# Neutrino Physics with SNO+

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# Neutrino Physics with SNO+: Final Report

## 1 Introduction

SNO+ has a broad physics program, with the primary goal being a search for the phenomenon of neutrinoless double beta decay (NLDBD), a process possible only if the neutrino is its own antiparticle, or a "Majorana" fermion. Such a discovery would substantially alter our understanding of particle physics, including introducing the need for a non-Higgs mechanism for generating particle mass, and place constraints on the as-yet-unknown neutrino mass. In an extensive solar-neutrino program SNO+ will measure the *pep* neutrino flux, a line source at 1.4 MeV, to 10% (5%) precision with 1 (3) years of data, and also extract the spectrum of $^{8}$B neutrinos to low energy. We should thus definitively determine the shape of the solar neutrino spectrum at low energies, either observing or ruling out new physics effects in the vacuum-matter transition region. SNO+ will resolve recent ambiguity in the abundance of heavy elements in the Sun, and test our understanding of solar fusion, by detecting the low-energy CNO and *pp* solar neutrinos, respectively. SNO+ will detect antineutrinos produced inside the Earth (geoneutrinos), enabling us to differentiate between models for heat production in the Earth. Detection of antineutrinos from nearby reactors will enable us to improve precision on oscillation-parameter measurements. We will continually monitor for neutrinos from nearby supernovae, which, if detected, could allow us to better understand the role of neutrinos in stellar core collapse, and potentially to determine the unknown hierarchy of neutrino masses.

This grant supported the design, construction, and operation of a stable source of Cherenkov light for precision optical calibrations of the liquid scintillator-based SNO+ detector. This enables us to understand and model the detector response at a detailed microphysical level, a requirement for extraction of the robust, high-precision physics results necessary for convincing discovery potential. Also supported are the calibrations of hit-level PMT data necessary for extraction of calibration constants from the source data, and for optimizing performance of reconstruction algorithms. This will improve detector energy resolution, a critical factor in NLDBD sensitivity.

## 2 Project Deliverables

The original deliverables for this award are laid out below:

- Design, construction, and deployment of the Cherenkov source: an optical calibration source for SNO+;
- Necessary modeling and simulations to determine a calibration plan for the Cherenkov source;
- Develop tools for hit-level PMT calibrations and extracting the PMT angular response;
- Perform electronics and PMT calibrations on a regular basis during detector operations;
- Automate the electronics calibrations process;
- Deploy and analyse data from the Cherenkov source;
- Lead SNO+ physics analysis efforts.

During the award period the scope of work was expanded, with Dr. Baktash's approval, to include DAQ development and detector commissioning for SNO+, as well as work on several SNO analyses, with the goal of providing physics publications during the grant period. This has not impacted completion of the original deliverables of this grant.

# 3 Progress During Award Period

## 3.1 Cherenkov Source

We are constructing a source of Cherenkov light to be used as a calibration source for the absolute PMT efficiency, and to monitor the scintillator optical properties. The Sudbury Neutrino Observatory (SNO) made use of a $^8$Li calibration source. $^8$Li is a $\beta$ emitter with an end-point energy of $\sim$ 13 MeV. The SNO calibration source was fed $^8$Li produced by the $^{11}$B(n,$\alpha$)$^8$Li reaction in a DT generator and transported using a carrier gas (primarily helium) into a spherical decay chamber [1]. $^8$Li decay produces a $\beta$ and 2 subsequent $\alpha$ particles, with very short half life, from decay of the daughter $^8$Be nucleus. The SNO decay chamber was a thin metal sphere, allowing the $\beta$s to escape into the detector. For SNO+ the source will be modified by replacing the metal sphere with a thick acrylic shell, in which the $\beta$ particles will produce Cherenkov light before being absorbed. Included in the source design is a PMT housed above the decay chamber, in order to detect scintillation light produced by the $\alpha$ particles in the helium gas, thus providing a tag for source events. In order to prevent scintillation photons propagating through the acrylic, and to enhance the tagging efficiency, the chamber is lined with opaque followed by reflective and wavelength-shifting films.

