PROSPECTS FOR DEEP UNDERGROUND SCIENCE IN THE US

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ABSTRACT

The Homestake Mine in South Dakota is the proposed site for a new underground laboratory in the US. Several large underground physics experiments are being proposed in Homestake. I will summarize the physics goals, sensitivities, and status of three of these projects: i) the Large Underground Xenon (LUX) dark matter experiment ii) the demonstrator for the MAJORANA neutrinoless double-beta decay experiment, and iii) the Long Baseline Neutrino Experiment (LBNE).

1. The Homestake Mine

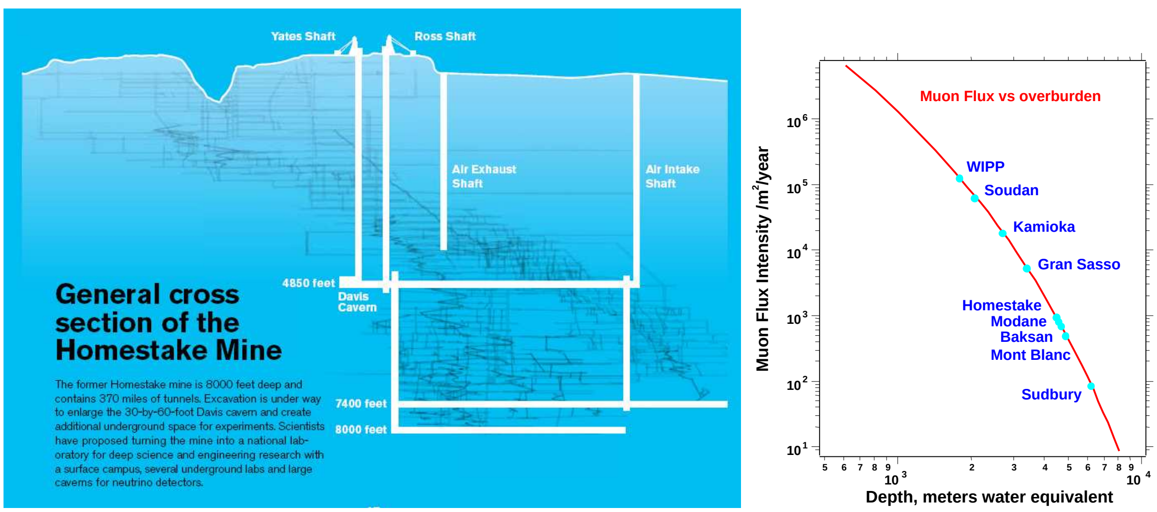

Figure 1: The cross-section of the Homestake Mine (left) and the muon flux intensity in muons/m^2/year versus overburden (right). The overburden of the worlds deepest underground laboratories are indicated, including the 4850 foot level of the Homestake Mine.

The Homestake Mine, located near the town of Lead, South Dakota, USA, is being considered as a potential site for underground science in the continental United States. Homestake is the deepest mine in the western hemisphere with shafts down to 8000 feet in depth and with 370 miles of tunnels (see Fig: 1) [1)]. The Homestake Mine was the site of the Nobel prize winning solar neutrino experiment lead by Ray Davis. The radio-chemical neutrino experiment, which operated from 1969 to 1993 demonstrated that there was a significant deficit of electron neutrinos from the sun.

In July of 2007 the US's National Science Foundation (NSF) initiated the process to produce a technical design for a Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake mine and selected the University of California-Berkeley to lead the effort. Unfortunately, in December of 2010 the National Science Board recommended terminating the 2011 NSF funds for the DUSEL facility development. Following the NSF decision, the US Department of Energy DOE established an ad-hoc review committee in May of 2011 to advise the DOE on the cost effectiveness of pursuing the Homestake site for implementing the DOE programs in neutrino physics, double-beta decay, and dark matter. The committee issued its report in July of 2011 and the DOE is expected to make a decision on the fate of underground science efforts at Homestake mine in late 2011 or early 2012.

