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The Quantum Nature and Mass of the Neutrino

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The Quantum Nature and Mass of the Neutrino

FY19 Annual Laboratory Continuation Progress Report

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Overview

Over the last 100 years we have learned a much about the neutrino, but there remain interesting questions about this weakly interacting particle. In particular, at LLNL we are developing experiments to measure short baseline oscillation, the mass and the quantum nature of the neutrino, the latter two are within the scope of DOE-SC NP and are the subject of this report. The 2015 long range plan recommended tonne-scale neutrinoless double beta decay experiments as the top **new** project priority and this experiment will target the quantum nature of the neutrino. The LLNL team is motivated and focused on developing the best technology for this experiment which is a liquid xenon time project chamber called nEXO. On a longer time scale, LLNL is also developing technology to measure the neutrino mass with tritium decay experiments.

Work on nEXO at LLNL started in 2015 with an LDRD and program development funds to develop the nEXO concept, publish sensitivity predictions, explore alternatives and risks, and to build a credible project team and this effort is on going. In addition, we received $?? in FY19 of research funding from DOE-SC NP and LLNL manages $880k of pre-conceptual R&D for the nEXO collaboration of which $194.7k is scope executed at LLNL. The Project 8 effort is solely funded by the LLNL LDRD.

LLNL has a long history of building large projects, science projects and time projection chambers, but nEXO is in fact the first project of this scale that LLNL is prepared to lead for DOE-SC NP. We have the tools, skills, people and motivation to make nEXO a reality. The current program development dollars are used to prepare the nEXO concept for down select and CD1. These internal LLNL dollars pay for a number of things including project staff to organize the nEXO collaboration for the various reviews that lie ahead, to develop the draft plans and structure to manage the project as well as setting up an external advisory committee. The current LDRD is exploring alternatives that effect the risk profile as well as possible performance improvements. The DOE-SC NP base funding is targeted at simulation and analysis of the nEXO concept in preparation for the down select and refinement of the understanding of the detector as well as scientific effort on the large xenon test stand (LXTS) that will burn down one of the largest risks to the nEXO project. Lastly, LLNL is leading the pre-conceptual R&D effort and managing the funds for the nEXO collaboration. The results of this effort are reported elsewhere, but the scope of this executed at LLNL will be reported here and is primarily the engineering and construction of the LXTS experiment.

The primary technical contribution of LLNL to the Project 8 concept is the formation and study of atomic tritium. Atomic tritium is necessary for Project 8 to reach the ultimate sensitivity. LLNL has considerable experience with tritium and is well suited for this crucial work.

Although the focus of this work is strictly fundamental science, there has already been one significant spinoff to develop a new means to measure radio xenon in the air.

Recent Accomplishments

Analysis of Interactions in the Skin LXe

nEXO is a TPC with an open-cage design where no optical separator is used between the TPC volume and the xenon outside of the drift-field rings. This is a significant difference over other similar detectors. In the current design, about 25% of the LXe is located in the "skin" region outside the TPC field cage.

