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Letter of Interest

Search for Neutron-Antineutron Transition at Homestake DUSEL

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Executive summary

Our initial collaboration would like to propose for the Homestake DUSEL laboratory a new experimental search for neutron-antineutron (N-Nbar) transitions. We expect that the collaboration will grow as the project develops and a site to host the experiment is defined. The N-Nbar experiment will require a source of cold neutrons from a 3.5 MW TRIGA reactor, installed on top of a vertical shaft of ~1-km depth. The antineutron detector would be located at the bottom of the shaft. Homestake has a number of deep vertical shafts that might be suitable for such an experiment (e.g. shaft #5 with depth 5137′ seems to be a perfect candidate). The construction of the vertical vacuum vessel and a magnetic field shielding system, required to keep the neutron and antineutron energies degenerate, might be mechanically challenging and require substantial funding. Therefore, in this LOI we do not consider N-Nbar for the first round of experiments performed at DUSEL, but would like to propose as the first stages of the project: (a) to establish the feasibility of performing such an experiment at the Homestake Lab; (b) to identify a candidate shaft and study the technical issues of using this shaft in the experiment together with an initial assessment of the engineering design of the vacuum tube, magnetic shielding system, detector and reactor interface; (c) to develop a plan for use and maintenance of the TRIGA reactor, including the question of reactor ownership; (d) to prepare a more detailed proposal addressing issues of experiment integration with the Homestake Lab facilities and infrastructure, to develop a construction schedule and a project cost estimate.

"Discovering new laws is more important than simply discovering new particles"

Robin Staffin at SLAC, September 26, 2005

Physics motivation

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

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

Another powerful argument for N-Nbar oscillations comes from the attempts to understand the origin of matter in the universe. It has long been realized since the classic work of Sakharov [2] that a key requirement for understanding the dominance of matter over anti-matter in the universe is the presence of baryon violating interactions. Sakharov's scenario does not specify the mechanism of baryon number violation or shed any light on the question whether this violation would produce proton decay or N-Nbar oscillations. However, it was pointed out in the early 80's [3] that in the hot universe at temperatures above 1 TeV the Standard Model electroweak interactions conserving B–L at thermal equilibrium (*sphaleron* transitions) would violate baryon number and B+L number. Therefore any baryon asymmetry generated at earlier epochs (T > TeV) by B–L conserving interactions would be erased by the sphalerons. Thus, in order to understand the baryon asymmetry, the physics in the early universe must break B–L symmetry. This adds additional credibility to the seesaw models which provide such interactions. N-Nbar transitions therefore have also additional strong potential to throw light on the question of the origin of the matter-antimatter asymmetry in the universe.

Despite an intense experimental effort in the last three decades, proton decay has not been observed, thus ruling out the original SU(5)-based Grand Unification model (GUT) [4] and severely restricting SUSY-extended GUT models [5]. Since the SU(5) model conserves B–L symmetry, it also cannot explain the baryon asymmetry of the Universe (BAU). Searches for baryon-lepton instability with the violation of (B–L) should be more directly related to the possible explanation of BAU. These include searches for (a) non-traditional (B–L) violating nucleon decay (for example, $n \to \nu\nu\bar{\nu}$) with Δ(B–L) = 2, (b) neutrinoless double-beta decays with ΔL = 2, and (c) a most spectacular process of neutron to anti-neutron transition with ΔB = 2. The last process has an unambiguous signature (a star pattern of pions with ~2 GeV total energy) and can be searched for in an experimentally controlled environment with negligible background. With existing techniques the sensitivity of $n \to \bar{n}$ search can in principle be increased by a factor of ~1,000 compared to previous $n \to \bar{n}$ searches (with cold neutrons at ILL/Grenoble [6] and with neutrons bound inside nuclei at Soudan-II [7]). This letter addresses the possibility of a new experiment for $n \to \bar{n}$ search in the Homestake Lab.

