CENTER FOR ULTRA-LOW BACKGROUND EXPERIMENTS AT DUSEL*

Barbara Szczerbinska[a], Anrew Alton[b], Xinhua Bai[c], Mark Hanhardt[c]
Haiping Hong[c], Mark Horton[c], Stanley M. Howard[c], Dana Medlin[c]
Austin Nelson[c], Andre Petukhov[c], Bill Roggenthen[c], Dan Durben[d]
Kara Keeter[d], Michael Zehfus[d], Vince Guiseppe[e], Chaoyang Jiang[e]
Christina Keller[e], Dongming Mei[e], Jason Spaans[e], Yongchen Sun[e]
Keenan Thomas[e], Wenchang Xiang[e], Chao Zhang[e], Jose Alonso[f]
Jaret Heise[f], Robert McTaggart[g], Joel Rauber[g]

[a]Dakota State University, Madison, SD 57042, USA
[b]Augustana College, Sioux Falls, SD 57197, USA
[c]South Dakota School of Mines and Technology, Rapid City, SD 57701, USA
[d]Black Hills State University, Spearfish, SD 57799, USA
[e]University of South Dakota, Vermillion, SD 57069, USA
[f]Sanford Underground Laboratory, Lead, SD 57754, USA
[g]South Dakota State University, Brookings, SD 57007, USA

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The selection of Homestake Mine in Lead South Dakota by National Science Foundation (NSF) as the site for Deep Underground Science and Engineering Laboratory (DUSEL) opened new research opportunities in the state of South Dakota. One of many efforts allowing the scientists a significant participation in the activities planned at DUSEL was the creation of a 2010 Research Center focused on the production of ultra-low background materials or a Center for Ultra-low Background Experiments at DUSEL (CUBED). The main objectives of this research center are: (1) to bring together the current South Dakota faculty to develop a critical mass of expertise necessary for the state's full participation in the large-scale collaboration at DUSEL; (2) to increase the number of research faculty members in the state to complement and supplement existing expertise in nuclear physics and materials sciences; (3) to train and educate graduate and undergraduate students. The main research focus of CUBED is aimed at experiments searching for rare and difficult to detect phenomena such as neutrinoless double beta decay and dark matter. Major scientific activities proposed by CUBED include a low background counting facility, an underground crystal growth lab, a purification/depletion facility on noble gases, and an underground electroforming copper facility. We will provide detailed information of research activities at CUBED.

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1. Introduction

The Homestake Gold Mine located in Lead, South Dakota was the oldest, largest and deepest mine in the Western Hemisphere. Reaching more than 8000 feet underground it served as an economic engine for western South Dakota. In addition to the economic accomplishments, the mine served for approximately 20 years as the home for a seminal experiment in nuclear astrophysics. In the search for solar neutrinos, Ray Davis, a physicist at Brookhaven National Laboratory located a large tank of perchloroethylene in a mining cavity 4,850 ft underground. The experiment detected solar neutrinos, but at one third the rate predicted by current models for the energy production within the Sun. The discrepancy was confirmed by later neutrino experiments, and Ray Davis was awarded the 2002 Nobel Prize in Physics, the first and only Nobel Prize awarded to an experiment located in the State of South Dakota. Mining operations ceased at Homestake in late 2001, and the possibility of converting the extensive underground space into an interdisciplinary national laboratory began to take shape. The State formed the South Dakota Science and Technology Authority (SDSTA) to serve as landlord and to manage the property. $ 39 M was appropriated by the State Legislature, and $ 70 M was donated by T. Denny Sanford for the establishment of the Sanford Laboratory, with a primary focus on ultra-low background experiments. In 2007, National Science Foundation (NSF) selected Homestake as the site of a national Deep Underground Science and Engineering Laboratory (DUSEL). The location of a national science lab in South Dakota presents tremendous opportunities for a state with agriculture and tourism as the primary economic engines of the state and fits perfectly with the state's 2010 initiative, which outlines a series of goals to promote economic growth within South Dakota [1]. In response to planned experiments at Sanford Laboratory/DUSEL, South Dakota's governor announced the creation of a new 2010 center for ultra-low background experiments at DUSEL (CUBED), focused on underground materials purification and crystal growth experiments. Led by The University of South Dakota, CUBED Collaboration consists of 20 scientists representing seven institutions within the state. In addition, an external advisory committee for CUBED has been formed with scientists from Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, University of California Berkeley, University of North Carolina, Brown University, Princeton University and Sanford Laboratory.