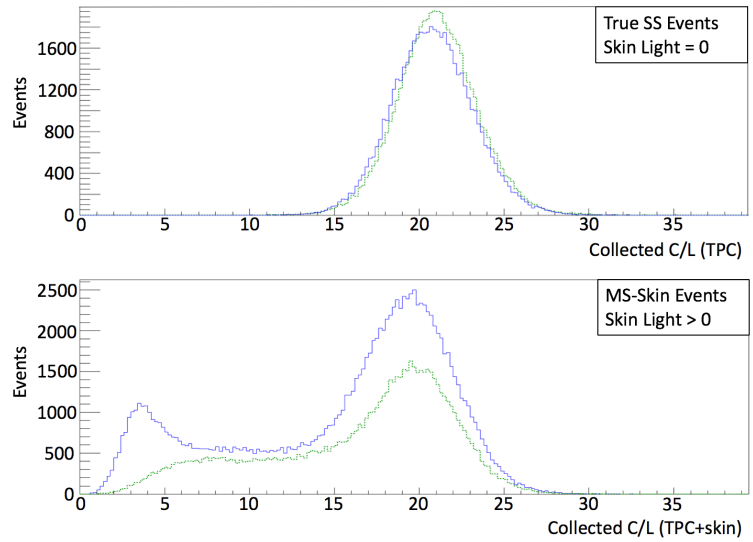

Figure 1: Distribution of the ratio of charge and light (C/L) signal from decays originating from ^{208}Tl (solid) and ^{214}Bi (dashed) contamination in the bulk of the copper of the nEXO TPC vessel. Single-sited events in the TPC with a coincident interaction in the skin LXe (MS-skin events, bottom plot) have a significantly different C/L ratio than true SS events in the TPC (top).

The response of an open-cage TPC to particle interactions is significantly different then that of TPCs with an optically-isolated active volume. The open design enables detection of scintillation light for interactions in the skin LXe without the need for a separate detection system. While the charge signal is lost for interaction in the skin region, the scintillation light alone still provides valuable information that can be exploited in the analysis. At the same time, the open-cage design introduces some challenges in the reconstruction of events with simultaneous interactions in both the TPC LXe and skin LXe where the total (combined) scintillation light is detected but not the total charge.

Tyana Stiegler (LLNL postdoc) is completing a detailed study of the implications of nEXO's open-cage configuration and the impact on the background rate, primarily from ^{238}U and ^{232}Th contaminations. Tyana studied coincident energy depositions in both the skin and the TPC LXe. This situation can arise either as a result of a decay with the emission of multiple coincident particles (usually γ-rays) or from a Compton interaction in the skin followed by a photoelectric absorption in the main TPC – both these events could lead to $0\nu\beta\beta$ backgrounds.

Potential SS events in the TPC that have only coincident interactions in the skin LXe result in a skewed charge-to-light signal ratio, as shown in Figure 1. Such difference can be exploited to identify and reject such backgrounds. Additional rejection power could be introduced by examining the light hit patterns on the photodetectors.

A paper has been drafted that describes the modeling and analysis of coincident skin events, quantifies the resulting background rates, and extrapolates the implications for nEXO's sensitivity. The paper is currently being reviewed by the collaboration and is expected to be submitted soon for publication.

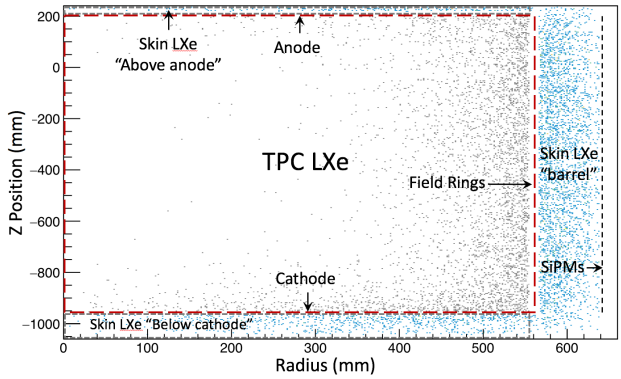

Figure 2: Position of time correlated Bi-Po interactions (Z vs Radius) produced in the skin LXe. ^{214}Po α decays in the skin LXe (blue) and time correlated SS events from ^{214}Bi coincident γs in the TPC LXe (grey). The Bi-Po tagging efficiency for these decays was carefully estimated via detailed simulations.

Detailed Analysis of Background from Correlated Bi-Po Decays

The implications of an active LXe skin volume must also be considered with respect to another background component of nEXO. Internal ^{222}Rn, with its radioactive daughters, is a well known liquid xenon contaminant that has been studied in detail by the EXO-200 experiment. Of particular concern is the ^{222}Rn-daughter ^{214}Bi which decays includes a γ-ray with an energy that is only 10 keV away from the ^{136}Xe $0\nu\beta\beta$ Q-value ($Q_{\beta\beta}$= 2458.07 $\pm$ 0.31 keV). The ^{214}Bi β decay is followed by ^{214}Po α decay with a half-life of 163μs. By tagging the α decay, this correlated Bi-Po decay chain can be identified, and the resulting background events rejected. As part of her work on extending nEXO's analysis to fully account for the effects from the skin liquid xenon, LLNL's Tyana Stiegler evaluated in detail the tagging efficiency for Bi-Po decays in the nEXO skin LXe.

