Research Statement

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Neutrino masses and mixing have provided the first direct evidence of physics beyond the Standard Model of Elementary Particles. Neutrinos experience a very different mixing compared to the quarks, and recently, hints of underlying symmetries in the neutrino mixing matrix have been exposed. Both the absolute neutrino mass scale and the ordering of neutrino masses remains unknown, and the evidence of non-zero mass prompts the question of whether neutrinos are their own antiparticles (Majorana fermions) or distinct from their antiparticles (Dirac fermions). Along with questions of their intrinsic properties, the weakly interacting nature of neutrinos means they can provide unique insight into the fusion cycles of the Sun and the complex mechanisms behind the core-collapse explosions of galactic supernovae. Currently, the most critical problems in neutrino physics can be summarized as follows:

1) Are neutrinos their own anti-particles (Dirac or Majorana)?
2) Do neutrinos and anit-neutrinos oscillate differently? (Is δ_{CP} non-zero?)
3) What is the ordering of the three neutrino masses?
4) What is the absolute neutrino mass scale?

With the SNO+, CAPTAIN, and DUNE experiments I am investigating these problems using two state-of-the-art technologies: metal-loaded liquid scintillation detectors and liquid argon detectors.

Large underground liquid scintillator detectors have unparalleled sensitivity to neutrino physics on the MeV-scale. SNO+ is planning to use 780 tons of liquid scinitllator loaded to 0.3% concentration with natural Tellurium (0.8 tons of ^{130}Te) to search for a process called neutrinoless double beta decay ($0\nu\beta\beta$). The $0\nu\beta\beta$ process (${}^{\mathrm{A}}_{\mathrm{Z}}X \rightarrow {}_{\mathrm{Z+2}}^{\quad\mathrm{A}}X + 2e^-$) violates lepton number by two units and only occurs if neutrinos are their own antiparticles contrary to the standard two-neutrino double beta decay (${}^{\mathrm{A}}_{\mathrm{Z}}X \rightarrow {}_{\mathrm{Z+2}}^{\quad\mathrm{A}}X + 2e^- + 2\bar{\nu}_e$) allowed by Standard Model physics. The $0\nu\beta\beta$ mode is considered to be the most powerful tool for determining the Dirac/Majorana nature of the neutrino and provides constraints on the neutrino mass scale. With 0.3% Tellurium loading, SNO+ will be among the most sensitive $0\nu\beta\beta$ experiments in addition to probing a wide range of interesting phenomena involving solar neutrinos, nucleon decay, reactor neutrino oscillations, geo-neutrinos, and supernova neutrinos.

An experiment called the Deep Underground Neutrino Experiment (DUNE) proposes to build a 40-kt liquid argon Time Projection Chamber (TPC) neutrino detector in the Sanford Underground Research Facility, 1300 km away from a ν_μ neutrino beam at Fermi National Laboratory, in order to make precision measurements of neutrino oscillation parameters and probe the neutrino mass ordering via ν_e appearance and ν_μ disappearance. Additionally, such a detector would have the unique ability to measure the pure electron neutrinos produced during the neutronization burst of core-collapse supernovae. A detailed understanding of neutrino interactions on argon and their associated backgrounds is required for DUNE to make such measurements. I plan to further our understanding of the signals and backgrounds in DUNE by making cross-section measurements of neutrons and neutrinos on argon with CAPTAIN (Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos). The CAPTAIN program is developing two liquid argon TPCs to place in particle beams. Neutrinos produced from pion decay-at-rest span the energy range of supernova neutrinos and would provide supernova-neutrino-like events in liquid argon detectors, where data currently lacking. The Booster Neutrino Beam (BNB) is an excellent pion decay-at-rest source of neutrinos and future beam runs with the five ton CAPTAIN detector at this facility is under investigation.

As the excitement surrounding neutrinos continues to grow, I plan to further my involvement in the study of supernova neutrino detection in liquid argon. I will do this with the development of a realistic supernova neutrino event generator for detector simulations and by proposing to move CAPTAIN to the BNB to obtain the first measurements of neutrino interactions on argon at supernova neutrino energies. Such research is a critical path to a successful underground physics program with the DUNE far detector.

Future Research Plan

Supernova neutrino event reconstruction poses an enormous challenge for the underground physics capabilities of DUNE and has never been demonstrated with liquid argon technology. A first measurement of pion decay-at-rest neutrinos in liquid argon could be achieved with the CAPTAIN detector at the BNB. Therefore, I plan to pursue the following research:

Investigate the feasibility of locating CAPTAIN at the BNB to obtain the first-ever neutrino-argon data in the supernova energy regime. This includes taking neutron background measurements at the MI-12 Hall during the fall of 2015, creating a neutrino generator to predict the signal sensitivity in CAPTAIN, and presenting a full proposal to the Fermilab PAC.

