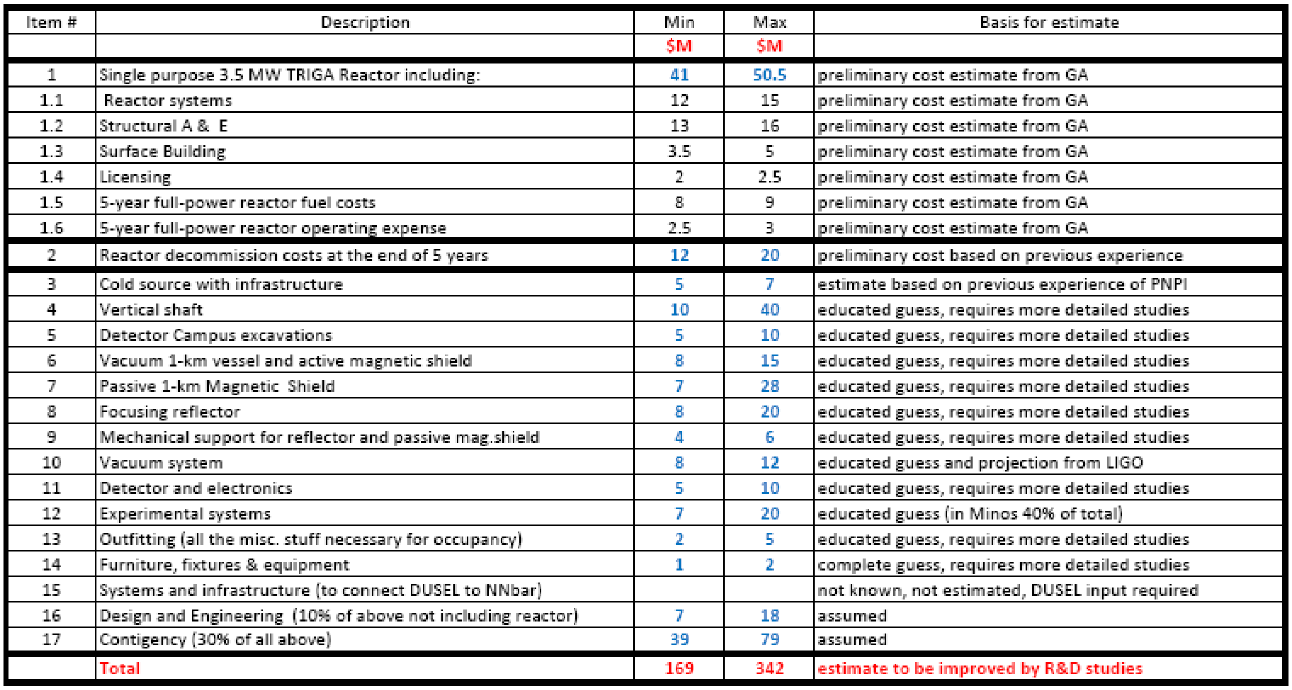
In 2006 the Homestake Program Advisory Committee [18] has found "this proposal of significant scientific merit, and endorsed consideration as a long-range possibility for DUSEL. For the Early Implementation Program, the PAC recommends the engineering and feasibility studies needed to develop a full proposal 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 nano-Tesla, 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".

Following these recommendations as well as recommendations of November 3-4, 2007 DUSEL meeting at Washington, DC the proponents of the NNbar experiment are proposing a roadmap for the development of the project.

2007-2008:	Scientific and Technical Review of the NNbar physics and experimental method;
2008-2009:	Included in S4: Feasibility study, CDR, project schedule and cost estimate;
2009-2010:	Included in 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

Proposed NNbar can be one of experiments performed at the DUSEL "Vertical Facility" which was discussed at the meeting in the working group B2 ("Other Uses") .

Table 1. Cost range of proposed NNbar experiment. The costs shown in this table represent a highly conservative min-max range that has been prepared without the benefit of detailed preliminary engineering studies. The proposed R&D effort will provide the information required for preparation of a reliable cost estimate.



Item #	Description	Min	Max	Basis for estimate
		$M	$M	
1	Single purpose 3.5 MW TRIGA Reactor including:	41	50.5	preliminary cost estimate from GA
1.1	Reactor systems	12	15	preliminary cost estimate from GA
1.2	Structural A & E	13	16	preliminary cost estimate from GA
1.3	Surface Building	3.5	5	preliminary cost estimate from GA
1.4	Licensing	2	2.5	preliminary cost estimate from GA
1.5	5-year full-power reactor fuel costs	8	9	preliminary cost estimate from GA
1.6	5-year full-power reactor operating expense	2.5	3	preliminary cost estimate from GA
2	Reactor decommission costs at the end of 5 years	12	20	preliminary cost based on previous experience
3	Cold source with infrastructure	5	7	estimate based on previous experience of PNPI
4	Vertical shaft	10	40	educated guess, requires more detailed studies
5	Detector Campus excavations	5	10	educated guess, requires more detailed studies
6	Vacuum 1-km vessel and active magnetic shield	8	15	educated guess, requires more detailed studies
7	Passive 1-km Magnetic Shield	7	28	educated guess, requires more detailed studies
8	Focusing reflector	8	20	educated guess, requires more detailed studies
9	Mechanical support for reflector and passive mag.shield	4	6	educated guess, requires more detailed studies
10	Vacuum system	8	12	educated guess and projection from LIGO
11	Detector and electronics	5	10	educated guess, requires more detailed studies
12	Experimental systems	7	20	educated guess (in Minos 40% of total)
13	Outfitting (all the misc. stuff necessary for occupancy)	2	5	educated guess, requires more detailed studies
14	Furniture, fixtures & equipment	1	2	complete guess, requires more detailed studies
15	Systems and infrastructure (to connect DUSEL to NNbar)			not known, not estimated, DUSEL input required
16	Design and Engineering (10% of above not including reactor)	7	18	assumed
17	Contigency (30% of all above)	39	79	assumed
	Total	169	342	estimate to be improved by R&D studies