In the meantime, with funding from the state of South Dakota, the NSF and a $70M private donation from Denny Sanford, the Homestake mine has been operating as an underground scientific research facility under the name of Sanford Laboratory. Two early physics projects are proceeding at Sanford Laboratory: the LUX dark matter experiment, and the demonstrator for the MAJORANA $0\nu\beta\beta$ experiment. In these proceedings I will briefly review the science and status of dark matter, $0\nu\beta\beta$, and long baseline neutrino projects at Homestake Mine.

2. Early Science at Sanford Laboratory: Dark Matter and $0\nu\beta\beta$

Two physics projects are currently proceeding at the 4850 foot level of the Sanford Laboratory in the Homestake Mine: i) the Large Underground Xenon (LUX) dark matter experiment [2], and ii) the demonstrator for the MAJORANA $0\nu\beta\beta$ experiment [3]. In Fig: 2 the proposed layout of the LUX dark matter experiment and the MAJORANA demonstrator at the 4850 foot level of the Homestake Mine is displayed. The LUX experiment will be located in the Davis cavern, the site of Ray Davis's solar neutrino experiment.

2.1. Large Underground Xenon (LUX)

The Large Underground Xenon (LUX) experiment is a cryogenic Nobel liquid dark matter experiment that is designed to detect energy depositions from the interactions of Weakly Interacting Massive Particles (WIMPS) with atomic nuclei. The LUX detector is a two-phase (liquid/gas) xenon Time Projection Chamber (TPC) which utilizes 350kg (300kg active region) of liquid xenon. The detector measures both the scintillation and ionization signal from interactions in the detectors. By using the ratio of the two signals, the detector can separate electron recoil and WIMP/neutron recoil signals. A schematic of the LUX detector is shown in Fig: 3. To veto cosmic muons and shield from background radiation, the LUX detector is immersed in an 8m diameter water tank.

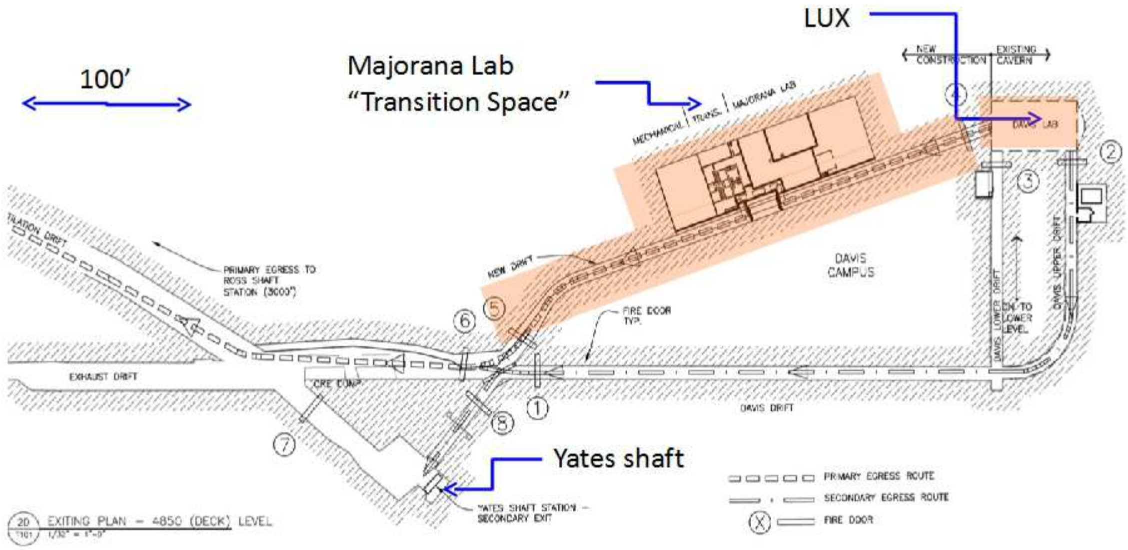

Figure 2: The proposed layout of the LUX and MAJORANA demonstration experimental spaces in the Homestake Mine.