2. Project overview

Neutrinos and dark matter are believed to hold the key to physics beyond the standard model of particle physics. However, very little is known about the general properties of neutrinos such as absolute mass and magnetic moment, particle type (Dirac or Majorana), and the number of species. The planned future experiments are intended to address these properties utilizing rare event physics processes such as neutrinoless double beta ($0\nu\beta\beta$) decay [2] and neutrino oscillation which would clearly show that the neutrino is a Majorana particle and that the lepton number is not conserved. We know nothing about the nature and quantity of dark matter in the universe. One of the most appealing candidates for dark matter is the Weakly Interacting Massive Particle (WIMP) [3], which is a particle beyond the Standard Model. The search for WIMPs via their elastic scattering interaction with nuclei would help to determine the mass and cross-section of a WIMP. The emphasis on experiments centered on dark matter and neutrinoless double beta decay is consistent with the priorities identified by a national panel (Particle Physics Project Prioritization Panel or P5 report) as some of the most important physics projects to be pursued in the 21st century: The Deep Underground Science and Engineering Laboratory would offer a major new facility for US particle physics. Located in the Homestake mine in Lead, South Dakota, DUSEL would be an underground laboratory housing a wide spectrum of experiments. When the first parts of the laboratory begin operation around 2017, DUSEL would be a key element in the US particle physics program. A large detector for long-baseline neutrino physics would be part of the initial suite of experiments, as would detectors for dark matter and double beta decay experiments. Extremely low event rate for both types of experiments requires large mass exposures of sensitive detectors with small internal backgrounds and sufficient shielding against external backgrounds at a deep underground site.

CUBED Research Center provides a unique mechanism for scientists within South Dakota to develop a critical mass of expertise necessary for South Dakota's full participation in the large scale collaborations focused on the neutrinoless double beta decay and dark matter exploration planned at DUSEL. These discovery opportunities have tremendous funding potential, both through the NSF-sponsored research programs, and as commercial opportunities due to the materials production techniques developed in this center. The main areas of interest to CUBED are: (1) an underground crystal growth laboratory; (2) a low background counting facility; (3) a copper electroforming facility and, (4) a purification/depletion facility for noble gases. The expected scientific outcomes will impact undergraduate and graduate education in the state of South Dakota, and may also fuel economic growth in the areas of materials development and production.

3. Project background

Experiments searching for rare events require an unprecedented level of purity in the materials used to construct the detector, and must be located in an ultra-low background environment. The community recognizes that to fully exploit this exciting physics program and achieve the planned sensitivity one needs the shielding of a deep underground laboratory and an underground ultra low background facility to screen materials for radioactive contamination. The physics goals of upcoming double beta decay experiments with germanium targets are to probe the quasi-degenerate neutrino mass region as low as 100 meV and demonstrate that backgrounds can be achieved at or below 1 count/ton/year in the $0\nu\beta\beta$ decay peak region of interest (ROI). On the other side, the dark matter experiments with germanium detectors will require backgrounds less than 1 count/ton/year to be sensitive to WIMP-nucleon cross-section of 10^{-46} cm^2. Due to relatively long half lives (0.8 years, 5.3 years, and 12.3 years for ^{68}Ge, ^{60}Co, and ^{3}H, respectively), it is clear that cosmogenic production of ^{68}Ge, ^{60}Co and ^{3}H creates important backgrounds for the next generation neutrinoless double beta decay and dark matter experiments with germanium as the targets. The production rates are substantial [2] and steps must be taken to reduce exposure of the target to cosmic rays, reduce the resultant cosmogenic isotopes within the target after exposure. The best way to avoid the cosmogenic production is to produce germanium crystals underground. Because the cosmogenic production is dominated by cosmic-ray neutrons [2] and the direct contribution from cosmic-ray muons is at a level of a few percent, the depth needed to significantly reduce the cosmogenic production is on the order of 10 MWe to 100 MWe depending on the reduction factor desired for the experiments. To address this major problem the experiments must construct detectors in an ultra-low background environment [3].