The source design has been completed, and the final technical drawings were included in the BY13 report. Two prototype sources were constructed, as reported in the BY15 report. This process highlighted some possible improvements, which were implemented in the final design – including shortening the can to reduce the overall weight, and adding a port to facilitate leak checking after each deployment. Construction of the final source was completed and reported in the BY16 report. Approval was granted from the SNO+ source committee for deployment in water. Source deployment procedures were defined to protect the cleanliness and integrity of both source and detector, and were reviewed by the SNOLAB review committee.

The source was shipped to site and deployed in the light-water phase of SNO+ in spring of 2018. The PMT collection efficiency was extracted from this data with percent-level precision, demonstrating the necessary methods for calibration of the final LS-filled SNO+ detector. These calibrations are expected to proceed in spring 2019, once the SNO+ detector is filled with LS.

## 3.2 Hit-level PMT Calibrations

The PMT Calibration Working Group, led by UCB postdoc Dr. Javier Caravaca, is responsible for calibrating the electronics and data acquisition (DAQ) systems as well as the hit-level PMT response. Full PMT waveforms are not recorded, thus a correction is required for the charge pedestal value. The PMT hit time is measured using a TAC (time-to-amplitude converter) with a common-stop approach, thus a time-slope calibration is required for conversion of ADC-count times into nanoseconds. The channel trigger uses a constant discriminator threshold, rather than a constant-fraction trigger, which means we must correct for the pulse rise time: a pulse with higher charge will cross threshold more quickly. A complete understanding of the shape of the single photoelectron charge spectrum is required to model this effect accurately in simulation. UCB is responsible for all stages of hit-level PMT calibrations.

PI Orebi Gann wrote a software module designed to extract charge-pedestal and time-slope information from electronics calibration (ECA) data, consisting of forced detector triggers. UCB postdoc Dr. Caravaca has made substantial improvements and extensions to this module, several presented in the BY15 report. In this BY Dr. Caravaca has tested each sub-system on SNO+ commissioning data with a water-filled detector, and the ECA is now successfully operating during physics data taking. Dr. Caravaca completed a detailed study of an effect termed "Time-since-last-hit" (TSLH), in which he demonstrated that the channel pedestals are dependent on the time

since the channel was last read out. He has since optimized the ECA rate and occupancy and the detector thresholds in order to minimize this effect, and has completed the necessary tools to embed pedestal calibrations in physics data taking in order to monitor this effect in real time. He has also implemented a cross check on this effect using crosstalk hits, which are now successfully identified and flagged in data.

UCB post-doctoral researcher Dr. Freija Descamps completed a software module to extract the charge spectrum and rise time effects from optical calibration data (PCA calibrations). The original scope of work was completed during BY14, which involved the necessary processors and procedures to extract these calibrations from deployment of the single, isotropic laserball source. In BY15 she expanded this module to include calibrations based on the embedded fibre light-injection system, TELLIE. During BY16 Dr. Descamps used the PCA code to estimate the PMT gains, which was then used to adjust the operating HV values. First data from the deployed laserball calibration source was analysed, and timing constants extracted and used to process physics data. Data taking using the TELLIE fibres is ongoing, using a tool developed by Dr. Descamps to gauge the quality of the data. After Dr. Descamps' departure, Dr. Caravaca took over the PCA calibrations. Several complete PCA analyses using fibre data have since been completed and compared to the results from laserball data. This will allow in-situ monitoring of the PMT response during the LS phase, without requiring deployment of a source and, thus, without the inherent risks of contamination.