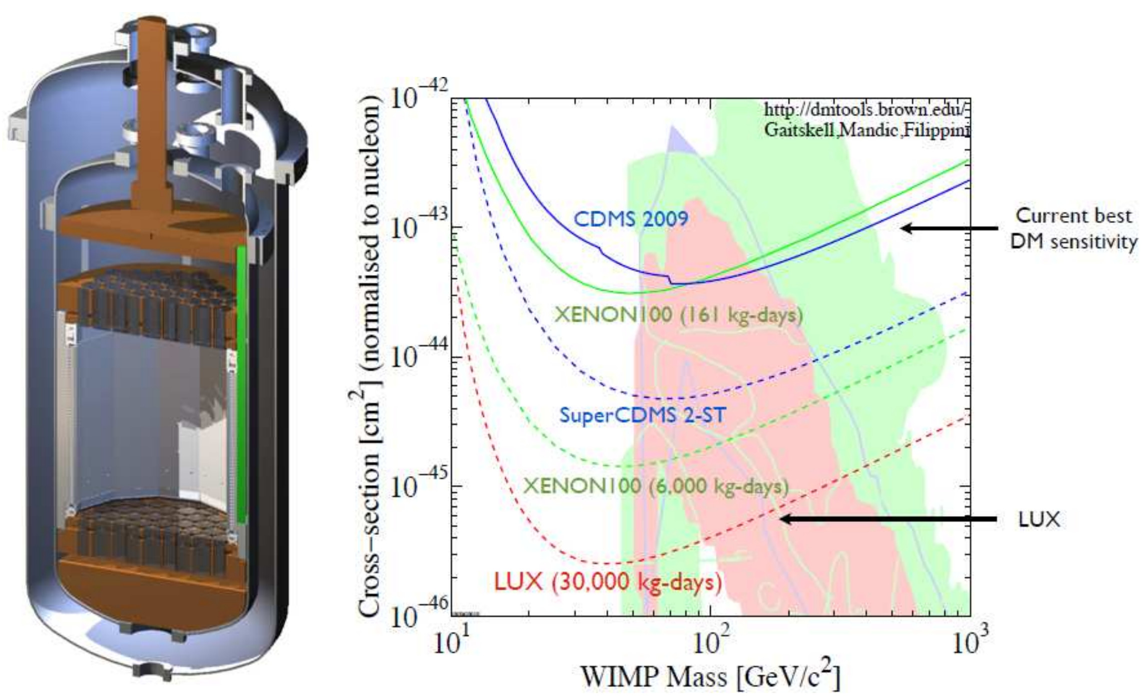

Figure 3: The LUX detector schematic (left) and the projected LUX sensitivity as a function of WIMP mass (right).

A surface facility has been constructed at Sanford Laboratory which is a duplicate of the underground layout with a smaller water tank. The LUX detector has now been assembled in the surface facility and deployed in the water tank as of May 2011.

The underground facility in the Davis laboratory at the 4850 level is currently in preparation. The expected sensitivity of the LUX dark matter search as a function of WIMP mass and interaction cross-section compared is shown in Fig: 3. The sensitivity curves from other dark matter experiments are overlaid with the allowed regions from several theoretical models (shaded regions in figure). The LUX experiment is expected to set some of the best limits on direct dark matter searches.