4. CUBED research activities

4.1. Low background counting facility

Ultra-low background detectors with the grown crystals or purified noble liquids in search of rare events or weakly interacting particles require radioactive background from cosmic rays and natural radioactivity of unprecedented low levels. As the very components of the experimental apparatus are potential sources of background radiation, it is necessary to screen the components using ultra-sensitive detectors in shielded facilities. Since the best screening facilities currently available in shielded sites at the Earth's surface are still insufficient to measure the required levels of radioimpurity, CUBED will create an ultra-low background counting facility (ULBCoF) at DUSEL. ULBCoF will house two low background gamma-ray detectors in a highly efficient clover-leaf configuration of four germanium detectors each. These detectors will utilize ultra-pure materials for the components to keep background levels as low as possible. Additional detectors can be used for monitoring radon levels in lab air and water systems. We will develop background rejection techniques using low background detectors, active and passive shielding, veto systems, pulse shape discrimination techniques, and atmosphere control systems to reduce radon levels. A few essential requirements determine its main features: (1) simple assembly and quick establishment; (2) use of existing technology and commercially available materials; (3) easy underground access; and (4) capability of screening any type of material.

Each low background detector is about 10 cm in diameter and 8 cm in length, and has high-resolution, cold-FET energy readouts. The pulse shape discrimination has been well studied at Los Alamos National Laboratory [4] and requires commercially available electronics.

The sensitivity will be enhanced with radiopure materials for detectors, structures, and shielding to further reduce unwanted background events. The inner shielding is 10-cm of oxygen-free high conductivity (OFHC) copper with 99.99% purity. The contamination of ^{238}U and ^{232}Th in this material is less than 100 μBq/kg [5]. Outside the copper shielding, a 5 cm layer of 30% borated polyethylene is used to absorb the low-energy neutrons produced in the lead by muons. After the borated polyethylene layer, a 30 cm layer of lead is utilized to stop environmental gamma rays from entering the detector. The outermost shielding is a 50 cm layer of pure polyethylene bricks to stop the neutrons produced from the surrounding rock. Muon veto detectors are placed outside the outer shielding, providing coverage of 4π.

4.2. Underground crystal growth laboratory

At least 1000 kg of single crystal Ge is needed for the neutrinoless double beta decay experiments [6]. Additionally, NaI/CsI crystals are needed for dark matter searches [7, 8]. Commercially available crystals are produced on the Earth's surface but this leads to an increase in the cosmogenic production of ^{68}Ge and ^{60}Co in enriched ^{76}Ge. If these crystals reside on the surface for as little as a week, these cosmogenic isotopes seriously degrade the sensitivity of the next-generation, double beta decay experiments. This imposes strict constraints on the time to produce and transport such crystals. These constraints are removed if the material purification and crystal growth is performed underground. One goal of CUBED is to construct an underground crystal growth facility at DUSEL to provide ultra-pure crystals for use in neutrinoless double beta decay experiments and in direct dark matter searches.

Many steps are required to convert polycrystalline materials such as Ge into a gamma-ray spectrometer. The electronic-grade polycrystalline Ge starting material is zone refined within a quartz tube filled with high-purity H_2 and Ar. Ingots of electronic-grade Ge approximately 75 cm long are held horizontally in a high-purity silica boat as a radio frequency (RF) coil surrounding the quartz tube melts a small vertical section of the ingot. As the ingot is slowly drawn through the coil, the advancing side of the molten section carries the impurities leaving a trailing solid that is more pure. Therefore, the last liquid to solidify at the ingot's end contains an increased impurity level. Repeated passes from one end to the other, sweep the impurities to one end of the ingot. This impure end is removed to leave the desired higher-purity portion. Production rates can be increased by drawing multiple ingots through multiple coils within one quartz tube. Purity is determined using a Hall Effect measurement. The ingot is broken into pieces to avoid contamination (from sawing) and loaded into the crystal-growing furnace.

Large single crystals of Ge are grown using the Czochralski technique [9]. Figure 1 is a drawing (on the left) and the photograph (on the right) of the crystal growing unit to be used in this work. A precisely cut Ge seed crystal is oriented and affixed to the end of a rotating shaft that is lowered into the molten Ge. The crystal grows from the seed crystal as it is slowly withdrawn from the melt while maintaining the temperature just above the fusion temperature. The rate of crystal withdrawal and temperature of the melt are adjusted to control the crystal's dimensions.