The concept of $n \to \bar{n}$ transitions was first proposed [8] as a possible explanation of BAU and was developed within the framework of the unification models in [9]. In ref. 9, it was pointed out that there is an intimate connection between the seesaw scale and N-Nbar oscillations in the context of Pati-Salam type models. In non-supersymmetric versions of these models $\tau_{NNbar} \propto M^5_{Seesaw}$, where τ_{NNbar} is the characteristic transition time for N-Nbar oscillation, and only for $M_{Seesaw} \sim 10^5\,GeV$ or below does the oscillation time fall into an experimentally observable range. Clearly if the seesaw scale is around 10^{11} GeV then N-Nbar oscillations would be unobservable. A major recent theoretical development in this area is that once the above model becomes supersymmetric, despite the fact that the seesaw scale is high there are accidental symmetries of nature that allow the dependence of τ_{NNbar} on M_{Seesaw} to be much weaker (i.e. square rather than 5th power) [10]. This weakening dependence on M_{Seesaw} makes N-Nbar transitions in such models observable at the level of sensitivity achievable in the next generation of experiments. It is also then possible to understand completely the origin of matter (without the need for sphaleron transitions) using the N-Nbar generating interactions [11].

There is also a possibility to understand $n \to \bar{n}$ transitions in other theoretical contexts such as extra dimensional models [12-14] where new physics emerges from lower energy scales. An example is the class of models with a low quantum gravity scale where unification occurs at ~100 TeV. In these models additional theoretical mechanisms typically must be introduced to suppress proton decay [12-14] that otherwise would occur too fast. Most of the suppression mechanisms proposed so far leave $n \to \bar{n}$ transitions unaffected. From this ansatz S. Nussinov and R. Shrock [14] have found that in the models with large extra dimensions, $n \to \bar{n}$ oscillations might occur not too far below the current limits. G. Dvali and G. Gabadadze considered [12] a general mechanism of non-conservation of global charges in a brane universe with large extra dimensions. Baryon or lepton number conservation can be violated inside the "baby-branes" (black holes) created by quantum fluctuations of 3-dimensional vacuum into the extra dimensions. Since all Standard Model interactions live in a 3+1 dimensional brane, only iso-singlets of the Standard Model (like n_R) can be taken away from the brane into the black hole where global charge (baryon number) can be violated. In this model baryon number violation cannot occur via proton decay and the only particles that practically can contribute to the violation of baryon or lepton charges are n_R and ν_R. While the question of the existence of a neutral right-handed particle, Majorana neutrino, is still a subject of intensive experimental search, the right-handed component of the neutron n_R is part of the Standard Model. From this point of view the observation of $n \to \bar{n}$ transition could be an experimental demonstration of the existence of extra dimensions. It is interesting to note that the lowest order observable $n \to \bar{n}$ operators would exist at an energy scale of ~ 100 TeV (close to low quantum gravity unification scale).

Oscillations are known to occur in nature with other neutral particles: neutrinos and neutral mesons (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 which is sufficiently long-lived to conduct a practical experiment, may uncover new processes in nature.

Probability of $n \to \bar{n}$ oscillations in vacuum is proportional to the square of t neutron observation time: $(t/\tau)^2$, where τ is the characteristic 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 dumping. For the neutron observation time of 1 s the Earth magnetic field must be screened down to *nanoTesla* level and the residual gas pressure in the vacuum volume should be better than 10^{-4} Pa in order to keep dumping negligible. Experimentally established [6] limit on the $n \to \bar{n}$ oscillation time in vacuum is $\tau > 8.6 \times 10^7 s$ that is essentially larger than a free neutron lifetime. Therefore it is more appropriate to discuss $n \to \bar{n}$ transitions rather than oscillations.

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

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

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

In 1994-1995 a new high-sensitivity approach to a $n \rightarrow \bar{n}$ 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 $n \rightarrow \bar{n}$ search could be achieved at HFIR by a combination of its high thermal flux, a cold neutron moderator, and most essentially by an elliptical focusing reflector [16] concentrating cold neutrons onto the target. However the HFIR reactor, which is operated in the US by BES office of DOE, is not available for fundamental physics experiments.

To increase the time of observation of the neutron one needs to slow down the neutrons. For the case of a horizontal beam of neutrons gravity becomes an important perturbation to the motion of the neutrons. We therefore propose a vertical layout for the N-Nbar experiment to compensate for the defocusing effect of gravity together with a small dedicated research reactor as the source of cold neutrons. The lower power density of the smaller reactor may also allow the use of new types of cold neutron moderators, which can further reduce the average neutron speed. Such an arrangement can provide a sensitivity exceeding the sensitivity of the experiment that was proposed for HFIR. With a vertical layout the sensitivity can be a factor of >1,000 higher than in the previous best $n \rightarrow \bar{n}$ search experiment [6] which established a limit for $n \rightarrow \bar{n}$ oscillation time of > $8.6\times10^7 s$. *The possibility of a large increase in sensitivity of the experimental search for neutron $\rightarrow$ antineutron transitions is a central motivation for this Letter of Interest.*