2.2. The MAJORANA Demonstrator

The MAJORANA experiment [3)] seeks to search for neutrinoless double-beta ($0\nu\beta\beta$) decay using high purity Ge diode detectors. The isotope ^{76} Ge is a candidate nucleus for neutrinoless double-beta decay and Ge detectors use a detector material up to 86 % enriched with the desired isotope. The goal of MAJORANA is to build a tonne scale experiment at one of the worlds leading underground facilities. Such an experiment would be sensitive to neutrino masses of 20-40 meV if the hierarchy is inverted. To achieve the desired sensitivity requires backgrounds below 1 count/tonne/yr. MAJORANA proposes to use very low background cryostats built from ultra-clean electro-formed copper. The shielding for MAJORANA is low-background passive copper and lead with an active muon veto. To demonstrate that the background levels needed to reach the desired sensitivity can be achieved using the proposed cryostat and shielding technology, a demonstrator project with 30kg of enriched Ge crystals is currently being assembled at Sanford Laboratory. A schematic of the demonstrator design is shown in Fig: 4.

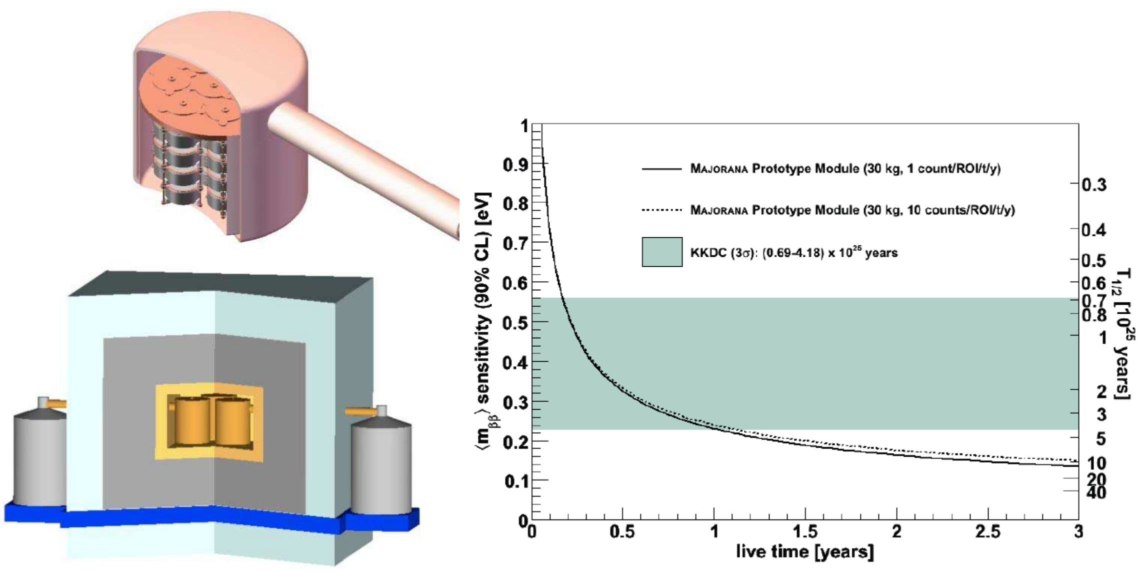

Figure 4: The MAJORANA prototype design (left) and the sensitivity as a function of live-time (right).

The MAJORANA demonstrator detectors are mounted on strings in ultra pure cryostats made of electro-formed copper. An electro-forming laboratory has been completed at the 4850 level and is currently operating. Two cryostats with up to 7 strings of enriched Ge detectors are expected to be deployed in Sanford Laboratory by 2014. The sensitivity of the MAJORANA 30kg demonstrator as a function of lifetime is shown in Fig: /reffig:maj. The solid curve is the sensitivity expected if a background level of 1 count/region-of-interest/yr is achieved and the dashed line is the sensitivity expected if a background level of 10 counts/region-of-interest is achieved.

3. The Long Baseline Neutrino Experiment (LBNE)

There are three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) made up of a superposition of three mass eigenstates (ν_1, ν_2, ν_3). It is believed that mixing between the flavor states is responsible for the phenomenon of neutrino oscillations. As there are at least three generations mixing, a complex phase (δ_{CP}) determines the amount of violation of charge-parity (CP) symmetry. Our current knowledge of the parameters governing neutrino oscillations is summarized in ref. [4]. The value of the mixing angle, θ_{13} is unknown, but is limited to be $< 10^\circ$ at the 90% C.L. The sign of the mass difference Δm^2_{31} which determines the ordering of the mass eigenstates is also unknown and the value of δ_{CP} is unknown. The current generation of neutrino oscillation experiments have limited sensitivity to the value of δ_{CP} and the mass hierarchy. The goal of the next generation of neutrino oscillation experiments is to determine whether CP is violated in the neutrino sector and unambiguously determine the mass hierarchy.