Another critical input to understanding SNO+ data is the number of online channels. There are a number of ways in which a channel can malfunction, including (but not limited to) a faulty cable, a faulty PMT base, or a blown resistor. These channels are turned off in the detector, and reproducing the impact of the number and locations of offline channels is critical in order to understand the light yield and detector response during different periods of data taking. PI Orebi Gann wrote the original code to reproduce the detector state in the Monte Carlo simulation. Dr. Descamps and Dr. Caravaca developed software modules to read out pertinent detector information from the DAQ systems, and these were substantially updated to deal with new DAQ configurations, and to synchronise with the automated near-line systems, which are responsible for uploading run-by-run detector configuration settings to the SNO+ database.

Graduate student Ed Callaghan has taken on the task of developing the PMT noise processor, first developed by UCB undergraduate Kevin Knuckolls. This processor evaluates the dark noise rate detector wide on a run-by-run basis. Ed has implemented this analysis in the nearline framework, which processes runs on site as data is output from the detector. The extracted PMT noise rates are automatically uploaded to the analysis database. The calculation has been improved to better take into account channels that are offline, and current effort is to integrate statistics across multiple runs in order to extract noise rates for individual PMTs.

### 3.3 Data Acquisition and Detector Commissioning

UCB postdoc Dr. Freija Descamps led the SNO+ Data Acquisition (DAQ) Working Group, and both Drs. Caravaca and Kefelian and Mr. Land contributed to DAQ development. UCB took over responsibility for SNO+ DAQ efforts in March 2015. At that time there was serious concern about the state of the data acquisition software, and the safety of detector operations. Under Dr. Descamps' leadership the state of the DAQ was transformed. The DAQ group commissioned the detector, under Dr. Descamps' guidance, over the winter of 2016-17 and delivered a robust, stably operating detector to the collaboration for quality physics data taking. Drs. Descamps and Caravaca and Mr. Land were heavily involved during commissioning, and all spent extensive time on site operating the detector during this award period. Development of the DAQ tools has been extensive; highlights are presented here.

UCB led development of an alarm framework and graphical user interface (GUI), which has been implemented from scratch during this BY. Dr. Descamps was involved in the design of the underlying database structure and wrote the first version of the GUI. Dr. Kefelian took over the GUI when she joined the group in November '16 and developed it extensively – alarms are now centralized, have been thoroughly tested, and over 500 alarms are implemented from 5 different subsystems (detector control, DAQ, slow controls etc). Mr. Land implemented a fast HV monitor within this framework that has been critical in understanding some early issues with HV tripping on the electronics crates.

A major step forwards is that the detector control software (ORCA) is now aware of the full detector state. ORCA reads back the state from an underlying detector database, which means that the detector GUI accurately reflects the hardware state, giving the expert operator full knowledge and control. A nominal value for each parameter of the detector state can be defined, and a comparison of current to nominal values is used to set triggers in ORCA, thus avoiding operator-dependent variations, and the risk of human error.

Dr. Caravaca implemented a complete protocol for non-expert operators, including a GUI, complete HV descriptions and trigger status monitoring. He has defined a set of standard runs that automatically load the defined detector state from a database on run start and set these parameters in the detector, thus allowing non expert operators to take robust, quality physics data.

Dr. Kefelian completed a study of the CAEN digitizer board, which is used to digitize the analog trigger sums output by the detector. This provides important information for identifying and rejecting instrumental backgrounds from the final data set. The CAEN board was observed to occasionally get out of sync with the detector, and sometimes to drop events: such that events written out from the detector were missing CAEN data. The cause was identified as a full buffer on the CAEN when detector rates spike due to dropout on the trigger sums. Dr. Kefelian's work has been used to optimise detector thresholds to minimize this issue, and she completed this work by implementing an alarm to warn the operator when this occurs so that they can resolve the issue in realtime.

Dr. Descamps supervised addition of new tools to the DAQ and detector control, including automated trigger scans that help to understand trigger thresholds and efficiency, and detector state monitoring tools that can be used by operators to check the state of the detector during data taking.