Brief description of experiment

The conceptual design for a vertical N-Nbar experiment proposed for the Homestake Lab (see Figure 1) includes a dedicated 3.4 MW TRIGA research reactor [17] (to be purchased from General Atomic Company) as the neutron source. This unique reactor possesses an annular core with a vertical through tube for convenient insertion of a cold neutron moderator and extraction of the cold neutrons. To reach maximum sensitivity in an $n \rightarrow \bar{n}$ search, the neutrons should be cooled to the lowest possible temperature (average velocities < 1,000 m/s) using a cold moderator and maintained in free flight as long as possible (~1s). Thus, the reactor should be installed at the top of a vertical mineshaft of $\gtrsim$ 1 km depth with a diameter of a few meters. The experiment requires a large elliptical focusing reflector [16] with the cold source at one focus that intercepts neutrons in a wide solid angle and directs them along ~ 1 km vacuum flight path onto the annihilation detector. The *vertical* layout of the flight path is needed to keep the slow neutrons from striking the vacuum walls during the observation time.

A focusing neutron reflector needs to be installed inside the vertical vacuum chamber. The vacuum chamber should have a vacuum better than 10^{-4} Pa. The Earth's magnetic field inside the vacuum chamber needs to be shielded along the 1-km flight path by active and passive magnetic shields down to the level of few *nanoTesla*. Requirements similar to these have been achieved in the previous ILL/Grenoble-based experiment [6]. The magnetic field seen by the neutrons in the apparatus could be periodically checked in situ if necessary by polarizing the neutrons via transmission through polarized ^{3}He gas near the moderator and then measuring the precession angle of the neutrons in the magnetic field using a polarized ^{3}He polarization analyzer at the conversion foil. Antineutrons will be detected by an antineutron annihilation detector located in the experimental hole at the bottom of the mineshaft. The experiment could also in principle be performed in an inverse configuration with the reactor at the bottom of the vertical mineshaft and detector at the top. The proposed antineutron detector (see Figure 2) could be similar to the one used in the experiment [6] at the ILL/Grenoble reactor: a thin ~100μm carbon foil can serve as the antineutron annihilation target. This target is viewed through the cylindrical walls of the 2.2-m diameter vacuum chamber by a tracking detector that reconstructs the annihilation star of several pions to the position of the carbon-film target, thus providing excellent discrimination against background events (which originate mostly by cosmic ray interactions). The tracker would be surrounded by a calorimeter, a cylindrical layer that measures the energies of the annihilation products (which on average are stars of 5 pions) and which provides a trigger signal for readout. The calorimeter would be surrounded by a scintillator veto system for cosmic ray-induced events.

The sensitivity of the $n \to \bar{n}$ search experiment is proportional to the flux of neutrons through the annihilation target and the square of the time-of-flight in the vacuum from the location of last scattering in matter (source or reflector) to the target. According to our simulations (see Figure 3) in the proposed experimental scheme after 3 years of operation the sensitivity of the $n \to \bar{n}$ search can be a factor of > 1,000 higher than in the previous experimental search at ILL/Grenoble reactor [6] due to the very long flight path and due to the focusing neutron reflector. With a "zero-background" detector and with the very distinctive signature of $\bar{n}$ annihilation, 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, $\gtrsim 10^{35}$ years, that cannot be obtained in the intranuclear search with large underground detectors. To our knowledge, no other practical schemes for $n \to \bar{n}$ search exist with a comparable sensitivity.

The above estimate assumes the use of a standard liquid D_2 cold neutron source. The sensitivity can be further improved if the development of a new "very cold neutron" (VCN) moderator recently proposed by the group of J. Carpenter at ANL [18] is successful. Paul Sherer Institute in Switzerland is holding a workshop on this idea in February 2006. Also, a VCN moderator is considered as a possible option for the second target station at the SNS. Research into new types of cold and ultracold neutron moderators is planned at the LENS cold neutron source under construction at the Indiana University Cyclotron Facility (IUCF) and at the ultracold neutron source under construction at the PULSTAR reactor at North Carolina State University. These efforts could further increase the sensitivity of the proposed N-Nbar experiment by an order of magnitude (see Figure 3).