Figure 2 shows a map of the position of time correlated Bi-Po interactions in nEXO (Z vs Radius) produced in the skin LXe. In order to generate this data, the existing simulation code for nEXO was upgrade to properly account for time-correlated event and the microphysics of alpha energy deposits in liquid xenon. Thanks to the characteristic signal of alpha interactions in liquid xenon in terms of both total light and photodetector hit pattern, we have estimated the efficiency for detecting α decays from ^{214}Po in nEXO skin where we can rely only on the collected light signal. This translates into an efficiency for tagging Bi-Po for a given choice of a veto coincidence window. The conclusions of this work are being finalized in a paper and support the original simplified assumptions that entered the background estimation for nEXO's published sensitivity result[1].

NEST Improvements and Integration with nEXO's Simulations

The Monte Carlo simulations that were used to compute nEXO's sensitivity reach determined the ability to discriminate single-site from multi-site interaction without accounting explicitly for the production of charge and light signal following the interaction of particles with the liquid xenon medium. Instead, they relied only on Geant4 energy deposits and a clustering algorithm tuned to mimic EXO-200 performance with conservative improvement justified by nEXO's specific hardware design. More sophisticated simulations are being developed which require an accurate

[1] Albert, J. B., et al, [nEXO Collaboration] "Sensitivity and discovery potential of the proposed nEXO experiment to neutrinoless double-β decay". Phys. Rev. C 97, 065503 (2018).

model of the details of the microphysics of particle interactions in liquid xenon. The NEST (Noble Element Simulation Technique) code is the standard for this type of simulations and is broadly used in the dark matter community to determine the ionization and scintillation produced in liquid xenon. LLNL's staff member Jason Brodsky, who is a member of both nEXO and NEST collaborations, worked in FY19 to incorporate NEST2.0 within the nEXO codes, and to add new features like the ability to access NEST particle lineage (or type) from outside of NEST and to save NEST computed quantities at a highly granular level. This work is critical to efforts like the Bi-Po simulations, the skin LXe analysis, and the analysis of SS/MS performance from simulated charge waveforms.

LXTS

The large xenon test stand (LXTS) is designed to test one of the top risks to the nEXO project, the high voltage stability. This is a complex and large system that will replicate the conditions of the full nEXO experiment and therefore provide high confidence of a particular high voltage design and mitigating this risk.

The LTXS is cooled with HFE7000 as will be done with nEXO, and we have installed a dewar for this HEF7000 and done initial circulation tests. EXO-200 also attempted to pump the HEF7000 with a mechanical pump and were unsuccessful. We have research this and expect to solve this and the next rounds of tests will happen soon. We have also install two large cryocoolers and did initial cooling tests of the HFE7000.

The large tanks have been pressure tested and a safety note is now in place to operate them. They are in the process of bolting them to the floor and we plan to do cool down tests shortly after they are mounted to the floor.

The system controls and process have been advanced and we have an initial design. We determined that we need to finalize the pump that we will use for the xenon before we can finalize the controls and process. We are studying a bellows pump and hope to make the final selection soon. This pump would also be a candidate for the final nEXO design and we will have lots of relevant data after using it on the LXTS. We have also developed a new method of xenon recovery that has significant advantages over the current methods. We have developed what we call the reentrant tube. This is a device that can mount in the top of an aluminum cylinder that passively prevents freezing of the inlet while cryopumping. A picture of the device is in figure 3. It has been pressure tested to over 19,000psi, and a prototype has been thermally tested as well and it matches the finite element analysis calculations. A full test of this system is expected in the coming months. We expect to publish this as it is a significant advance in the state of the art.

nEXO's Leadership

LLNL is spending internal program development funds to prepare the nEXO concept for down select. The team assembled at LLNL so far includes the project director, the project manager, a deputy project manager, a project controls analyst, a subsystem manager and a chief mechanical engineer. We are actively searching for a systems engineer to round out this initial team. We have also started to assemble an external advisory committee to advise LLNL senior management on the best direction for this initial project team.