The proposed Long Baseline Neutrino Experiment (LBNE) utilizes a new neutrino beam-line located at Fermi National Accelerator Laboratory in Batavia, IL to send a beam of neutrinos 1300km to massive detectors located deep in the Homestake Mine. The neutrino beam is a traditional horn focused beam generated using 120 GeV protons from the Fermilab Main Injector. The neutrino beam is composed of mostly muon neutrinos with a wide-band energy spectrum peaked at 3 GeV. By changing the polarity of the horn currents, a muon anti-neutrino enriched beam can be generated. The combination of the wide-band beam energy and the longer baseline of LBNE allows the experiment to search for CP violation and measure the neutrino mass hierarchy using the oscillation of muon (anti-)neutrinos to (anti-)electron neutrinos.

Two detector technologies have been proposed for LBNE: a 200 kton water Cherenkov detector located at the 4850 foot level, and a 34 kton fine-grained liquid Argon time-projection-chamber located at the 800 ft level of the mine. Preliminary conceptual designs of the water Cherenkov and liquid argon detectors are shown in Fig: 5.

The LBNE detectors will also be used to significantly improve on the existing limits of proton decay, and as supernova neutrino detectors. Currently, only one of the proposed detector technologies will be selected for the conceptual design phase of

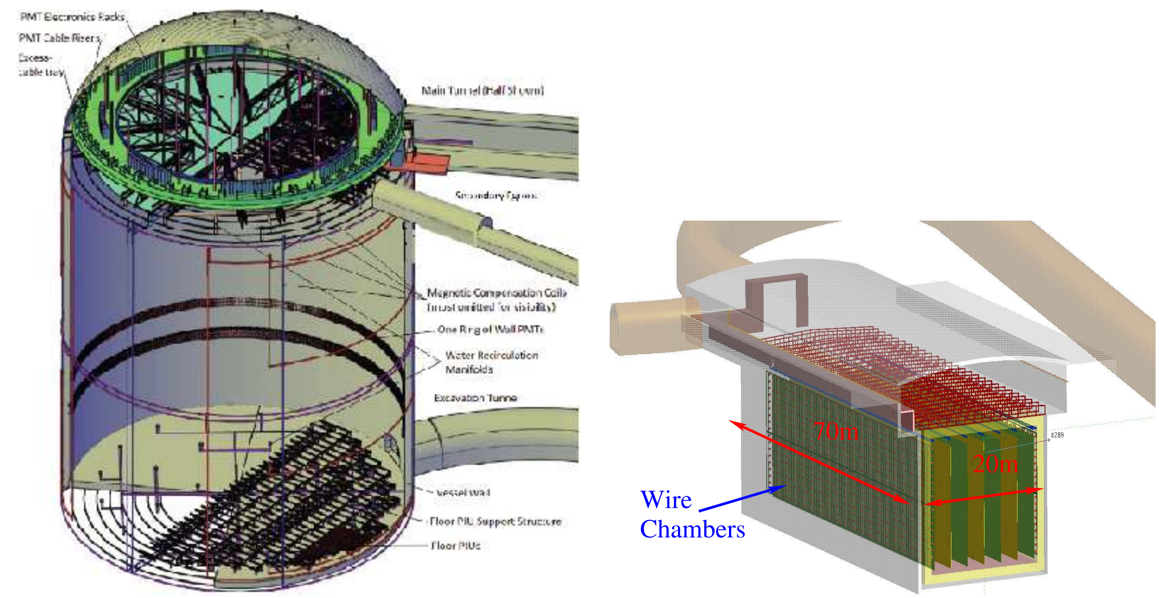

Figure 5: A 200 kton water Cherenkov module (left) and a 34 kton Liquid Argon detector (right).