Table 1 compares the different sensitivities for $n \rightarrow \overline{n}$ search by known experimental methods [18]. The sensitivity of the previous cold neutron beam experiment [6] (at ILL/Grenoble) and the approximately equivalent sensitivity of intranuclear search in the Soudan-II experiment [7] correspond here to unity.

Table 1

Method	*Present limit*	*Possible future limit*	*Possible sensitivity increase factor*
Intranuclear (N-decay expts)	$7.2\cdot10^{31}$ yr = 1*unit* Soudan II	$7.5\cdot10^{32}$ yr (Super-K) $4.8\cdot10^{32}$ yr (SNO)	× 16
Geo-chemical (ORNL)	none	$4\cdot10^{8}\div1\cdot10^{9}$ s (Tc in Sn ore)	× 20 –100
UCN trap (6×10^{7} ucn/sec)	none	~ $1\cdot10^{9}$ s	× 100
Cold horizontal beam	$8.6\cdot10^{7}$ s = 1*unit* @ILL/Grenoble	$1\cdot10^{9}$ – $3\cdot10^{9}$ s (HFIR@ORNL)	× 100 –1,000
Cold Vertical beam	none	$3\cdot10^{9}$ – $1\cdot10^{10}$ s (Homestake)	× 1,000 –10,000

Space requirement and unusual technical issues

1. We anticipate using one of the vertical shafts available at Homestake Lab with depth ≥ 1 km and diameter ~ 15’ (existing remote Shaft #5 seems to be an excellent candidate for this experiment providing minimal interference with other experiments at DUSEL). The infrastructure of Homestake Lab would allow the construction of the detector at the bottom of the shaft and a long vertical vacuum tube with magnetic shielding and focusing reflector inside the shaft providing construction access from the top and bottom of the shaft together with the required electrical power and ventilation. Construction of the vertical vacuum tube with accompanying services will be one of the major technical challenges of the proposed experiment.

2. We assume that the TRIGA reactor can be purchased from General Atomics and installed at the Homestake site by the company. Besides the electrical power required for the operation of the reactor, 3.5 MW cooling towers would need to be constructed on the surface together with cryogenic equipment for the cold moderator.

3. As one of the possible solutions of the issue of licensing, maintenance and ownership of the TRIGA reactor we would like to propose a scheme where the University of South Dakota will assume ownership of the reactor and will create a Nuclear Engineering department at the University that will maintain the operation of the reactor during the N-Nbar experiment and at a later time when the reactor can be used for the purposes of the Homestake Lab operation, for student training, for production of radioisotopes, and for material studies. The reactor will be a major educational asset for the training of nuclear engineers. The future of energy production in the US is likely to involve nuclear power reactors and will require a new generation of specialists educated and trained at Universities to build and operate these reactors.

4. The presence of a small research reactor in the DUSEL may have other uses as a neutron activation-assisted low-level counting facility and a local production facility for short-lived radioactive isotopes for detector calibration. The reactor could be used as a source of antineutrinos for calibration of neutrino detectors located at the Homestake Lab. However, for some experiments planned at DUSEL the closely-located reactor, even of low power, can obviously be an additional source of antineutrino background. The reactor neutrons are not likely to be a background problem for the dark matter searches and other sensitive experiments at DUSEL. However, we anticipate studying this question more carefully in the future. Also, other possible applications for the intense neutron field at the secondary focus of the reflector remain to be investigated.

5. Reactor operation safety: due to its special fuel design, TRIGA reactors are considered to be the safest reactors for operation according to information provided by the General Atomics. We assume a long-time operation of the reactor at Homestake Lab beyond the time scale of the N-Nbar experiment and at the end of reactor operation a standard decommissioning and decontamination procedure that exists for research reactors.

Timeline of the project development

Stage 1 (R&D), 1-2 years from now: we anticipate during this stage that our Collaboration working together with the Homestake Lab:

(a) will establish the feasibility of performing the N-Nbar experiment at the Homestake Lab;

(b) will identify a candidate shaft and study the technical issues of using this shaft in the experiment together with an initial assessment of the engineering design of the vacuum tube, magnetic shielding system, detector and reactor interface;

(c) will develop a plan for use and maintenance of the TRIGA reactor including the question of reactor ownership;

(d) will prepare a more detailed proposal which would address the issues of experiment integration with Homestake Lab facilities and infrastructure, develop the construction schedule and the project cost estimate.