The activities of this initial team are focused on the down select and this falls into two categories of developing and documenting the conceptual design that will be considered as well as generat-

Figure 3: The reentrant tube in the test fixture before pressurizing to over 19,000psi.

ing the plans to execute a project. We have developed drafts of a number of the top level plans including the project management plan, and we have reorganized the scientific and technical team to document and deliver a competitive conceptual design including an initial bottoms up cost and schedule.

Coordination of nEXO's Simulations, Analysis and Software Group

During the past year, LLNL continued to lead nEXO's simulations group activities, as Samuele Sangiorgio maintained the role of coordinator for the group. After the release of the sensitivity paper in 2018, the scope of the group was broadened to better meet the needs of the collaboration during this phase of the effort. The "nEXO Monte Carlo Group" was renamed "nEXO Simulations, Analysis and Software Group". While the main mission of the group remained the same – i.e. supporting the experimental design and informing R&D through physics-driven modeling of the experiment's performance – S. Sangiorgio recognized that a more sustained and cohesive effort would be necessary on the software development. With new postdocs and students joining the group, the lack of a common software infrastructure created difficulties in maintaining and efficiently executing the simulations long term. As coordinator for the group, Sangiorgio established efforts to ensure that all the existing codes would be ported to a common infrastructure based on the SNiPER (Software for Non-collider Physics ExpeRiments) framework. This is also part of a long-term strategy to lay the foundation for nEXO's analysis software. As a way to bootstrap the software development, Sangiorgio organized a one-day mini-workshop at Stanford that brought together most of the nEXO's S.A.S. group. The first part of the day focused on tutorials and plans for using SNiPER and integrating it with our codes. Later on, we switched to discussing

the nEXO software development ecosystem, including guidelines for documentation, repository management, software build management, and coding style. According to all participants, the workshop was successful and productive.

Starting from the work outlined in the nEXO's sensitivity paper, Sangiorgio also prioritized efforts within the simulations group to improve the level of details and fully demonstrate the assumptions behind the sensitivity result. This included efforts at LLNL to simulate nEXO's performance in rejecting correlated Bi-Po events and to properly account for the interactions in the xenon skin volume outside of the TPC field cage.

In addition to setting the priority for the nEXO's S.A.S. group, Sangiorgio's effort included setting the agenda and coordinating the weekly group meetings, reviewing the groups products, and reporting to the nEXO's collaboration leadership.

Cherenkov-based Discrimination

Since FY18, LLNL has supported a LDRD project called "The Next Breakthrough in Neutrino Physics" aimed at technologies that could enhance important neutrino science goals including neutrinoless double beta decay ($0\nu\beta\beta$). One of these technologies that deserves a note here for its complementary relationship with DOE-supported research at LLNL is Cherenkov-based discrimination for $0\nu\beta\beta$.

Cherenkov-based discrimination identifies directional signals in a liquid xenon TPC such as nEXO or a nEXO successor experiment. This enables the identification of $0\nu\beta\beta$ events by observing two directional signals from the two electrons produced in the decay and the rejection of backgrounds which will generally have a single directional signal. Directional signals are observed using Cherenkov photons produced by the passage of recoil electrons in xenon. These Cherenkov photons often arrive at the experiment's light sensors before scintillation photons due to the highly-wavelength-dependent index of refraction in liquid xenon.

Results from the LDRD research show that this technique can improve experimental sensitivity by between 20-40% depending on the scenario [2]. This amount reflects limitations imposed primarily by the kinematics of the neutrinoless double beta decay and electron scattering in liquid xenon. This potential improvement may motivate some sensor readout R&D needed to implement this approach in nEXO or in a successor experiment.