LBNE. The decision on LBNE detector technology is expected by the end of 2011.

3.1. Long Baseline Physics

The baseline LBNE design assumes a 700kW beam running for 5 years in neutrino mode and 5 yrs with anti-neutrinos. Fig: 6 illustrates the projected 3 and 5 σ discovery limits for the neutrino mass hierarchy and CP violation obtained with a 200 kton water Cherenkov detector. The Super-Kamiokande detector simulation was used to estimate the LBNE water Cherenkov detector response [5]. The sensitivities with a 34 kton liquid Argon TPC were found to be very similar.

The proposed LBNE project will be able to achieve 3 σ or better sensitivity to the mass hierarchy and CP violation for values of $\sin^2 2\theta_{13} > 0.03$. The indications from global fits to neutrino oscillation data [4] indicate that $\theta_{13} > 0$ at the 3 σ level, with the most probable value being $\sin^2 2\theta_{13} = 0.08$ - which is in the region with 5 σ LBNE sensitivity.

3.2. Proton Decay

Grand Unified Theories (GUTS) predict that the lifetime of the proton could be within reach of LBNE. The current best limits on proton decay lifetimes are summarized in [6,7,8]. The two most experimentally accessible proton decay modes are $p \to e^+\pi^0$ and $p \to K^+\nu$. Water Cherenkov detectors are most sensitive to the $p \to e^+\pi^0$ mode, and the current best limits are set by the Super-Kamiokande

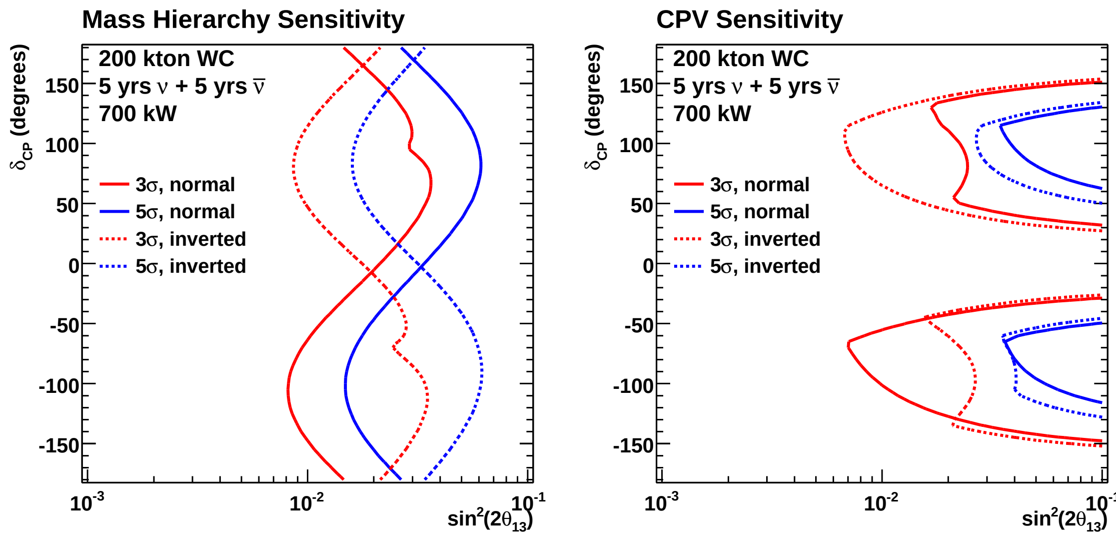

Figure 6: LBNE sensitivity to the mass hierarchy(left) and CP violation (right). The plots are assuming a 200 kton water Cherenkov detector, a 700 kW beam with exposure of 5 yrs neutrinos and 5 yrs anti-neutrinos.

detector. The charged kaon in the $p \to K^+\nu$ mode can best be detected using a fine grained, totally active liquid argon TPC. The projected sensitivity of the proposed LBNE detectors to the two proton decay modes are shown in Fig: 7.