Stage 2, next 1-2 years: Following the approval of our project by DUSEL Homestake Program Advisory Committee we will plan submit a Proposal to DOE and/or to NSF for the construction of the N-Nbar experiment and get the project approved by the funding agencies as CD-0.

Stage 3, next 1 year: Preparation of Technical Design Report, reviews and approval by funding agencies.

Stage 4, next 2 years: Construction of the experiment at Homestake Lab.

Stage 5, following 3 years: Experiment running; reaching designed sensitivity at the end of the 3rd year.

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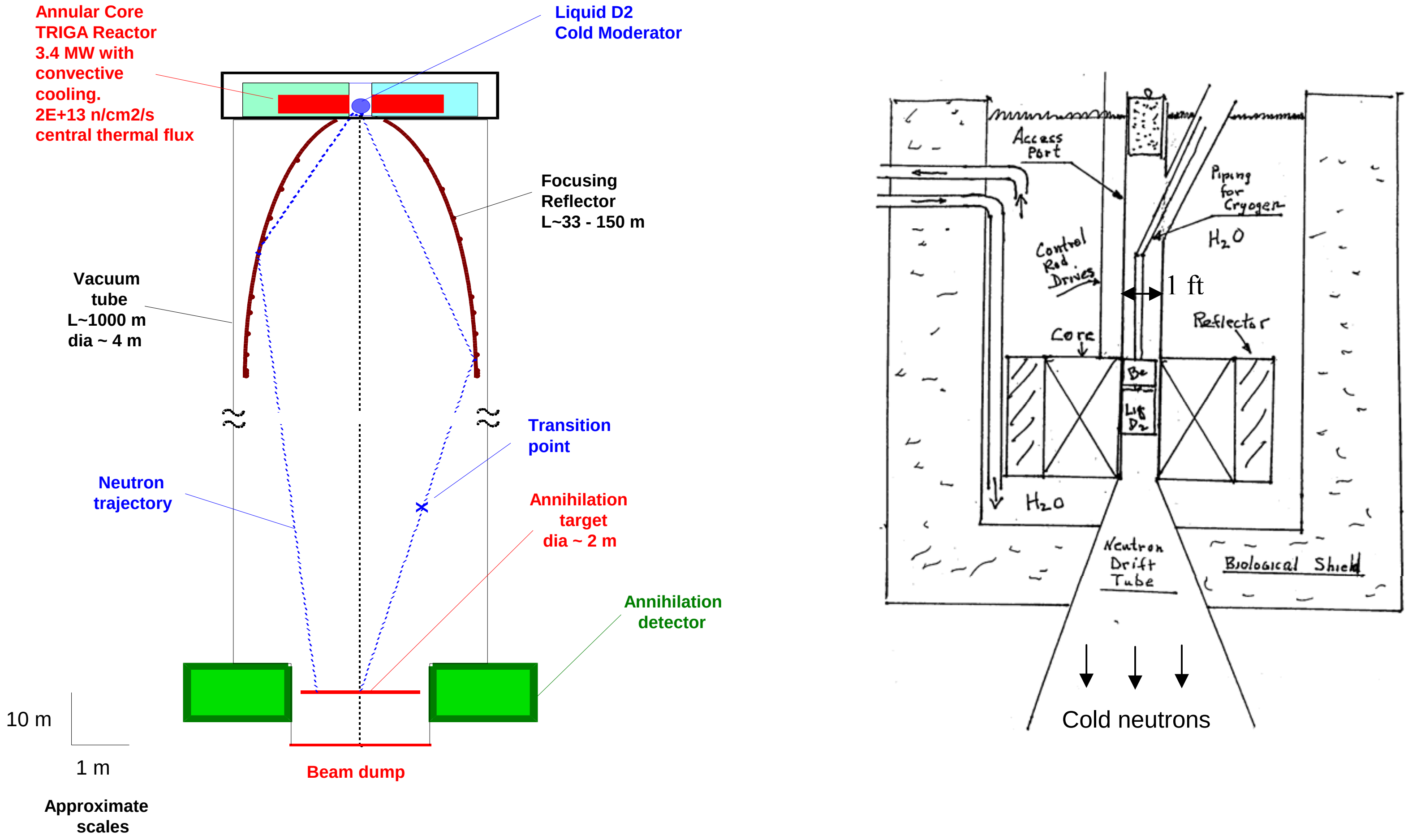


Figure 1. Left: schematic view of the vertical N-Nbar experiment. Right: schematic drawing of the TRIGA reactor with thermal water convection, annular core and 12-inch throughout vertical tube (courtesy of W. Whittemore / General Atomics).