4. Major R&D Issues for S4

The following R&D issues for NNbar experiment development are proposed to be included in S4 process:

(a) Potential show stoppers that need elaborate assessment:

- *Safety, Regulatory, and Legal Issues for the neutron source at DUSEL.* This study will include assessment of the potential South Dakota public concerns about the reactor at DUSEL site and also the development of detailed plans for reactor ownership, licensing, safety, operation, and decommissioning. NNbar Collaboration includes a number of Nuclear Engineering experts from Universities (NCSU, UT) and Oak Ridge National Laboratory with significant experience in licensing, operation, and decommissioning of the research reactors who are qualified to address these issues. Also, existing established contacts with General Atomics (GA), the Southeast Universities Nuclear reactor Institute for Science and Education (SUNRISE Consortium), and International Group on Research Reactors (IGORR) should facilitate these studies.

- *Large vacuum chamber safety.* The proposed NNbar experiment concept includes vertical vacuum chamber with the length 1-1.5 km and diameter 4-5 m with total vacuum volume up to 30,000 m^3 with front window for the neutron entrance. This large vacuum volume represents a potential hazard in case of failure. A detailed engineering safety analysis will be performed.

- *Reactor backgrounds for other DUSEL experiments.* The proposed 3.5 MW TRIGA reactor at a distance of ~ 2 km from the main underground DUSEL campus is a source of antineutrinos (with flux comparable with the flux of solar neutrinos) 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 at DUSEL site.

(b) Other technological and cost issues that need to be addressed in R&D S4 studies:

The feasibility of the technological items listed below, while demonstrated at small scales, must be proven for the large-scale DUSEL NNbar experiment. The feasibility of these technological issues will be addressed by detailed engineering and simulation studies which will allow the development of a conceptual design and cost estimate.

- *Vertical shaft engineering*. The vertical shafts available at DUSEL will be surveyed to find a candidate shaft or a plan for construction of a new vertical shaft will be developed. The physical dimensions of the available shafts and particularly the straightness of the candidate shafts will be addressed in the engineering study or measured. A measurement of 3-component Earth magnetic field along the vertical shaft and the investigation of possible of magnetic anomalies will be important for the design of the magnetic shielding of the NNbar experiment at DUSEL.

- *Conceptual design of the vacuum chamber*. The vertical vacuum chamber for NNbar experiment will have a volume up to 30,000 m^3 and must be designed and constructed with wall supports. It also must incorporate the active and passive magnetic shielding as well as the focusing reflector. Previous experience of construction of large vacuum chambers in LIGO project will be used for a design guidance.

- *Conceptual design of the active and passive magnetic shield*. All 3-components Earth magnetic field need to be actively compensated and passively shielded down to a residual level of ~ 1 nT. The magnetic shielding system must be designed with the supports inside the vacuum tube and with construction and installation scenarios. Such a design will allow the preparation of a reliable cost estimate.

- *Conceptual design of the neutron focusing reflector* The physical parameters of the elliptical focusing reflector (length, diameter, position, required quality of reflection) will be simulated and optimized in a parametric study along with cost and other system parameters. The economical production of large-area reflectors must be addressed along with possible international collaborations in this area. Conceptual design, cost estimate, and construction scenario will be prepared in engineering studies.

5. Education and Outreach

From an educational and outreach standpoint, proposed NNbar development study provides opportunities for spreading knowledge about DUSEL, increasing science literacy and science content, and improving networks with target audiences of undergraduate students and general public at the proponents Universities and in South Dakota. 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 cold neutron source design for the NNbar experiment at DUSEL. The goal of attracting undergraduates to the research will be accomplished through an engineering and physics workshop near the DUSEL facility. For this 2-3 day workshop, a group of undergraduate students from South Dakota universities as well as from the pool of students involved directly with this research project in the proponent's home institutions will be recruited. This workshop will overlap with a scientific meeting so that there will be direct contact and shared ideas between the students and science professionals. Another planned activity will be a workshop for the South Dakota science teachers where DUSEL science ideas and technical challenges will be discussed and the teachers will be provided with the materials about DUSEL and NNbar project for their science class presentations.

The goals of the education plan for the public are to spark interest in science at DUSEL and to highlight science career paths. Local public outreach will be achieved through the public seminars/lectures that will be associated with the project meetings. These seminars will reach out to public audiences at college campuses, from K-12, and local community groups. Seminar material will consist of slides on scientific topics (e.g. "antimatter in the universe", "does a mirror universe exists?" etc.) on energy resources, the role of nuclear technology in the future and how these issues relate 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 means for both education and research training. Assessment of E&O plan will include questionnaires as well as interviews.

6. References

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