This research complemented other nEXO work ongoing at LLNL. Simulation tools developed for the study of Cherenkov-based discrimination were adapted for use in the other simulation-based work on nEXO. This LDRD also supported ongoing participation in the nEXO experiment by an additional researcher, Dr. Brodsky, enhancing institutional expertise in nEXO-related topics at LLNL.

Tritium Cracking

LLNL is an institutional member of the Project 8 collaboration, whose goal is to measure the mass of the electron anti-neutrino with a sensitivity of 40 meV. To attain this goal, the collaboration is performing a high-resolution measurement of the endpoint of the tritium spectrum. Previous

[2] J. P. Brodsky, S. Sangiorgio, M. Heffner, and T. Stiegler, "Background discrimination for neutrinoless double beta decay in liquid xenon using Cherenkov light," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 922, pp. 76–83, Apr. 2019.

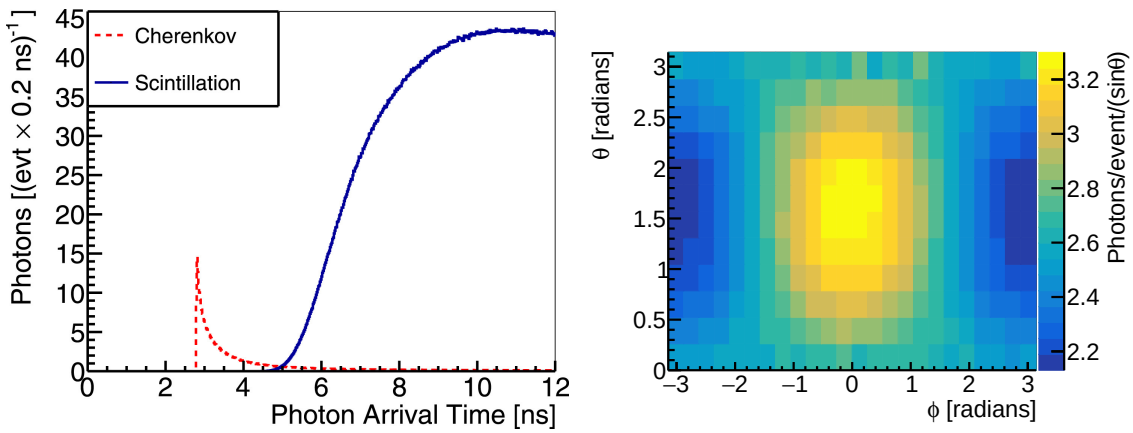

Figure 4: Left, the arrival time of photons at sensors 60 cm away from a $0\nu\beta\beta$ event. Cherenkov photons arrive sooner since some have longer wavelengths and a faster group velocity in liquid xenon than the UV scintillation photons. This difference in arrival time allows for analysis of the Cherenkov photons separate from the scintillation signal. Right, the direction of individual Cherenkov photons (relative to the mean direction of Cherenkov photons) from a single background recoil electron. While no characteristic ring shape is observed, a directional signal is preserved despite electron scattering in the xenon.

experiments that have used tritium to this end have relied on molecular, diatomic tritium (T_2). The internal energy modes of the T_2 molecules, though, would limit Project 8's sensitivity to 100 meV. Therefore, to attain its goal, Project 8 must use atomic tritium (T).

An LLNL focus within Project 8 is to perform a first-ever measurement of the absolute tritium cracking efficiency and atomic flux. The purpose of this measurement is to ensure adequate flow to fill the Project 8 decay chamber in a timely manner. The molecules are thermally cracked by flowing T_2 gas through a tungsten capillary at up to 2600 °K. Using LDRD funds, we have commissioned a thermal cracking testbed with deuterium gas (D_2), in advance of anticipated tritium cracking in the coming year (see Fig. 5). We are taking a staged approach to these measurements, with the first goal being to make a relative measurement of D_2 and T_2 cracking efficiency as a function of cracker heating power and gas flow rate.

Preliminary measurements during a recent commissioning run show a clear indication of D_2 cracking (Fig. 6). The system was run with the cracker on full power and the D_2 flow maximized until the system achieved stability. Then over the course of two hours the cracker power was ramped down in discrete steps, and ramped up again. An additional test was performed by closing and opening the shutter, which was a plate that could be moved into and out of the beam coming from the capillary.