A complete DAQ commissioning document was compiled, which lists the full requirements, tests, and limitations of the current DAQ. Priorities for improvement prior to LS phase have been identified and plans are underway. These include resolving the current CAEN data loss in order to cope with the higher rates expected in scintillator by reading it out via optical fibre, and expanding the scope of operations available to non-expert operators.

UCB has also been heavily involved in developing processes to run in the "nearline" framework, which is the first level of run processing once data is output from the detector. Dr. Descamps implemented the run and run-level DAQ tables. The former extracts the correct run start and stop times using the 10MHz clock times for the first and last valid events. This table is used to evaluate detector livetime, and has already helped to identify a now-resolved issue in the event building process. The latter includes all the run-by-run settings so that the detector state can be exactly reproduced in the Monte Carlo simulation. The code that reports the number of online channels has also been substantially improved to deal with edge cases.

### 3.4 SNO+ analysis

PI Orebi Gann is one of two Physics Analysis Coordinators (PAC) for SNO+. As such, she is responsible for defining the analysis priorities and ensuring completeness and accuracy of the SNO+ calibration analyses, low-level analyses (such as PMT calibrations), and final physics analyses. This includes representing the analysis effort and priorities in discussions of topics such as detector thresholds, physics priorities, calibration plan, and detector schedule. These discussions and decisions are taken by a small executive group consisting of the two PACs, the detector manager, the site coordinator, and the calibration lead. Orebi Gann organised and ran several analysis workshops aimed at understanding detector behaviour and performance and moving towards scientific results from water-phase physics data. It is ultimately the responsibility of the PAC to produce physics results in a timely manner, to ensure we are ready for data taking in LS and Te phases, to manage resources and define physics priorities, and ensure the completeness of calibration plans.

Dr. Descamps took on the role of water-phase AC in order to manage the transition from detector commissioning to stable physics data. This has been handled smoothly, with excellent communication between detector and analysis groups, such that the detector is operating stably, taking robust, high quality physics data.

Mr. Land is heavily involved in data processing, and has made many improvements to this subsystem, including implementing a priority queuing system to more efficiently generate Monte Carlo, and is working on incorporating US grid resources into the processing structure.

Postdoc Richie Bonventre is responsible for the analysis of external backgrounds during the water phase. This is a critical analysis both for water-phase physics (nucleon decay, solar axions) and for understanding the sensitivity of the NLDBD search. The dominant backgrounds for a NLDBD search in SNO+ are i) $^{8}$B solar neutrinos (as measured by SNO) and ii) radioactivity from external regions of the detector. This latter background is most sensitively measured during the early light water phase. Richie took over the work originally developed by student Jeff Prouty, identified and fixed a source of bias in the fits, and has further developed it into an extended maximum likelihood fit in three dimensions, using reconstructed energy, position, and direction in detector coordinates (dot product of the position and direction vectors, so-called "$U.R$") to fit for eight background sources: $^{214}$Bi and $^{208}$Tl in each of the acrylic vessel (AV), external light water ($_{ext}H_2O$), hold-down rope net (HDropes) and PMTs. Richie has incorporated systematic effects in each observable, and estimated the sensitivity during the SNO+ water phase to each external background as a function of run length, energy threshold, and radial range. The impact of systematics has been fully studied and propagated to the final nucleon decay and NLDBD analyses. Now that SNO+ is taking physics data, Richie has run his analysis on early data in order to measure the external background levels.

Postdoc Morgan Askins is responsible for a maximum likelihood fit expected to place world-leading limitson invisible modes of nucleon decay from the water phase. Student Mr. Land is responsible for a maximum likelihood fit to extract the solar neutrino flux and spectrum from this same data set. Each will form the central result of a peer-reviewed journal publication, expected to be submitted this calendar year.

Dr. Bonventre led the SNO+ solar neutrino working group for several years, and this role has since been passed to Dr. Caravaca. Under their leadership the group developed a multidimensional fit to extract the low-energy solar neutrino fluxes from pure LS data, and to extract the shape of the $^{8}$B spectrum even during the Te-LS phase. This effort has now been taken over by UCB graduate student Ben Land.

