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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 Homestake DUSEL laboratory a new experimental search for transitions of neutron to antineutron. We expect that collaboration will grow as the project will develop and site hosting the experiment will be defined. N-Nbar experiment will require a source of cold neutrons, based on the purchased 3.5 MW TRIGA reactor, installed on the top of the vertical shaft of 1-km depth or more. Detector of antineutrons should be located at the bottom of the shaft. Homestake lab has number of deep vertical shafts that could be suitable for such an experiment (Shaft #5 with depth 5137' seems to be a perfect candidate). Although we assume using simple and well prototyped experimental techniques, the construction of the vertical vacuum vessel and the Earth magnetic field shielding system might be mechanically challenging and require substantial funding. Therefore, in this LOI we do not consider the proposed experiment for the first round of experiments performed at DUSEL, but would like to propose as the first stage of the project: (a) to establish principle feasibility of performing such an experiment at the Homestake Lab; (b) identify the candidate shaft and study technical issues of using this shaft in the experiment together with initial assessment to engineering design of the vacuum tube, magnetic shielding system, detector and reactor interfacing; (c) develop a plan for use and maintenance of the TRIGA reactor including the question of reactor ownership; (d) prepare more detailed proposal addressing issues of experiment integration with Homestake Lab facilities and infrastructure, develop construction schedule and the project cost estimate.

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

Robin Staffin at SLAC, September 26, 2005

Physics motivation

In the last three decades, despite the extensive experimental efforts, proton decay was not observed, thus ruling out the original SU(5)-based Grand Unification model [1] and severely restricting SUSY-extended GUT models [2]. In the parallel theoretical developments the concept of baryon instability has been essentially modified, showing clearly that proton decay with modes suggested by SU(5) and SUSY-extended models cannot explain the baryon asymmetry of the Universe (BAU), which remains the only existing experimental indication of baryon number violation in nature. It was realized theoretically [3] that Standard Model electro-weak interactions (*sphaleron* transitions) in the hot universe at temperatures above ~1 TeV erase BAU to zero if the latter was generated by (B–L)-conserving interactions at the unification energy scale. The (B–L) number is conserved in the Standard Model, in SUSY-SU(5), and for the most proton decay modes that were so far the main focus of the experimental nucleon instability search. Thus, the proton decays like $p \to e^+\pi^0$ predicted by the original SU(5) [1] or $p \to K^+\bar{\nu}$ predicted by SUSY-extended models [2], even if experimentally found, will not provide an explanation for BAU. Searches for baryon-lepton instability with the violation of (B–L) should be experimentally performed as more directly related to the explanation of BAU. These processes 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) most spectacular process of neutron to anti-neutron transition with ΔB = 2. The last process has an unambiguous signature and can be searched in the experimentally controlled environment without background when one observed event will signify a discovery. With presently existing techniques the sensitivity of $n \to \bar{n}$ search can be increased by large factor > 1,000 as compared to the previous $n \to \bar{n}$ searches (with cold neutrons at ILL/Grenoble [4] and with neutrons bound inside nuclei at Soudan-II [5]). This letter addresses the possibility of a new experiment for $n \to \bar{n}$ search in Homestake Lab.

Search for $n \to \bar{n}$ transitions was first proposed [6] as possible explanation of BAU. Possibility of observation of $n \to \bar{n}$ transitions has been considered in several recent theoretical papers. K. Babu and R. Mohapatra [7] have shown that for a large class of supersymmetric models with spontaneously broken (B–L) symmetry $n \to \bar{n}$ oscillations can occur at an observable level even though the scale of (B–L) breaking is very high ~ 2×10^{16} GeV, as suggested by gauge coupling unification and neutrino masses. Authors illustrate this phenomenon in the context of a class of recently proposed seesaw models that solve the strong CP problem and the SUSY phase problem based on parity symmetry. They obtained an *upper limit* on $n \to \bar{n}$ oscillation time in these models: $t_{osc} < 10^9$–10^{11} sec. This suggests that a modest improvement of the current experimental limit $t_{osc} > 8.6\times10^7$ sec [4] will either lead to the discovery of $n \to \bar{n}$ oscillations, or will considerably restrict the allowed parameter space of an interesting class of seesaw models. Prediction of the possible observation of the $n \to \bar{n}$ transitions in the next generation search experiment is given also in the recent paper [8].