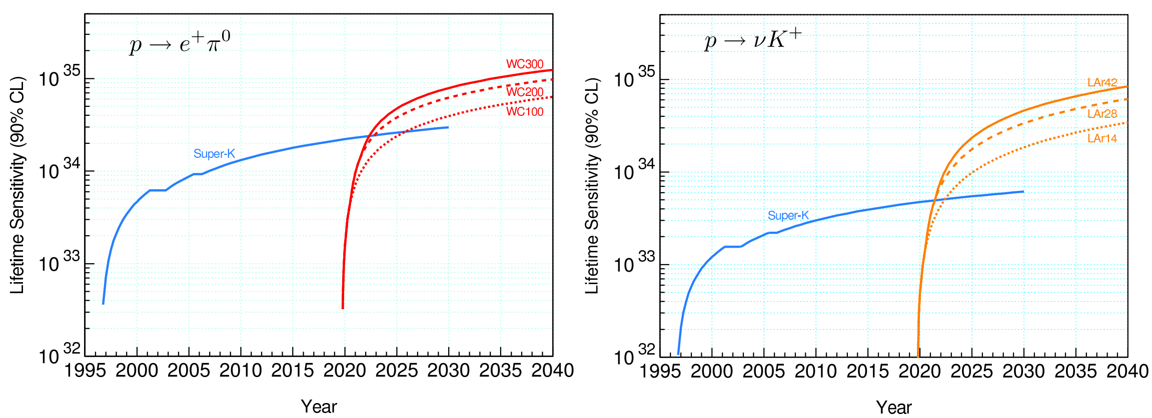

Figure 7: LBNE sensitivities to proton decay versus live-time. On the right are the sensitivities achieved with various water Cherenkov detector masses with the decay mode $p \to e^+\pi^0$. On the right are the sensitivities to $p \to \nu K^+$ with various liquid argon detector masses.

3.3. Supernova Neutrinos

Core collapse supernovae emit neutrinos in a burst that could last a few tens of seconds. Detection of supernova neutrinos would provide invaluable information about supernovae [9,10]. Half the neutrinos are emitted in the first second. The neutrino energies are of order 10 MeV. The three neutrino flavors are present in roughly equal amounts in the neutrino burst. In 1987, a total of 19 neutrino events from supernova SN1987A [11,12] were detected in the IMB and Kamioka water Cherenkov detectors, approximately 3 hrs before telescopes detected the light signal. SN1987A was located 55 kpc away in the Large Magellanic Cloud.

The expected rate of core collapse supernovae in the Milky Way is 2-3 per century. The LBNE neutrino detectors can detect very large neutrino signals from a nearby core collapse supernova. The different neutrino interactions in water Cherenkov and liquid argon detectors imply that each detector technology is sensitive to different components of the supernova neutrino burst. In particular the liquid argon detector is most sensitive to the electron neutrino component of the signal whereas the water Cherenkov detector is most sensitive to the anti-electron neutrino component. Tables 1, and 2 summarize the expected neutrino event rates for different neutrino species in a liquid argon and water Cherenkov detector respectively. The event rates assume a supernova at a distance of 10 kpc.

Table 1: Supernova neutrino rates in a liquid argon detector at Homestake

Channel	LAr 17kt Events
$\nu_e +^{40}\text{Ar} \rightarrow e^- +^{40}\text{K}^*$	1154
$\bar{\nu}_e +^{40}\text{Ar} \rightarrow e^+ +^{40}\text{Cl}^*$	97
$\nu_x + e^- \rightarrow \nu_x + e^-$	148
Total	1397