We will finish the commissioning and testing of the 0.3 ton Mini-CAPTAIN detector in the fall of 2014. Mini-CAPTAIN will allow for the testing of our electronics and DAQ, and provide much needed operational experience necessary for the five ton CAPTAIN detector. I have a leading role in the commissioning of the photon detection system for Mini-CAPTAIN, a system that I am already involved in designing. Mini-CAPTAIN will be positioned in the WNR neutron beam facility shortly after. I plan to participate in the neutron beam run and data analysis for Mini-CAPTAIN as this will provide an exciting first look at the capabilities of reconstructing high-energy events where neutrons are produced in final state interactions. The neutron beam will also provide low energy neutron events that could provide neutrino-like neutral-current scattering events on argon. The neutral-current scattering signal from neutrons could identify key signatures (high-energy de-excitation gamma) used for the detection of similar events from neutrinos at the BNB.

The commissioning of the five ton CAPTAIN detector will finish in 2016 and will open the door to data taking in a neutrino beam. I am investigating the possibility of running the five ton detector in a neutrino beam created from stopped pions (<60 MeV) at the Booster Neutrino Beam at Fermilab. Neutrons produced near the target and from cosmic rays impinging the CAPTAIN detector could create large backgrounds and must be mitigated by a combination of tuning the detector distance from the BNB target and determining the proper shielding. Realistic signals from pion decay-at-rest neutrinos in CAPTAIN must also be predicted to determine the overall sensitivity. In particular, I would like to use the measurements obtained with the CAPTAIN at the BNB to develop a real-time trigger for the DUNE far detector.

The feasibility studies of running CAPTAIN at the BNB will initially require that I make six trips out to Fermilab, each stay lasting for about two weeks, over a period of about 6 months. I would plan to start these studies in July of 2015. During my time at Fermilab, I will take neutron background measurements just outside the MI-12 hall and get the necessary feedback about the BNB characteristics from local experts at Fermilab. I will use the neutron measurements to determine where to position the CAPTAIN detector and how much neutron shielding and infrastructure will be needed. These backgrounds will need to be incorporated into the CAPTAIN detector simulations for comparison of the BNB neutrino signal. I also plan to incorporate the simulations[7] of BNB pion decay-at-rest neutrinos into our detector simulations. Upon completion of the feasibility studies I will put together a proposal for the Fermilab PAC to run CAPTAIN at the BNB and present it on behalf of the CAPTAIN collaboration.

Past and Current Research

I am currently an Nuclear Science and Security Consortium Postdoctoral Fellow at The University of California, Davis working on DUNE, CAPTAIN, and SNO+. The following is a summary of my research activities throughout my graduate and post-graduate career:

- **CAPTAIN and DUNE**: The Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos (CAPTAIN) collaboration was formed with the goal of making important physics measurements related to the detection of neutrinos in LArTPCs from intense beams, the Earth's atmosphere, and astrophysical phenomena [5]. We are in the process of commissioning two liquid argon detectors, referred to as Mini-CAPTAIN (0.3 ton fiducial mass) and CAPTAIN (five ton fiducial mass). These detectors will be positioned in different particle beams to collect data from high-energy neutrons (up to 0.8 GeV) and neutrinos in the energy ranges 1−10 GeV and <60 MeV. The goal of these measurements will be to constrain our knowledge of spallation neutron products that are backgrounds to supernova neutrino detection, cross-sections of events mimicking the electron neutrino appearance signal in DUNE, and identify the signatures of neutrons created by long-baseline neutrino interactions to improve energy reconstruction capabilities.

My involvement with CAPTAIN has been to measure the cross-sections of spallation neutron reactions in liquid argon that produce backgrounds for supernova neutrino detection. To accomplish this, I'm leading the commissioning of a dedicated neutron beam facility at the Crocker Nuclear Laboratory 67 MeV proton cyclotron. The (n, p) reaction cross-sections on argon (experimentally unknown above 15 MeV) are being measured up to 65 MeV by exposing both liquid and gaseous argon vessels in the beam-line. This work is being done with the help of a team of several students which I'm currently mentoring (Nick Walsh, Daniel Coelho, and Kyle Bilton). In addition to cross-section measurements, I also have a leading role in the development of the CAPTAIN photon detection system, which will be made up of approximately two dozen Hamamatsu R8520-500 1-inch PMTs. I am also working on the development of a detector simulation to model the light collection in the CAPTAIN detectors. The photon detection system and simulation studies will improve our knowledge of the interaction times in liquid argon detectors with up to nanosecond accuracy.

Neutrino interactions of less than 60 MeV on the argon nucleus present a critical challenge to supernova neutrino detection, due to the lack of experimental data from charged-current neutrino absorption on ^{40}Ar producing excited states of ^{40}K. I am leading feasibility studies for running the CAPTAIN detector at the Booster Neutrino Beam (90 degrees of target) to detect pion decay-at-rest neutrinos. This would be the first-ever measurement of neutrino interactions on argon in the supernova energy regime. I am also developing a supernova event generator to predict what kinds of signals we'll see from these neutrinos in CAPTAIN. These efforts will provide insight into supernova neutrino detection and could provide a realistic mechanism for real-time triggering of supernova neutrinos in DUNE.