In presently popular models with low quantum gravity scale where unification occurs at ~100 TeV there is a problem that proton would decay too fast and some additional theoretical mechanisms must be introduced to suppress this decay [9,10]. Most of suppression mechanisms proposed so far suppress proton decay but not the $n \to \bar{n}$ transition. From this ansatz S. Nussinov and R. Shrock [11] 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 [9] general mechanism of non-conservation of global charges in a brane universe with large extra dimensions. Baryon or lepton numbers can be violated inside the "baby-branes" (black holes) created by quantum fluctuations of 3-dimensional vacuum into extra dimension. Since all SM interaction live in 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. In this respect the observation of $n \to \bar{n}$ transition would 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 live at the energy scale of ~ 100 TeV (close to low quantum gravity unification scale).

There was an extensive discussion for a new possibility of $n \to \bar{n}$ search in the Physics Study group at Snowmass in July 2001. Idea of 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 HEPAP Subpanel Report on the Long-Range Planning for US HEP (January, 2002, page 21) the idea of $n \to \bar{n}$ experiment was mentioned in the following way:

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

In 1994-1995 a new high-sensitive approach to the $n \to \bar{n}$ experimental search was proposed utilizing the horizontal cold neutron beam of the high-flux research reactor HFIR at Oak Ridge National Laboratory [12]. High sensitivity of the proposed $n \to \bar{n}$ search was obtained by combination of a high thermal flux, a cold neutron moderator, and most essentially by a focusing reflector [13] concentrating cold neutrons onto the target. Since the HFIR reactor, operated in US by BES office of DOE was not available for fundamental physics experiments, the concept of the proposed experiment was modified. Vertical layout of experiment compensating for the defocusing effect of gravity together with small dedicated research reactor as the source of cold neutrons can provide sensitivity even exceeding the sensitivity of an experiment proposed for HFIR. With vertical layout the sensitivity can be factor of >1,000 higher than in the previous best $n \to \bar{n}$ search experiment [4] where a limit for $n \to \bar{n}$ oscillation time > $8.6\times10^7 s$ has been established. *The possibility of large increase in sensitivity of the experimental search for neutron → antineutron transitions is a central motivation for this Letter of Interest.*

Brief description of experiment

The scheme of the vertical experiment that is being proposed for the Homestake Lab (see Figure 1) includes a dedicated research 3.4 MW reactor of TRIGA type [14] (to be purchased from General Atomic Company) with annular core and throughout vertical tube. To reach maximum sensitivity in $n \to \bar{n}$ search the bulk of produced neutrons should be cooled down to the lowest possible temperature (average velocities < 1,000 m/s) using conventional cold moderator technique and maintained in-flight for a maximum time (~1s). Thus, the reactor should be installed on the top of the vertical mineshaft of $\gtrsim$ 1 km in depth with diameter of few meters. The scheme of high-sensitivity experiment requires large elliptical reflector [13] that intercepts neutrons in the wide solid angle and direct them along ~ 1 km vacuum flight path onto the annihilation detector. The *vertical* layout of the flight path will most efficiently mitigate the disturbing gravity effects that limits the sensitivity reach in the horizontal-layout experiment.