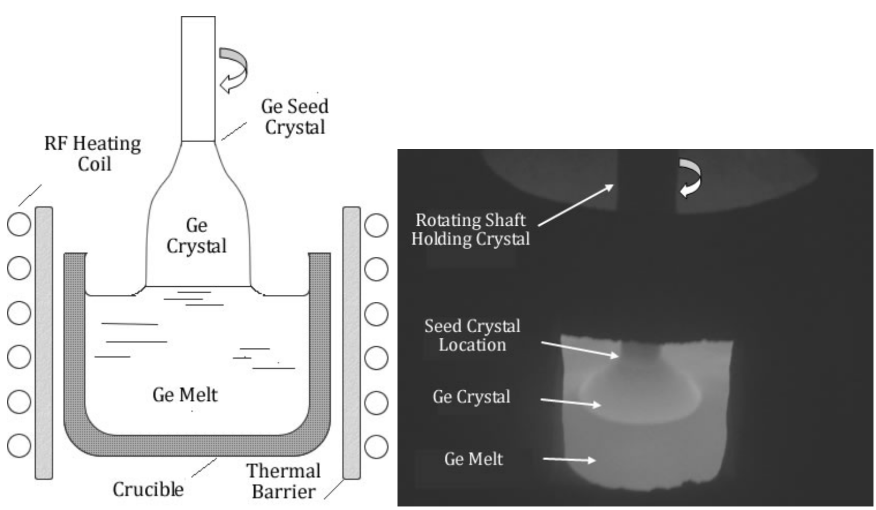

Fig. 1. Crystal growth with the Chochralski technique.

4.3. Underground copper electroforming

Ultra-pure copper is necessary material for constructing a low background detector with the grown crystals or noble liquids; however, the copper purity level needed for the cryostat design is several orders of magnitude greater than commercially pure copper available on the market. To further complicate the issue, the ultra-pure copper will experience contamination on the surface of the earth due to natural cosmic radiation in the environment. It would be difficult to manufacture ultra-pure copper at an electroforming manufacturing facility anywhere in the US and transport the copper to DUSEL without risking unwanted contamination. The solution to this problem is the development of an underground electroforming copper facility at DUSEL in which the overburden above the laboratory shields the copper from cosmic ray radiation.

Electroforming is a highly specialized process for fabricating metal parts by electro-deposition in a plating bath over a base form or mandrel which is subsequently removed. The advantage of the electroforming process is that it dependably reproduces the form or mandrel within several microns without the shrinkage and distortion associated with other metal forming techniques such as casting, stamping or drawing. Since the mandrel is machined as an outside surface for electroforming, close dimensional tolerances and high surface finishes can be held and maintained on complex interior configurations for the copper components.

Electroformed metal must be extremely pure, with ultra-high radiopurity of less than 0.1μBq/Kg. Multiple layers of electroformed metal can be electrochemically bonded together onto different substrate materials to produce complex structures with electroformed flanges and bosses. Electroforming should be thought of as a basic manufacturing process and a real solution in such a specialized instance. Figure 2 shows a schematic of the electroforming process. The positively charged electroformed metal source (anode) at the left (A) is broken down (ionized) in the copper electrolyte solution and

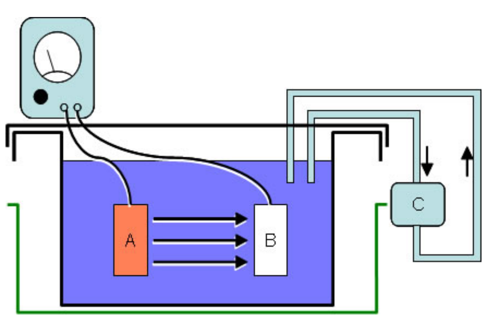

Fig. 2. Schematic of electroforming copper.

copper ions are attracted to the negatively charged mandrel (cathode B). Build-up is achieved over all mandrel surfaces at an approximate deposition rate of 0.002 inch (0.0508 mm) per day.