Table 2: Supernova neutrino rates in a water Cherenkov detector at Homestake

Channel	WCD 100kt Events
$\bar{\nu}_e + p \rightarrow e^+ + n$	27116
$\nu_x + e^- \rightarrow \nu_x + e^-$	868
$\nu_e +^{16}\text{O} \rightarrow e^- +^{16}\text{F}$	88
$\bar{\nu}_e +^{16}\text{O} \rightarrow e^+ +^{16}\text{N}$	700
$\nu_x +^{16}\text{O} \rightarrow \nu_x +^{16}\text{O}^*$	513
Total	29284

Observation of a supernova burst neutrino signal can also help to resolve some of the unknown neutrino mixing parameters such as θ_{13} and the mass hierarchy. Fig: 8 demonstrate the expected spectra of ν_e and $\bar{\nu}_e$ events in a liquid argon and a water Cherenkov detector respectively for normal hierarchy. The curve in red is the expected spectra for inverted hierarchy and the Ξ^2 of the fit to the wrong hierarchy is indicated on the figures. The studies indicate a that a supernova burst neutrino signal in the LBNE detectors has sensitivity to the neutrino mass hierarchy.

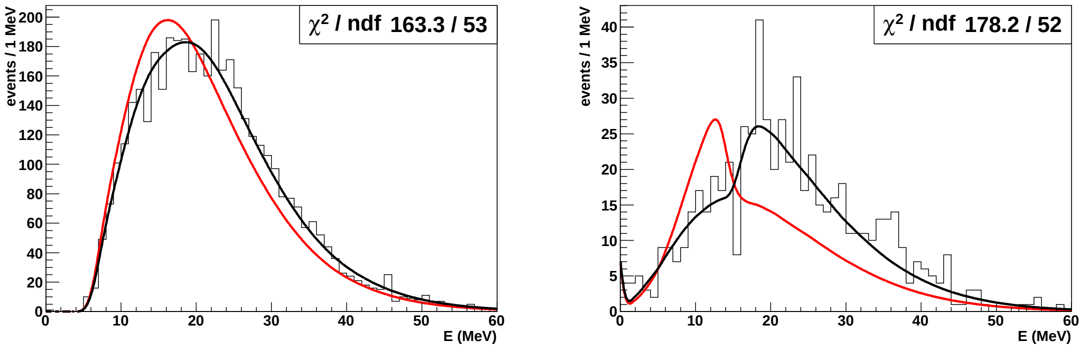

Figure 8: The supernova neutrino spectra from 10 kpc observed in the LBNE detectors for normal hierarchy (black) and the Ξ^2 from the fit to the opposite hierarchy (red). The figure on the left is the spectrum of mostly $\bar{\nu}_e$ observed in a 100 kton water Cherenkov detector. The figure on the right is the spectrum of mostly ν_e events observed in a 17kt liquid argon detector module.

4. Summary and Conclusions

The Homestake Mine has been a key player in the history of neutrino physics since the 1960s. In 2007, an effort to convert the defunct gold mine into a multi-disciplinary deep underground science and engineering laboratory was initiated by the US National Science Foundation (NSF). Following the Dec. 2010 termination of NSF support for the DUSEL facility development, the US Department of Energy DOE established an ad-hoc review committee in May of 2011 to advise the DOE on the cost effectiveness of pursuing the Homestake site for implementing the DOE programs in neutrino physics, double-beta decay, and dark matter. The committee issued its report in July of 2011 and the DOE is expected to make a decision on the fate of underground science efforts at Homestake mine in late 2011 or early 2012.

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The LBNE project, which proposes to use Homestake Mine as the site for massive neutrino detectors coupled to a high-power neutrino beam from Fermilab is proceeding with its conceptual design and detector technology selection. LBNE will be able to measure the neutrino mass hierarchy and detect CP violation at the 3 σ level or better for the region of non-zero θ_{13} values currently favored by global fits to the neutrino experimental data. The LBNE detector at Homestake will also extend the limits of the proton decay lifetime, and will be a superb detector for the neutrino burst from a core-collapse supernova within 15 kpc.

5. References

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