# THE MAJORANA DEMONSTRATOR: OVERVIEW AND STATUS UPDATE

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## ABSTRACT

The Majorana Demonstrator is being constructed at the Sanford Underground Research Facility (SURF) in Lead, SD, by the Majorana Collaboration to demonstrate the feasibility of a tonne-scale neutrinoless double-beta decay experiment based on $^{76}Ge$. The observation of neutrinoless double-beta decay would indicate that neutrinos can serve as their own antiparticles, thus proving neutrinos to be Majorana particles, and would give information on neutrino masses. Attaining sensitivities for neutrino masses in the inverted hierarchy region requires large tonne-scale detectors with extremely low backgrounds. The Demonstrator project will show that sufficiently low backgrounds are achievable. A brief description of the detector and a status update on the construction is given, including the work done at BHSU on acid-etching of Pb shielding bricks.

## INTRODUCTION

Ever since the elusive neutrino was first hypothesized by Wolfgang Pauli in 1931, it has been of great interest to nuclear and particle physicists and astrophysicists. Neutrinos are electrically neutral, elementary fermions (particles with spin ½) that interact weakly with matter and are produced in copious amounts in nuclear reactions and decays involving the weak interaction. They play key roles in the state of the early universe, in cosmology and astrophysics, and in nuclear and particle physics. In the 1960's, experimental chemist turned astrophysicist Ray Davis installed a chlorine-based neutrino detector in the Homestake Gold Mine in Lead, SD, to measure the flux of neutrinos from the Sun's core, emitted during various nuclear fusion reactions (Davis 1994; Cleveland et al. 1998). Located at the 4,850-foot level of the mine (1,478 meters in depth, or 4,300 meters water equivalent) in order to filter out background noise in the detector from cosmic rays, the Davis experiment at Homestake collected data between 1970 and 1994. With Davis's detector detecting approximately one-third of the neutrino flux predicted by theorist John Bahcall, this experiment was the origin of the Solar Neutrino Problem that ultimately led to a deeper understanding of particle physics. Davis was awarded a share in the 2002 Nobel Prize for Physics for this work.

The Homestake Mining Company closed the mine in 2003, and in 2006 a large portion of the property (including all of the underground workings) was donated to the state of South Dakota to be administered by the South Dakota Science and Technology Authority (SDSTA). Space around the original Davis Cavern has now been expanded and renovated to accommodate the next generation of underground science experiments, including experiments to further investigate the nature of neutrinos. Exploring the mass hierarchy and absolute mass scale of the neutrino and whether the neutrino can be its own antiparticle have been listed as one of the top priorities of astroparticle physics research. The report of the National Research Board, "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (Turner et al. 2003), identified the determination of the masses and nature of neutrinos as high priority questions in fundamental physics, with the potential to shed light on such topics as the unification of forces, evolution and matter density of the universe, synthesis of the elements of the early universe, the driving force of supernovae explosions, and why we live in a matter-dominated universe. The recent National Academy of Science report on underground science concluded that the direct detection of dark matter, neutrinoless double-beta decay and the long-baseline neutrino decay experiments are "of paramount scientific importance and will address crucial questions upon whose answers the tenets of our understanding of the universe depend." (Lankford et al. 2011).

There are three known observable types or "flavors" of neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$), named according to the particle with which they are associated (electron, muon, or tau). Conservation of lepton number requires that when a lepton (electron, muon, tau, or neutrino) is created in a nuclear reaction, a lepton of the same flavor is destroyed (or an antiparticle of the same flavor is created). Thus, in one of the nuclear fusion reactions in the Sun's core, a positron (anti-electron) is created in conjunction with an electron-flavored neutrino:

$$p + p \rightarrow d + e^+ + \nu_e$$

This "pp reaction" is one of the primary fusion reactions generating energy in the Sun's core. Two protons combine to form a deuteron, which consists of one proton and one neutron. In the process, one of the protons converts to a neutron and emits a positron, conserving electrical charge, and a neutrino, conserving lepton number.

While neutrinos were long thought to be massless, the Solar Neutrino Problem led to the discovery that neutrinos can change flavor from one type to another ("oscillate") and are thus required by quantum mechanics to have mass (Aharmim et al. 2008; Ashie et al. 2005; Araki et al. 2005; Ahn et al. 2006; Adamson et al. 2008). Although upper limits to the masses have been set, with the most recent results from the Planck Collaboration (Ade et al. 2013) indicating an upper limit for the summed neutrino mass of $\Sigma m_\nu = 0.23$ eV (electron volts; the mass of the electron is 511,000 eV), the absolute masses have not yet been determined. It is now known that the observable states of the neutrino flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are actually superpositions of neutrino mass eigenstates $\nu_i$, i = 1,2,3 (or possibly more) (Fritzsch and Zing 1995; Gonzalez-Garcia and Nir 2003). Experiments such as Super-Kamiokande (Fukuda et al. 1998), SNO (Ahmad et