Focusing neutron reflector needs to be installed inside the vertical vacuum chamber with vacuum better than 10^{-4} Pa. Earth magnetic field inside the vacuum chamber needs to be compensated along the 1-km flight path by active and passive magnetic shields down to the level of few *nT*. Requirements similar to these have been achieved in the previous ILL/Grenoble-based experiment [4]. Antineutrons transformed from neutrons during the flight through the vacuum chamber are to be detected by the antineutron annihilation detector located in the experimental hole at the bottom of the mineshaft. Inverse configuration with reactor at the bottom of the vertical mineshaft and detector on the top is also feasible and is the subject to engineering optimization. Proposed antineutron detector (see Figure 2) is similar to one used in experiment [4] at ILL/Grenoble reactor: thin ~100μm carbon foil serves as an annihilation target; it is viewed through the cylindrical walls of 2.2-m diameter vacuum by the 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 (originated mostly by cosmic rays). Tracker is surrounded by the calorimeter, the cylindrical layer that measures energy of the annihilation products (on average a star of 5 pions) and provides trigger signal for readout. Calorimeter is surrounded by scintillator veto system protecting from cosmic ray particle events.

Sensitivity of the $n \to \bar{n}$ search experiment is proportional to the flux of neutrons through the annihilation target and the square of time-of-flight in the free vacuum from source to target. According to our simulations (see Figure 3) in the proposed experimental scheme after 3 years of operation the sensitivity of $n \to \bar{n}$ search can be factor of > 1,000 higher than in the previous experimental search at ILL/Grenoble reactor [4] due to very long flight path and due to focusing neutron reflector. With zero-background detector and with very distinctive signature of $\bar{n}$ annihilation, even one observed event would constitute a discovery. If no events will be observed after three years of measurements it will corresponds 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 comparable sensitivity.

The sensitivity can be further enhanced if the development of a new Very Cold neutron moderator proposed by the group of J. Carpenter at ANL [15] will be successful. It should allow increasing the sensitivity of the proposed experiment by an order of magnitude (see Figure 3).

Table below [16] compares sensitivity of $n \to \bar{n}$ search by known experimental methods. Sensitivity of the previous cold neutron beam experiment [4] (at ILL/Grenoble) and approximately equivalent sensitivity of intranuclear search in Soudan-II experiment [5] are chosen as a unit of sensitivity here.

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

Space requirement and unusual technical issues

1. We anticipate using one of vertical shafts available at Homestake Lab with depth ≥ 1 km and diameter ~ 15’ (existing remote Shaft #5 seems to be excellent candidate for this experiment providing minimal interference with other experiments at DUSEL). The infrastructure of Homestake Lab should allow construction of the detector at the bottom of the shaft and 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 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 TRIGA reactor can be purchased from General Atomics and installed at the Homestake site by the company. Besides electrical power required for the operation of the reactor, 3.5 MW cooling towers should 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 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 later time when reactor will be used for the purposes of the Homestake Lab operation, for student training, for production of radioisotopes, and for material studies. We believe that future of energy production in US belongs to the nuclear power reactors and will require a new generation of specialists grown by the Universities who can build and operate these reactors.

4. Use of a small research reactor in the DUSEL, besides as a source of cold neutrons in $n \to \overline{n}$ experiment, will have other advantages. Among them: neutron activation assisting low-level counting facility and production of short-lived radioactive isotopes for detector calibrations. Reactor can 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 close-located reactor, even of low power, might be an additional source of antineutrino background. Interesting applications of vertical neutron beam can we envisaged (for neutron radiography, neutron interferometry, other fundamental physics experiments, and condensed matter applications) at the reactor facility with steady or pulsed TRIGA reactor operation after the completion of $n \to \overline{n}$ experiment.

5. Reactor operation safety: due to its special fuel design, TRIGA reactors are considered as most safe reactors for operation according to information provided by the General Atomics. We assume long-time operation of the reactor at Homestake Lab beyond time scale of N-Nbar experiment and at the end of reactor operation 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 that during this stage our Collaboration working together with Homestake Lab:

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

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

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

(d) will prepare more detailed proposal addressing issues of experiment integration with Homestake Lab facilities and infrastructure, develop 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 NSF for the construction of 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 experiment at Homestake Lab.