Since this preliminary signal, we have optimized the system by moving the cracker closer to the RGA. The intention is to perform a more careful measurement of the system, not only to obtain a more precise measurement, but to demonstrate long-term stability of the system in anticipation of Project 8 running continuously for a year or more. Once the system is fully characterized and understood with the deuterium gas, we will make the transition to tritium gas, and publish the relative cracking efficiency as stated above.

The value in this work is three-fold. The first motivation is to demonstrate tritium cracking using

a hot tungsten capillary. This would be the first-ever published data on atomic tritium production. The second motivation is to measure the absolute atomic tritium flux to evaluate the cracker apparatus for suitability to Project 8's needs. The third motivation is to establish tritium cracking performance relative to deuterium. This will allow other collaboration members to perform measurements at their home institutions with deuterium gas alone, and have confidence in the extrapolation to tritium cracking.

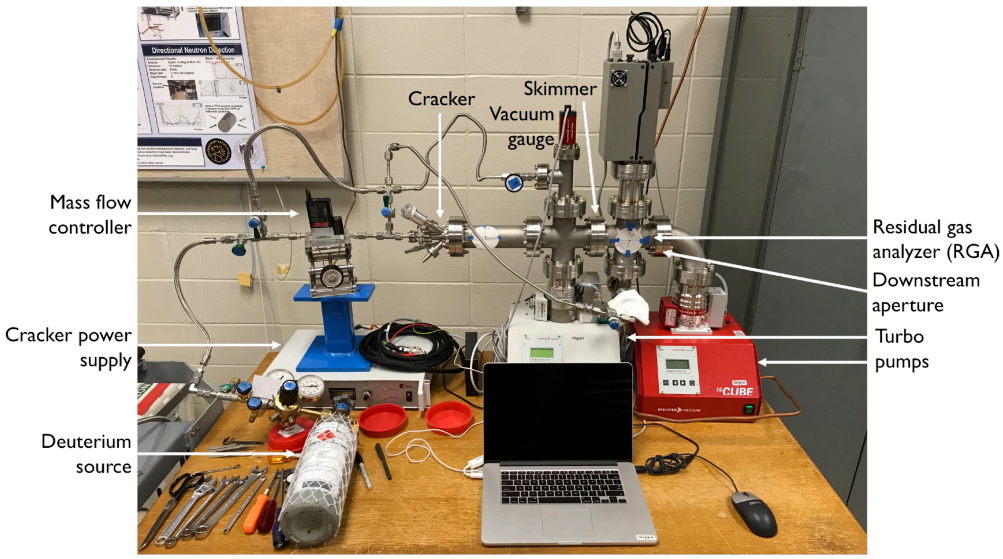

Figure 5: Tritium cracking testbed at LLNL. We are commissioning the system with deuterium gas before transitioning to tritium measurements in FY20.