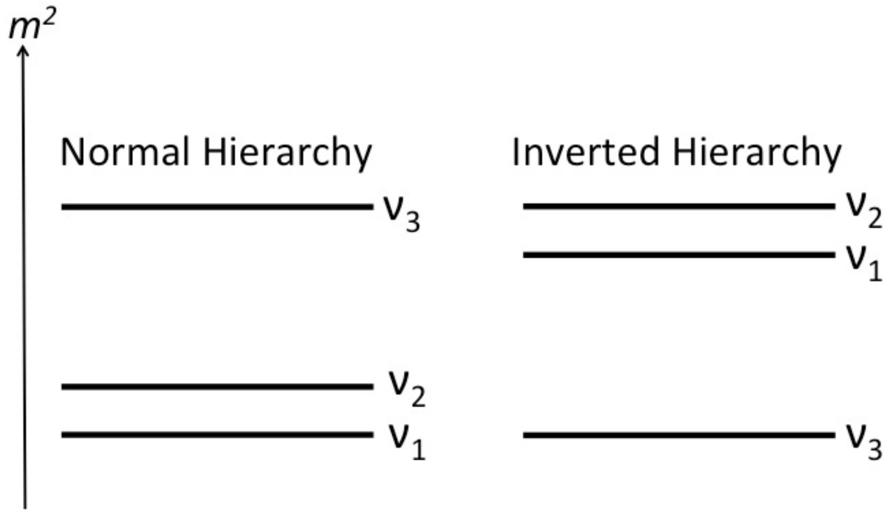


*Figure 1. Schematic of neutrino mass ordering for normal and inverted hierarchies.*

al. 2001), and KamLAND (Eguchi et al. 2003) have determined the differences between the squares of the masses of the mass eigenstates, e.g. $\Delta m^2 = m_2^2 - m_1^2$ , but do not indicate the hierarchy (see Figure 1).

Because the neutrino has mass and is electrically neutral, theoretically it could be either a Dirac fermion or a Majorana fermion, i.e., a particle that can serve as its own antiparticle (Freedman et al. 2004; Gutierrez 2006). One powerful method of determining the Dirac-Majorana nature of the neutrino that also promises to yield information on the neutrino mass is to detect the neutrinoless double-beta decay reaction.

A beta decay reaction occurs when an unstable nucleus "decays" to a lower-energy nucleus via the conversion of a neutron to a proton, emitting an electron and an electron-flavored antineutrino:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

For some nuclei, this process is not energetically allowed, although decaying to a state where two neutrons convert to protons is allowed. This is called double-beta decay:

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

Clearly, in order for lepton number to be conserved, if two electrons are created then two electron-flavored antineutrinos must also be created. However, if the neutrino is a Majorana particle, then it could act as its own antiparticle. In that case, one would be able to observe double-beta decay reactions in which no antineutrinos are emitted: neutrinoless double-beta decay, or $0\nu\beta\beta$. Such an experiment is a model-independent method to determine the Dirac-Majorana nature of the neutrino (Camilleri et al. 2008; Avignone et al. 2008). In a 0νββ experiment, one measures the energy of the emitted electrons in double-beta decay reactions. For "ordinary" double-beta decays, this energy would show up as a continuous spectrum extending up to the maximum energy of the reaction, called the endpoint energy. Since the two antineutrinos carry away some of the energy, the only time the two electrons would have the endpoint energy is when zero neutrinos are emitted. A neutrinoless reaction would appear as a small peak in the spectrum at the endpoint energy.

In order to see such a peak on top of the background of the energy spectrum from ordinary double-beta decay reactions, we need experiments designed with large-mass (tonne-scale) detectors and extremely stringent background reduction methods (backgrounds at or below ~1 count/tonne-year in the region-of-interest). Possible sources of background include cosmic ray muons; neutrons and radon (Rn) from the surrounding rock walls; and natural and cosmogenically-produced radioactive isotopes in the construction materials for the detector components. Uranium (U) and thorium (Th) decay-chain products are particularly problematic.

## METHODS

The Majorana Demonstrator (MJD) is currently being assembled in the Davis Campus on the 4850-foot level (4850L) of SURF by the Majorana Collaboration to demonstrate the feasibility of a tonne-scale 0νββ experiment in which the detector, composed of germanium crystals, is enriched in the double-beta-decay emitting isotope $^{76}$Ge. Details for the MJD design can be found elsewhere (Aguayo et al. 2011, Phillips et al. 2011, Schubert et al. 2012) so only a brief description is given here (see Figure 2).