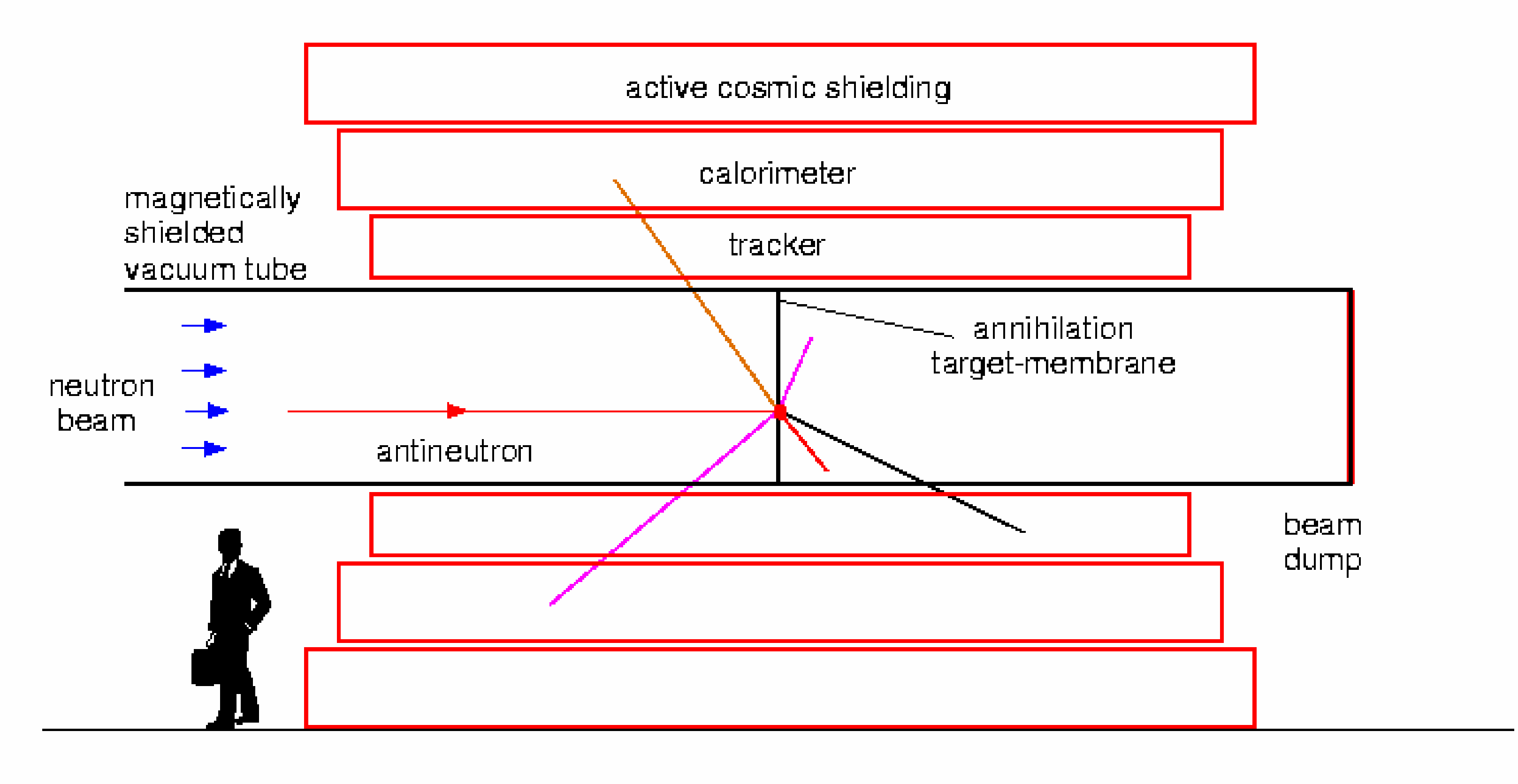
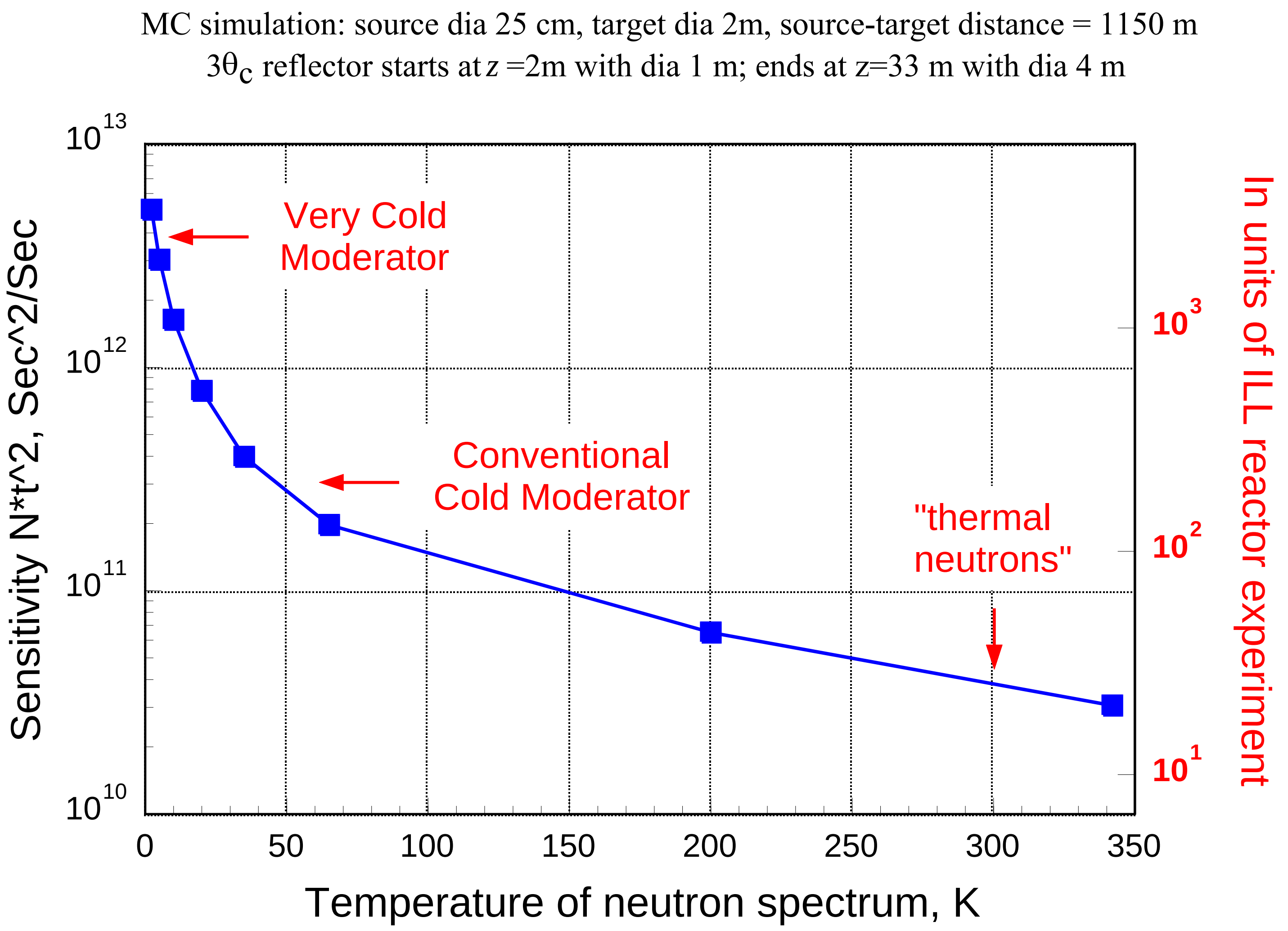


Figure 2. Generic antineutron annihilation detector similar to one used in ILL/Grenoble experiment [4]. Detector proposed for Homestake Lab should be rotated by 90 degrees to adopt vertical neutron beam.



MC simulation: source dia 25 cm, target dia 2m, source-target distance = 1150 m
$3\theta_c$ reflector starts at z =2m with dia 1 m; ends at z=33 m with dia 4 m

Figure 3. Monte Carlo simulation of the sensitivity of N-Nbar search experiment in terms of N· t^2 (Flux of cold neutrons through annihilation target times average time square of the free time-of-flight in vacuum) vs temperature of the neutron spectrum. Sensitivity is also shown in the units of sensitivity of the previous ILL-Grenoble based N-Nbar search experiment [4] where sensitivity $N \cdot t^2$ was 1.5×10^9 n·sec^2/sec and experiment running time was ~ 1 year.