### 3.5 SNO Analyses

PI Orebi Gann is the Physics Analysis Coordinator for SNO, a position held since September 2015. Orebi Gann is spearheading the push to complete a number of SNO analyses, including but not limited to those in which the UCB group is performing the analysis. These include a search for $n-nbar$ oscillations [3], which has been recently published in PRD, a search for *hep* neutrinos, and a search for Lorentz violating effects.

Three further analyses are being undertaken at Berkeley. A study of cosmogenic neutrons (cosmic muon followers) by student Ed Callaghan provides a critical handle on understanding spallation backgrounds for future underground physics experiments. Much interest has been expressed by the community in this result.

SNO data provides a unique opportunity to search for a finite neutrino lifetime due to the precision measurement of the energy spectrum made possible by the Charged-Current interaction. This study has been actively requested in a number of recent papers from the neutrino phenomenology community [**?**, **?**, **?**] and should produce a world-leading limit. Graduate student Mr. Land is the lead analyst in this effort. Mr. Land was supported on this grant with Dr. Baktash' approval for an interim period between startup support and his current fellowship provided by NSSC. Mr. Land has implemented a full fit of the raw SNO data under the neutrino decay hypothesis, reviving code used for the 3-phase SNO analysis [8]. In BY15 he reproduced the SNO fit results perfectly. He has replaced the polynomial survival probability with the neutrino decay model in order to extract a new lifetime limit directly from the SNO data. This new model has been fully tested with bias and pull tests in a range of background scenarios. The sensitivity of SNO has been extracted and the impact of systematics has been evaluated. IAn internal review within the SNO collaboration has been completed and the final analysis is currently being performed on the full data set. A paper is under preparation for submission to Phys. Rev. C.

Finally, a study of neutron multiplicity for fully contained atmospheric neutrino events in the SNO data set by Dr. Caravaca can shed light on details of neutrino-nucleus interactions and hadronic final state interactions. A precise measurement of neutron production as a function of the exiting lepton energy provides a test for different neutrino interaction models, and can also be used in cross section measurements.

## 4 Impact

Neutrinos are unique in the Standard Model of particle physics, with masses many orders of magnitude below other known fundamental particles. The reason is not yet understood, but could shed light on questions such as the absence of antimatter in our matter-dominated Universe. Their tiny masses and incredibly weak interaction strengths make neutrinos our "hidden messenger", probing otherwise unreachable regions: from the Earth's depths to the Sun's core, and distant supernovae.

UCB has undertaken a targeted plan of optical calibrations of the SNO+ detector, with the goal of measuring and monitoring the optical response of the PMTs independently of liquid-scintillator properties. This will allow a microphysical understanding and modeling of the detector in simulation, increasing both the precision and robustness of any physics result. UCB plays a leadership role in all SNO+ physics analyses, and is also heavily involved in detector DAQ and commissioning. With such a broad physics program, SNO+ has great potential both to advance our understanding of neutrinos, and to use neutrinos to understand the formation and behavior of our Universe. UCB is playing a leadership role in this highly competitive neutrino experiment, as well as producing physics publications from the legacy data set from the Nobel-prize winning SNO experiment.

# A Acknolwedgements

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# B Bibliography

## References

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[8] SNO Collaboration, *"Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory".* Phys. Rev. C **88**:025501 (2013).