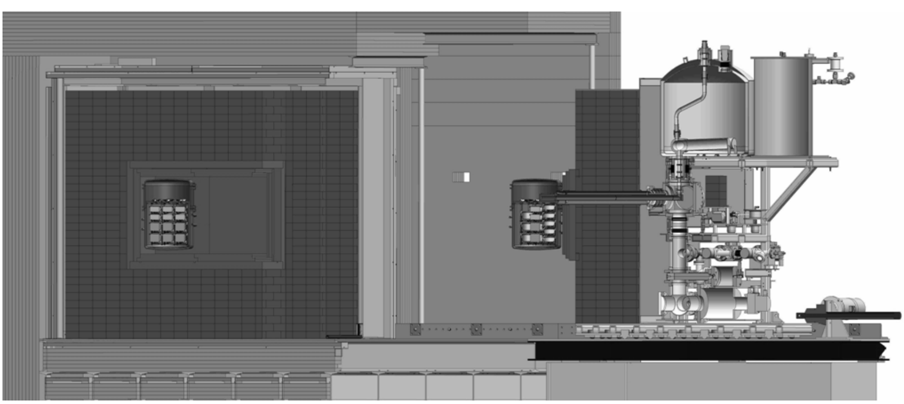

***Figure 2. The MAJORANA DEMONSTRATOR is shown here with both active and passive shielding in place. One cryostat is in place inside the shield while the other is being positioned for insertion. For scale, the inner copper shield is 20" high and 30" in length.***

The MJD will be comprised of approximately 40 kg of high-purity germanium (HPGe) detectors, with about 30 kg of material fabricated from 86% enriched $^{76}$Ge. The germanium crystals will be organized in "strings" of 3-5 flat cylindrical p-type point-contact (PPC) detectors of 0.6-1.1 kg each. The strings are currently being assembled inside a custom glove box with radon suppression in the Majorana clean room installed in the Davis Campus.

The Demonstrator will be constructed in three phases, starting with a prototype cryostat and followed sequentially by two production cryostats. The prototype cryostat will be fabricated from commercial copper and house two strings of natural germanium detectors, whereas the two production cryostats will be manufactured using electroformed copper and contain a mixture of natural and enriched germanium detectors. Data from the prototype detectors are expected by the end of 2013.

The components are being constructed in an underground ultra-clean clean room in the Majorana Laboratory space in the Davis Campus. The material for the production cryostats is ultra-pure copper that has been electroformed underground in the Electroforming Laboratory about 1 km from the Davis Campus, and the parts are machined in a clean machine shop in the underground Majorana Laboratory space in the Davis Campus.

The cryostats will be shielded from the surrounding environmental radiation by a passive shield with an innermost layer of electroformed Cu, then a layer of commercial high-purity Cu and a layer of high-purity lead (Pb). This shield is surrounded by an active muon veto to register cosmic radiation that penetrates to the 4850L, and a layer of polyethylene to shield the detector from neutrons.

For the Pb part of the MJD shield, 3500 virgin Doe Run bricks of the standard 2" x 4" x 8" (5.08 cm x 10.16 cm x 20.32 cm) size have been purchased from Sullivan Metals. Strict tolerances were required both for geometrical dimensions (± 0.03" (0.08 cm)) as well as for assay purity. In addition, approximately 3800 bricks were obtained from the University of Washington (UW). Some of the standard Sullivan bricks were machined to form approximately 1600 custom-sized bricks. To mitigate the risk of surface contamination on the machined Sullivan bricks and on the UW bricks which have been stored in a dirty environment, we decided that they would be cleaned using a series of baths of ultra-pure acids alternating with deionized water rinses.

The UW bricks were packed in skids containing 80 bricks each, and shipped to Black Hills State University (BHSU) where they were cleaned over a period of approximately seven months. A 12' x 12' (3.7 m x 3.7 m) modular clean room with an internal 6' x 4' (1.8 m x 1.2 m) gowning room was installed for this purpose at BHSU, located just 17 miles from SURF (see Figure 3). This clean room conforms to CL4 space procedures (with Class 10,000 to 1,000 cleanliness). Particle detector counts confirm that we have achieved better than Class 1,000 with good housekeeping procedures. Periodic industrial hygiene monitoring was performed, and no elevated levels of Pb dust were recorded. The 27' x 24' (8.2 m x 7.3 m) room housing the clean room was cleaned and prepared for the installation of a clean space (including updating the ventilation, servicing the fume hood, removing the floor tiles, polishing and sealing the concrete floor,


***Figure 3. The BHSU Clean Room, installed in Jonas Science room 165 on the campus of BHSU, located 17 miles from SURF. (a) Schematic of clean room. (b) Photo of JS 165 showing clean room and external prep/storage area.***

***Figure 4. Detailed photos of the BHSU Clean Room. (a) Pb bricks enter from the lower right of the photograph, and are transported to the fume hood for acetic and nitric baths and rinses. (b) After processing in the fume hood, Pb bricks are removed to the table for final rinse and isopropyl alcohol wash, and then set aside to dry on the table to the right. Once dry, bricks are triple bagged on this table, then they exit the clean room via the rollers at the bottom of the photograph.***

removing the ceiling tiles to expose the 12' (3.7 m) ceiling, cleaning and painting the walls and ceiling, and installing chemical safety equipment including an eyewash station and emergency shower) for the purpose of receiving Pb bricks in pallets, processing them in the BHSU clean room by etching with high-purity acids, and then bagging and repackaging them in preparation for transfer to SURF (see Figure 4). The pallets are stored in a facility just off-campus before and after processing.