- **SNO+**: The SNO+ experiment, much like KamLAND, is a multipurpose physics program with the primary goal of searching for $0\nu\beta\beta$ decay. The SNO+ detector is located 2.2 km underground in SNOLAB and will be filled with 780 tons of liquid scintillator. The initial filling of the detector is underway with ultra-pure water and will allow for nucleon decay searches. The second stage involves filling with ultra-pure scintillator with the goal of measuring reactor neutrinos, geo-neutrinos, and CNO and *pep* solar neutrinos. The final stage involves the loading the scintillator with ^{130}Te to 0.3% concentration (equivalent to 810.5 kg of isotope) in an effort to search for $0\nu\beta\beta$ decay. With 0.3% loading we expect to reach sensitivities to Majorana neutrino masses near the top of the inverted neutrino mass hierarchy with at least three years of data [6]. These optimistic physics goals come with a series of difficult challenges the most important being the sufficient removal of natural radioactivity from the liquid scintillator. Using my earlier experience on KamLAND, I'm leading our group at UC Davis in the development of a counting test facility that will assay the purified scintillator for Radon contamination before it is filled into the SNO+ detector. Thus, a level of reassurance would be provided that the background levels are sufficient and will prevent contamination of the active volume. The counting test facility will be integrated directly into the SNO+ scintillator filling system and operate *in-situ*. I'm also mentoring two graduate students (Morgan Askins and Teal Pershing) in neutron activation analysis studies of the SNO+ scintillator components in order to determine the concentrations of Uranium, Thorium, and Potassium down to acceptable levels ($<10^{-17}$ g of impurity per g of scintillator) for $0\nu\beta\beta$ decay physics. These studies could provide crucial evidence that the SNO+ scintillator process system is capable of producing scintillator that is clean enough to meet the proposed physics goals. I'm also investigating the possibility of removing radio-impurities from SNO+ scintillator using nano-filtration. A small nano-filtration system is being setup inside a clean-room facility at UC Davis and will be used to test a variety of membrane filters and system operating conditions (temperature, pressure, flow-rate, etc.). This information will be used to determine the feasibility of constructing a large-scale nano-filtration system for SNO+.

- **Double Chooz**: The Double Chooz experiment set out to measure the neutrino mixing angle, θ_{13}, using two identical, Gadollinium-loaded scintillator detectors at the Chooz reactor complex, in France. Precise knowledge of θ_{13} is necessary to understand the three-flavor neutrino mixing formalism. I joined the collaboration in 2012 and immediately took over as the far detector glove-box expert, a system responsible for keeping the detector in a controlled atmosphere during calibration source deployments and reducing systematic uncertainties on measurements of θ_{13}. After being appointed the data production coordinator, I had the privilege of processing the first reactor-off data, a direct measurement of the reactor anti-neutrino backgrounds. Additionally, I mentored graduate students (John Felde and Justin Dhooghe) and actively participated in the analysis of the reactor-off data and and the neutron capture on Hydrogen data that led to a background-model-independent measurement of θ_{13} [4]. Later on, my efforts were put towards the commissioning of the glove box for an off-axis detector calibration system that was used to validate the detector response with data already taken on-axis. This will give Double Chooz precise knowledge of how the detector responds to neutrino interactions for any locations inside the active volume and further reduce detector related uncertainties.

- **KamLAND**: KamLAND is a 1-kt liquid scintillator detector located about 1 km underground in the Kamioka Mine in Japan. One of our most notable accomplishments is the measurement the oscillation parameter Δm^2_{21} with unprecedented precision [1], which explicitly showed that oscillations were behind the neutrino flavor change mechanism. Around the same time, I was intimately involved in a massive campaign to reduce the concentration of Radon-born Lead in KamLAND liquid scintillator - the primary background inhibiting sensitivity to 862 keV ^{7}Be solar neutrinos. This solar neutrino branch directly probes the region near the transition to matter dominated flavor change mechanisms, known as the MSW effect. Our research group at Alabama played a leading role in the development of Lead isotope removal for KamLAND scintillator. My studies involved the Lead removal efficiency of the following chromatographic techniques: heating, distillation, and adsorption. My studies concluded that distillation was the best method for Lead removal and also showed no evidence of optical degradation of the scintillator [2]. The laboratory studies performed at Alabama impacted the design and commissioning of the actual KamLAND distillation system. I spent a total of two years onsite participating in the commissioning and operation of this system. This effort reduced backgrounds in the energy region below 1 MeV by roughly a factor of 10^5. After our purification campaign finished, in 2009, I lead the development of the KamLAND detector simulation that re-created a model of all the backgrounds relevant for solar neutrino detection. My detector simulation work, and a ^{7}Be solar neutrino analysis based on this simulation, was the topic of my dissertation. These studies eventually led to a final analysis with a much longer data set and produced the first independent verification of the ^{7}Be solar neutrino flux measured on Earth [3].

References

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