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

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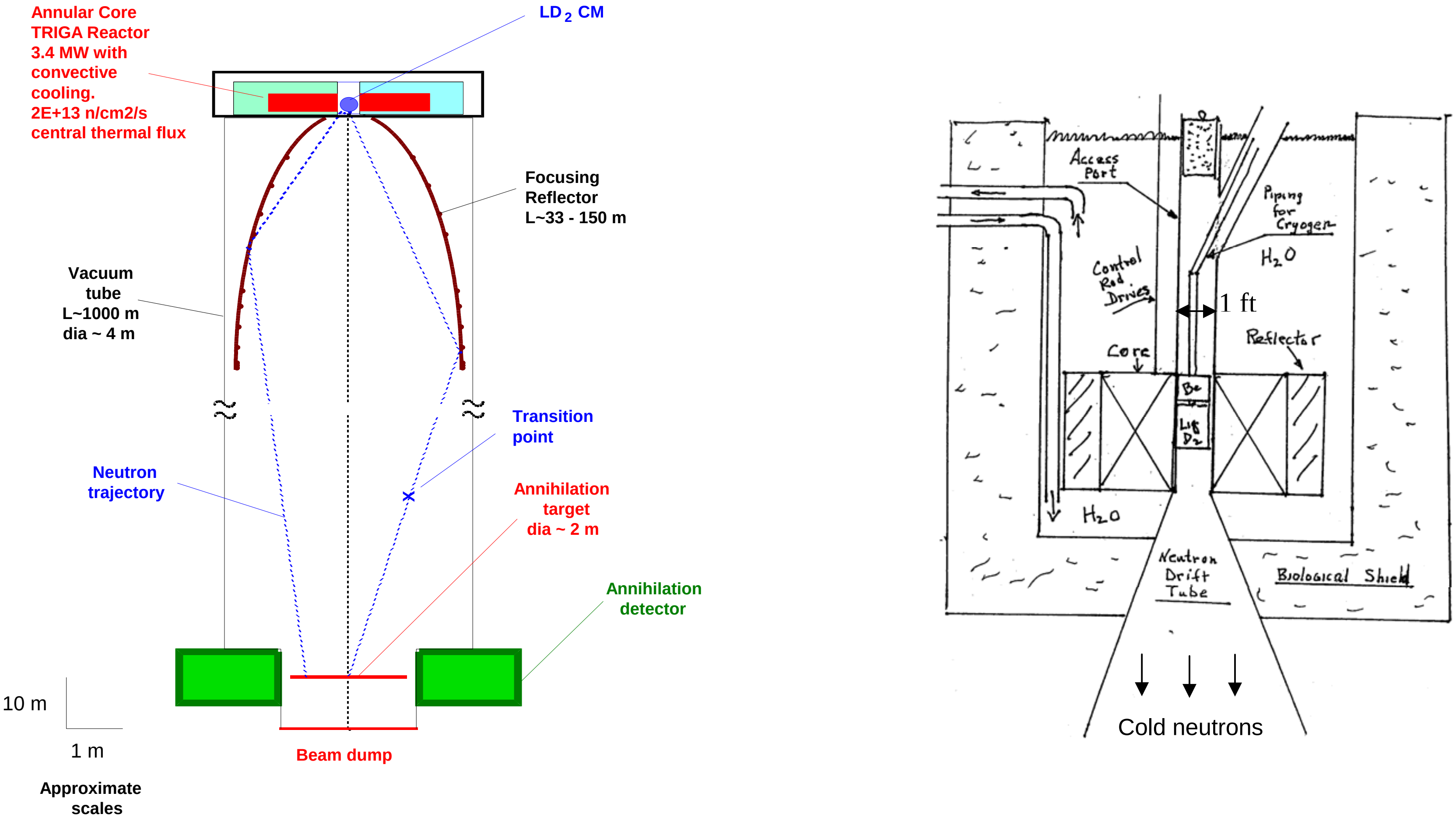


Figure 1. Left: schematic view of the vertical N-Nbar experiment. Right: schematic drawing of the TRIGA reactor with thermal water convection, annular core and 12-inch throughout vertical tube (Courtesy of W. Whittemore / General Atomics).