The acid etching procedure for the UW bricks was performed by a staff of three technicians per shift: one person handling the acetic bath and rinse, one person handling the nitric bath and rinse, and one person handling the isopropyl wash and placing the brick aside to dry. The procedure was as follows:

- The bricks are first soaked in an ACS-grade, pure acetic acid bath (3–13 minutes, depending on brick) and then scrubbed in the bath 1-2 minutes with a soft plastic brush.

- Each brick is then rinsed in two consecutive deionized water baths, and then transferred to a nitric acid (1–3%, once-used Optima) and peroxide bath (3%, non-stabilized, ACS-grade) and cleaned for 1-2 minutes.
- Each brick is again rinsed in another two deionized water baths, and transferred to a separate area outside the fume hood and away from the dirty brick entry, for a final rinse with ultra-pure isopropyl alcohol and allowed to air-dry.
- Once dry, each brick is triple-bagged before being transferred out of the clean room and repackaged in adapted pallets in preparation for transport underground.
- Each pallet is numbered, and samples are kept from each acid bath exchange and the corresponding pallet number is noted.

The acid bath samples have been sent to Pacific Northwest National Laboratory (PNNL) for assaying in order to determine the uniformity of the UW Pb bricks. Assaying each individual brick is not feasible, and individual "hot" bricks might be missed by random sampling. By assaying the used acid samples, we can trace any abnormal readings to a small subset of the total collection of Pb bricks, i.e. which pallet and which bricks within the pallet. Scrapings from a random sampling of bricks were also kept, and are available for assaying as well.

## RESULTS

Background mitigation is essential. By conducting the electroforming of the Cu for the cryostat components and the inner shield in a clean room underground, the collaboration is able to produce Cu with U and Th impurity levels ten times lower than commercial electroformed Cu, at less than $10^{-12}$ g/g.

Representative samples of the UW bricks both before and after acid etching are shown in Figures 5 and 6. The acid bath samples are being tested at Pacific Northwest National Laboratory (PNNL) for contaminants. Before cleaning, the bricks had various levels of contamination including: lead sulfide, lead oxide, lead carbonate, dust and potential elemental mercury. Preliminary results indicate acceptable levels of U and Th have been achieved, but final results are not yet available.

## DISCUSSION

The MJD string assembly is currently underway in the underground Majorana Laboratory space at SURF. Approximately 80% of all electroformed copper required for the Demonstrator has been produced, including all of the Cu components for the first cryostat. The machining of the electroformed Cu is underway, and Cu electroforming continues in the TCR for the second cryostat components and the inner Cu shield. All of the UW Pb shielding bricks have been processed and are awaiting transport to SURF, and the machined Sullivan Pb shielding bricks are beginning to be cleaned. The acid etching is expected to be completed by December 2013.

***Figure 5. Photograph of sample UW Pb bricks before acid etching.***

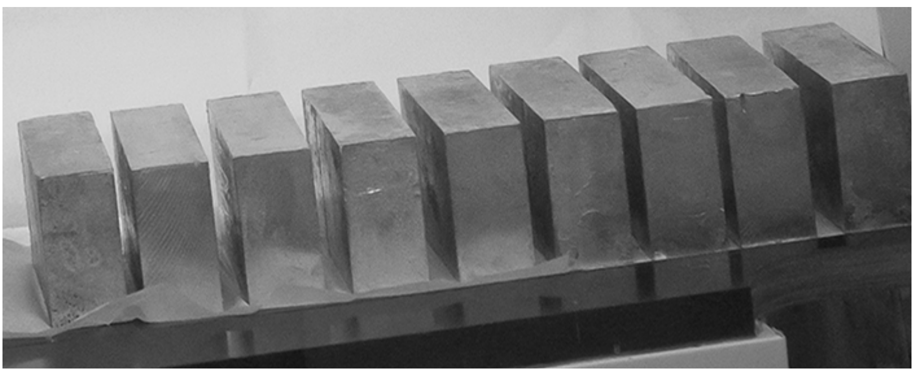

*Figure 6. Photograph of sample UW Pb bricks after acid etching.*

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