# C Publications in Report Period

- SNO Collaboration, ?The search for neutron-antineutron oscillations at the Sudbury Neutrino Observatory?, Phys. Rev. **D96**, 092005 (2017).
- SNO+ Collaboration, *"Current Status and Future Prospects of the SNO+ Experiment."* Advances in High Energy Physics vol. (2016), 6194250.
- SNO Collaboration, *"A Search for Astrophysical Burst Signals at the Sudbury Neutrino Observatory"*, Astroparticle Phys. **55**, 1-7 (2014).
- R. Bonventre *et al.*, *"Non-Standard Models, Solar Neutrinos, and Large Theta$_{13}$"*, Phys. Rev. **D88**, 053010 (2013).
- B. Aharmim *et al.*[SNO Collaboration], *"Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory"*, Phys. Rev. **C88**, 025501 (2013).
- B. Aharmim *et al.*[SNO Collaboration], *"Measurement of the $\nu_e$ and Total $^8$B Solar Neutrino Fluxes with the Sudbury Neutrino Observatory Phase-III Data Set"*, Phys. Rev. **C87**, 015502 (2013).

# D Invited Talks in Report Period

- "Solar Neutrinos with Theia"
  Invited talk at ?5th International Solar Neutrino Conference?, Dresden, Germany, June 2018
- "SNO+"
  Invited talk at ?Neutrino 2018? conference, Heidelberg, Germany, June 2018
- "Here be Dragons: Mysteries of the Neutrino"
  Invited seminar, Physics Department, CalTech, CA, May 2018
- "Here be Dragons: Mysteries of the Neutrino"
  Invited seminar, Physics Department, U. Laval, Quebec City, Apr 2018
- "The Physics Associated with Neutrino Mass"
  Invited plenary talk at 2017 CPAD ?New Technologies for Discovery? Workshop, Oct 2017
- "CHESS: Cherenkov / Scintillation Separation Experiment"
  Invited talk at 2016 FROST-ii Technical Workshop, Oct 2016
- "THEIA: An Advanced Scintillation Detector"
  Invited talk at 2016 FROST-ii Technical Workshop, Oct 2016
- "Here be Dragons: Mysteries of the Neutrino"
  Colloquium, Physics Department, North Carolina State University (NCSU), Apr 2016
- "Here be Dragons: Mysteries of the Neutrino"
  Colloquium, Nuclear Engineering Department, University of California, Berkeley, Apr 2016
- "THEIA: Physics Potential of an Advanced Scintillation Detector"
  Invited seminar at TUNL national laboratory, Apr 2016
- "Here be Dragons: Mysteries of the Neutrino"
  Colloquium, Physics Department, University of North Carolina (UNC), Apr 2016
- "Physics Potential of the Advanced Scintillation Detector Concept: THEIA"
  Invited talk at 2016 Frontiers of liquid Scintillator Technology Workshop (FroST). Mar 2016
- "THEIA: Physics Potential of an Advanced Scintillation Detector"
  Yale University Weak Interactions Discussion Group Seminar, Feb 2016
- "Here be Dragons: Mysteries of the Neutrino"
  Kristin Ralls Memorial Colloquium, Physics Department, Cornell University, Feb 2016
- "Unraveling the Secrets of the Universe with Neutrinos"
  Invited talk at the 2016 Breakthrough Prize symposium, UC Berkeley, Nov 2015
- "THEIA: Physics Potential of an Advanced Scintillation Detector"
  Invited talk at NuFACT 2015 international conference, Brazil, Aug 2015
- "Theia: Physics Potential of an Advanced Scintillation Detector"
  Invited talk at NDM 2015 international conference, Finland, June 2015