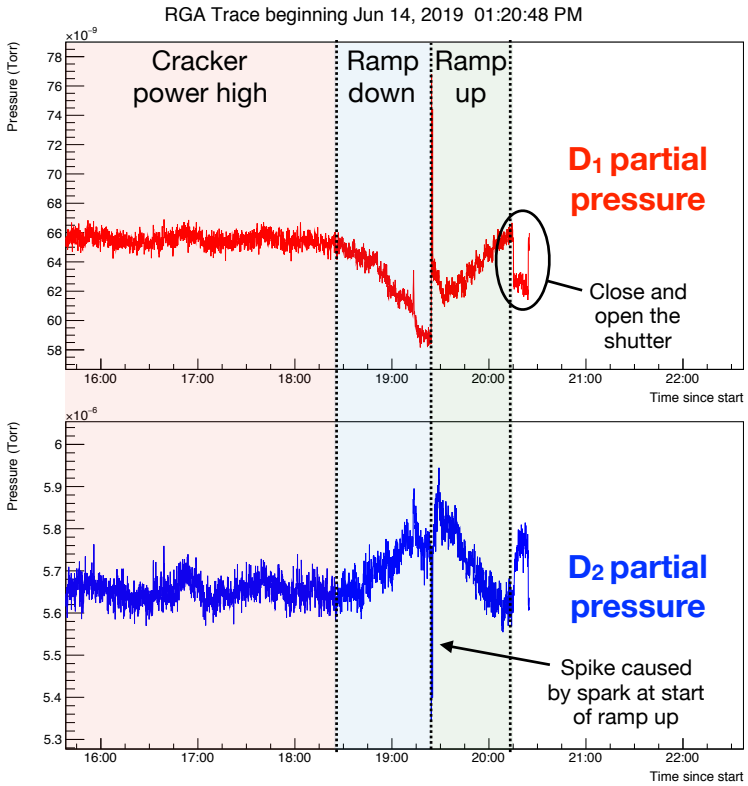

Figure 6: Preliminary indication of D_2 cracking using the LLNL testbed. The partial pressures of the atomic and molecular deuterium move in opposition, demonstrating deuterium molecules being broken apart into individual atoms at decreasing and increasing levels as the cracker heating power is lowered and raised.

Dissemination

nEXO

"The nEXO Experiment: A Tonne Scale Majorana Neutrino Search" Invited talk DNP Oct 2018. M. Heffner

Numerous Talks at collaboration meetings.

Contributed talk at the APS April Meeting, "Improved Sensitivity of nEXO to Neutrinoless Double Beta Decay", March 2019, T. Stiegler.

Contributed talk at Conference on Science at the Sanford Underground Research Facility, "The nEXO Experiment", May 2019, T. Stiegler

Contributed poster at LLNL's 2019 Postdoc Symposium, "Improved Modeling of the nEXO Detector for Neutrinoless Double Beta Decay", June 2019, T. Stiegler

"Simulation of charge readout with segmented tiles in nEXO", submitted to JINST, July 2019, https://arxiv.org/abs/1907.07512

"Characterization of the Hamamatsu VUV4 MPPCs for nEXO" NIM Volume 940, 1 October 2019, Pages 371-379, https://doi.org/10.1016/j.nima.2019.05.096

"Background Discrimination for Neutrinoless Double Beta Decay in Liquid Xenon Using Cherenkov Light" NIM Volume 922, 1 April 2019, Pages 76-83, https://doi.org/10.1016/j.nima.2018.12.057

"Study of silicon photomultiplier performance in external electric fields", JINST Volume 13, September 2018, https://doi.org/10.1088/1748-0221/13/09/T09006

"Imaging individual barium atoms in solid xenon for barium tagging in nEXO", Nature volume 569, pages203–207 (2019)

"VUV-sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO", IEEE Transactions on Nuclear Science (Volume: 65 , Issue: 11 , Nov. 2018), https://doi.org/10.1109/TNS.2018.2875668

"nEXO Pre-Conceptual Design Report", arXiv:1805.11142v2 [physics.ins-det]

"Sensitivity and discovery potential of the proposed nEXO experiment to neutrinoless double beta decay", Phys. Rev. C 97, 065503 (2018), https://doi.org/10.1103/PhysRevC.97.065503

Project 8

A.A. Esfahani *et al.*, "Electron radiated power in cyclotron radiation emission spectroscopy experiments", *Physical Review C* **99**, 055501 (2019).

Contributed talk, DNP Oct 2018, K. Kazkaz on behalf of Project 8

Collaboration meeting workshop and session chair, K. Kazkaz

Collaboration meeting presentations, K. Kazkaz and L. Tvrznikova

Team

- M. Heffner, PI
- K. Kazkaz, Staff Scientist, LLNL PI for Project 8, Level 2 Lead (Atomic Tritium Working Group)
- L. Tvrznikova, Postdoc
- S. Sangiorgio, Staff Scientist, Level 2 Lead for nEXO's Simulations, Software, and Analysis Group
- J. Brodsky, Staff Scientist
- T. Stiegler, Postdoc