4.4. Purification/depletion of noble gases

Noble gases serve as excellent detectors for dark matter searches, with argon being one of the preferred gases. Unfortunately, the presence of ^{39}Ar in naturally occurring argon, even at the level 10^{-15}g/g, provides an undesirable background as one scales up to multi-ton experiments. CUBED is exploring two methods to obtain argon depleted of ^{39}Ar. The first adapts the well known method of using thermal diffusion (TD) columns for isotope enrichment; the second looks at extracting argon from water reservoirs located in geologically old rock formations. We hope that using argon from underground wells as a starting material for the thermal diffusion columns may result in a depletion factor as large as one thousand. Such a detector will allow a 10 keV electronic recoil energy (keVee) threshold for direct dark matter searches with a sensitivity of 10^{-46} cm^2 or better.

Taking advantage of producing depleted argon from both the underground gas field [10] and the TD columns, the Darkside Collaboration [11] plan to build a depleted argon detector at Sanford Laboratory. We have studied background rejection using pulse shape discrimination as a function of electronic recoil energy and the external shielding requirement at the 4850-ft level. The results for the external shielding requirement are described in Fig. 3.

With a proper shielding, the target sensitivity is 1 event/ton/year in the energy range of interest (40 keV to 100 keV recoil energy). This allows us to achieve the WIMP-nucleon cross-section of 10^{-45} cm^2 in three years.

In connection with these efforts, one outstanding activity which must be pursued in order to make a large argon dark matter detector realistic for DUSEL is purification of the gas collected from underground wells and/or after thermal diffusion to achieve the purity level of 99.9999999% which will be used in the detector. Particularly significant are the contaminations in O_2, N_2, and H_2O, which are responsible for quenching of the scintillation light and/or disruption of the ionization signal [13].

Commercial instruments capable of measuring contamination of argon gas at the required levels are not presently available. It is therefore necessary to develop instruments to measure oxygen, nitrogen, and water vapor contaminants in noble gases such as argon at the sub-ppb level or better. The development of such instruments would also benefit other efforts in the field, namely the xenon- and neon-based detectors. Such technology would also likely be desirable commercially. We intend to design and build

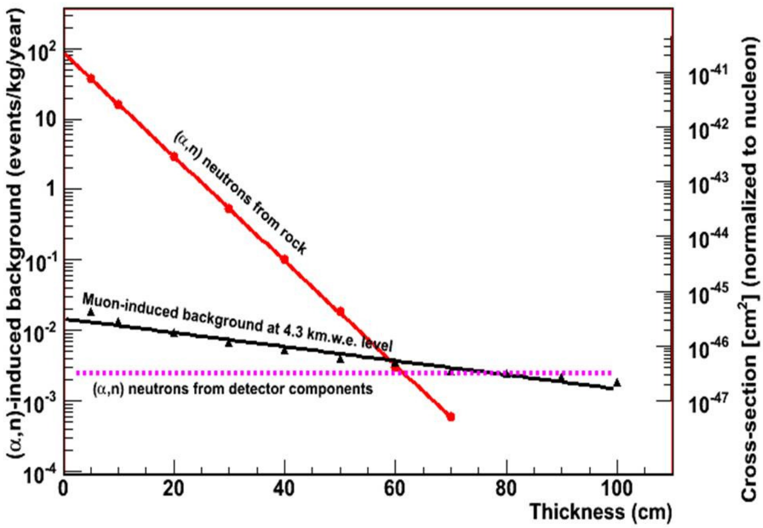

Fig. 3. External shielding as a function of the thickness of polyethylene. The (α, n) neutrons from rock is referred to [12].

a custom spectrometer based on cavity ring-down technology which will be sensitive to the sub-ppb range and will represent a significant improvement of the state-of-the-art technology.

5. Center economic and education goals

In addition to building collaborations among existing faculty, the CUBED center also initiates the process of increasing the number of trained physicists in South Dakota. New research faculty members will be hired using center funding to contribute to the development of DUSEL projects, and pursue external funding. The center also funds post-doctoral researchers, graduate students, and other skilled technical positions. Finally, the activities of the center will contribute to the recently approved state-wide Master's program in physics and will play an important role in the success of a proposed doctoral program in physics.

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