- "Here be Dragons: Mysteries of the Neutrino"
  Invited colloquium at U. of Chicago, May 2015
- "THEIA: Physics Potential of an Advanced Scintillation Detector"
  Invited talk at the Electronics and Instrumentation for Past and Future Discoveries symposium, U. Penn, May 2015
- "Physics Potential of an Advanced Scintillation Detector"
  Invited talk at the Second International Meeting for Large Neutrino Infrastructures, FNAL, Apr 2015
- "THEIA: Physics Potential of an Advanced Scintillation Detector"
  Invited seminar at Lawrence Livermore National Laboratory, Mar 2015
- "SNO+ & THEIA: Te-Loaded LS Detectors for NDBD and Other Physics"
  Invited talk at Workshop for the Intermediate Neutrino Program, BNL, USA, Feb 2015
- "The ASDC: Physics Potential of an Advanced Scintillation Detector"
  Invited talk at NuPhys 2014 international conference, London, UK, Dec 2014
- "The ASDC: Advanced Scintillation Detector Concept"
  Invited talk at NNN '14 international conference, Paris, France, Nov 2014
- "Solar Neutrinos: Present & Future"
  Invited review talk at NNN '14 international conference, Paris, France, Nov 2014
- "Everything Under the Sun: the Future for Solar Neutrinos"
  Invited review talk at Fundamental Symmetries Town Hall, Chicago, Sept 2014
- "Neutrinoless Double Beta Decay: a Whirlwind Tour"
  Invited review talk at NuFACT 2014 international conference, Glasgow, UK, Aug 2014
- "Everything Under the Sun"
  Invited review at Neutrino 2014, June 2014
- "Solar Neutrinos with WbLS"
  Invited talk at Water-Based Liquid Scintillator Workshop, LBNL, May 2014
- "Here be Dragons: Mysteries of the Neutrino"'
  Hamilton Colloquium, Princeton University, Feb 2014
- "SNO+: The Precision Era of Neutrino Physics"
  UC Davis physics department seminar, Nov 2013
- "Here Be Dragons: Mysteries of the Neutrino"
  San Francisco State University, physics colloquium, Oct 2013
- "Deep Scintillation Detectors for Solar Neutrinos"
  JinPing Town Meeting, Asilomar, CA, Sept 2013
- "Neutrinoless Double Beta Decay"
  TAUP Summer School, Asilomar, CA, Sept 2013

- "Here Be Dragons: Beyond The Solar Neutrino Problem"
  TAUP Summer School, Asilomar, CA, Sept 2013

- "Into the DEAP: Neutrinos and Dark Matter"
  Department of Energy Office of Science Graduate Fellowship Program Annual Research Meeting, LBNL, July 2013

| Name | Letter publications | Other refereed journals | Invited talks | Contributed talks & posters |
|---|---|---|---|---|
| G. D. Orebi Gann | 0 | 6 | 36 | 0 |
| F. B. Descamps | 0 | 1 | 1 | 1 |
| J. R. Caravaca | 0 | 1 | 5 | 3 |
| B. Land | 0 | 1 | 0 | 3 |

Note: PI Orebi Gann is jointly supported by DOE NP through LBNL, and via this ECA award. This list represents all talks presented during this report period - they are not clearly associated with one particular scope of work and therefore are not separated by funding source.

# E Training and Professional Development

Several post-doctoral scholars and graduate student researchers (GSRs) have been supported on this grant over the past 5 years. The work reported herein provides a wide range of opportunities for development of their skill sets as researchers, as well as exposure to a broader community of scientists and the cutting-edge physics they address.

PI Orebi Gann meets weekly with the research group, giving each group member a chance to report on and discuss progress. She also meets biweekly one-on-one with each postdoc and each GSR to discuss their own particular progress, plans, and priorities. Each group member has attended at least two conferences during this reporting period. The work under this grant allows each group member to play an active role in both hands-on hardware development (Cherenkov source design and construction, detector commissioning), low-level calibrations and analysis (PMT calibrations), and physics studies (external backgrounds, SNO analyses). The original plan for physics topics for both postdocs and GSRs under this grant was to play a lead role in both the solar neutrino and NLDBD searches in SNO+. Due to project delays these physics searches may fall outside the grant period, and so the group has taken on a number of SNO analysis topics in order to provide physics studies for student theses, and analysis leadership experience for the postdoctoral researchers. Each researcher is given the opportunity to present both invited and contributed talks at workshops and conferences.

The group is also exposed to a wider range of physics topics within the community at UC Berkeley, and at the neighbouring and closely collaborating institution of LBNL.