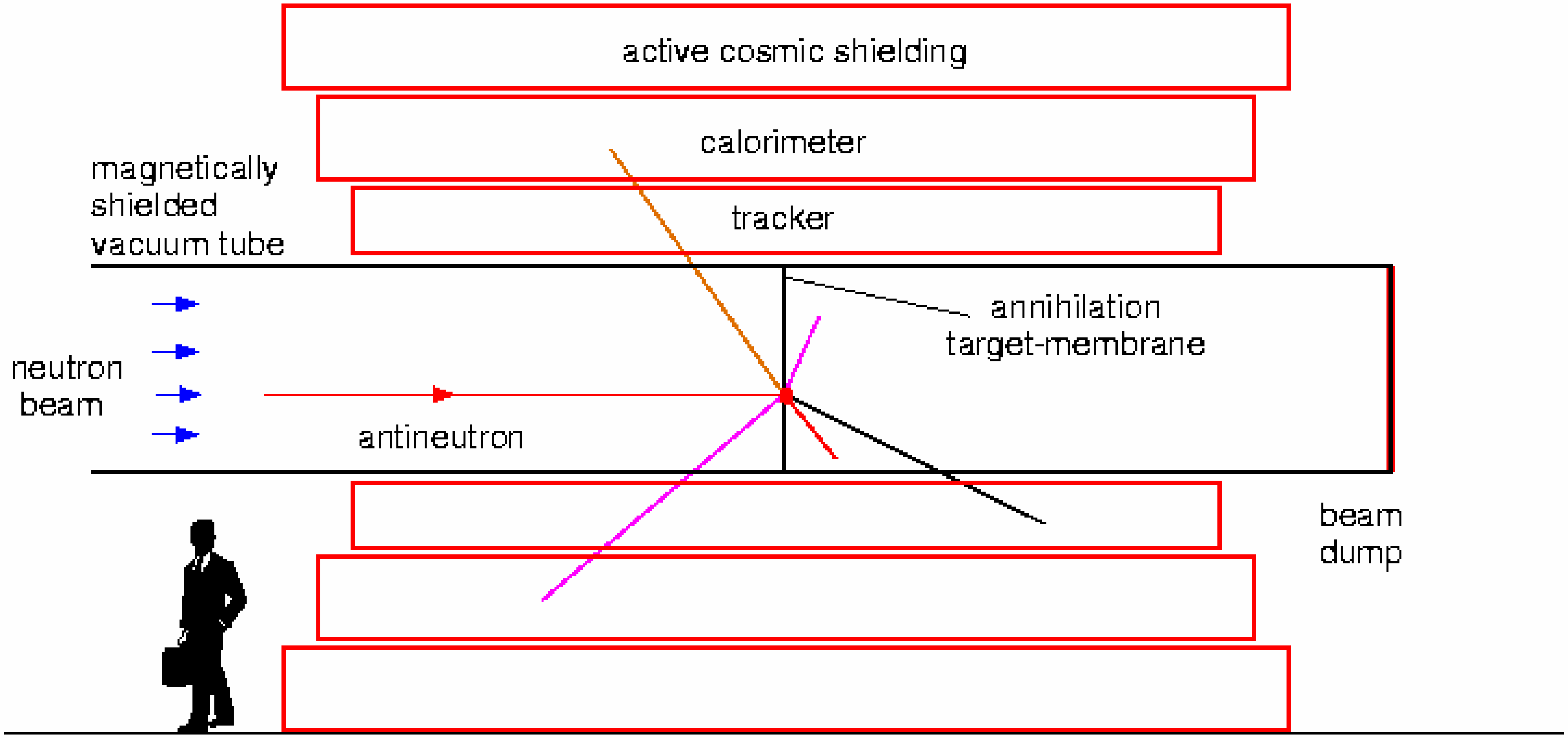
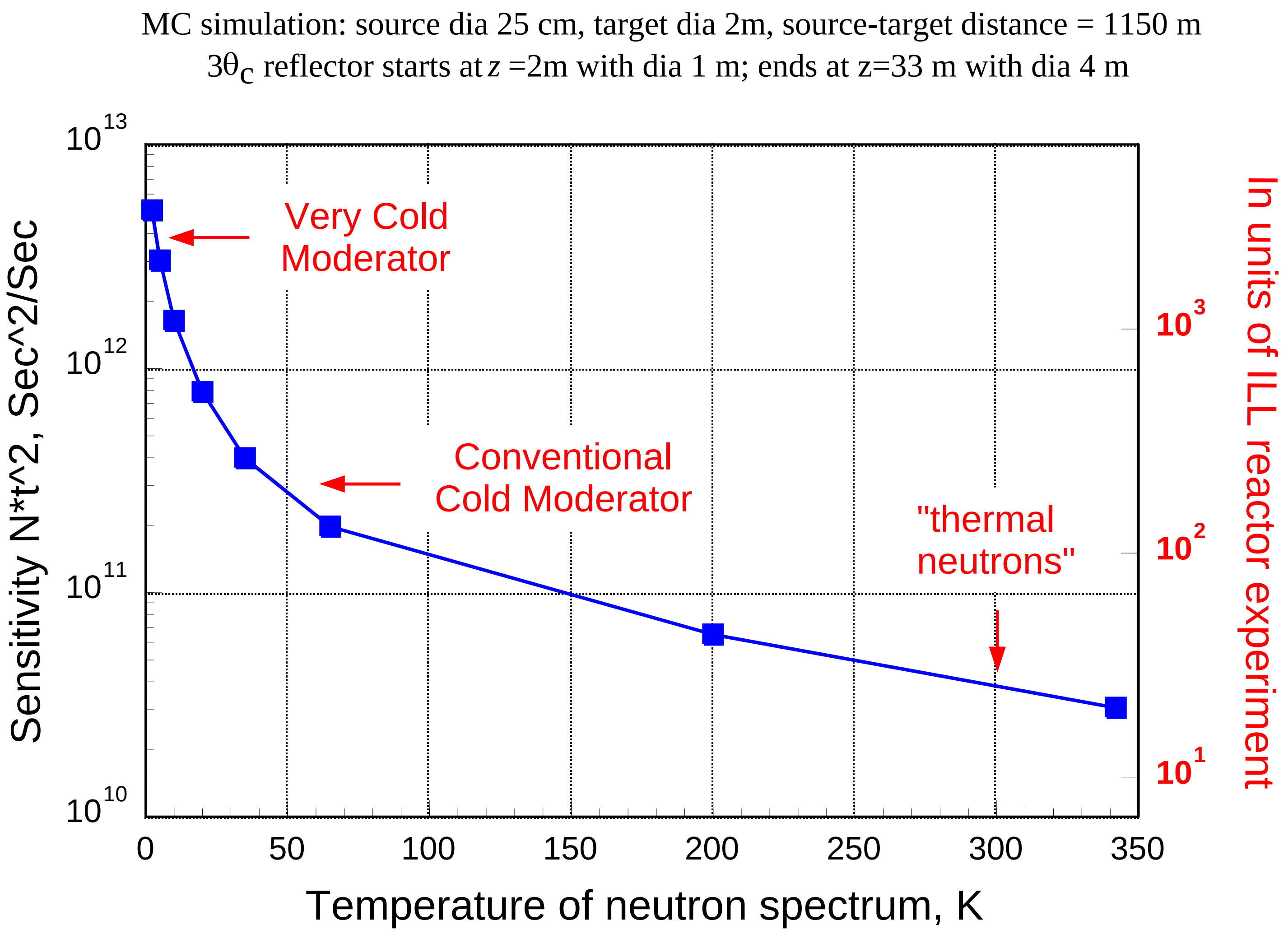


Figure 2. Generic antineutron annihilation detector similar to one used in ILL/Grenoble experiment [4].
Detector proposed for Homestake Lab should be rotated by 90 degrees to adopt vertical neutron beam


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 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·t^2 was 1.5×10^9 n·sec^2/sec and experiment running time was ~ 1 year.