Yale *Office of Sponsored Projects*

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courier
25 Science Park, 3rd Floor
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February 24, 2016

Universities Research Association, Inc.
1111 19th Street, NW #400
Washington, D.C. 20036

Re: Yale University – Ariana Hackenburg FNAL Visiting Scholars Application

To Whom It May Concern:

On behalf of Yale University, I am pleased to endorse the enclosed proposal to Universities Research Association, in support of our project titled "Study and Mitigation of Neutral Current Pi0 Background in LArTPCs" led by Ariana Hackenburg. We are requesting $13,343 total direct costs, no indirect costs, to support this program for the period of September 1, 2016 – August 31, 2017.

The University charges the Office of Sponsored Projects with the responsibility to review and submit proposals and to accept awards on behalf of the institution. My signature below indicates Yale's approval of this proposal and willingness to administer if it becomes an award.

Please feel free to contact me at gcat2@yale.edu should you have any questions or require further administrative information about this proposal, for all technical questions do contact the PI at: ariana.hackenburg@yale.edu.

Notification of any resultant award should be made to my attention.

Sincerely,

Maria Kwon

Maria Kwon,
Proposal Manager, SO/AOR

APPLICATION NO:__________
(*for URA use only*):

COVER SHEET URA VISITING SCHOLARS PROGRAM APPLICATION

All parts of this form MUST be filled out

APPLICANT INFORMATION
Name (*Last, First, MI*): Hackenburg, Ariana
Title/Status: Graduate Student

Home Institution: Yale University
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New Haven, CT 06511

Department: Physics
Tel. No. 631-891-7245
Email: ariana.hackenburg@yale.edu

CO-APPLICANTS
Name: N/A
Title/Status:
Home Institution:
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Name:
Title/Status:
Home Institution
Email:

TITLE OF PROPOSED ACTIVITY:
Study and Mitigation of Neutral Current Pi0 Background in LArTPCs

BRIEF DESCRIPTION:
The proposal of this document is to make a cross section measurement of the NC pi0 interaction channel on Liquid Argon. This task, while simply summed up in one sentence, will require a number of tools which are still in development. I propose to work at Fermilab in collaboration with those stationed there to improve these tools and accelerate the path to understanding this crucial background for MicroBooNE's flagship analysis.

NAME OF FERMILAB SPONSOR: Flavio Cavanna
Fermilab Division: Neutrino
Email: cavanna@fnal.gov

SOURCES OF SUPPORT

Amount Requested: $ 13,343 Duration (*months*): 12 Requested Start Date: September 1, 2016

Other sources of support for proposed work:

Prior URA Visiting Scholar Award, if any (*month & year*):
Sponsor:

GRANTS OR SPONSORED RESEARCH OFFICER (*in applicant's home institution*):

Name: Maria Kwon, Proposal Manager (SO/AOR)
Address: Yale University, Office of Sponsored Projects
25 Science Park – 3rd Floor, 150 Munson Street
P.O. Box 208327 New Haven, CT. 06520-8327

Tel. No. (203) 785-7837
Email: GCAT2@yale.edu

Signature: Maria Kwon **Date:** 02/24/16

URA Fellowship Proposal: Study and Mitigation of the Neutral Current Pi0 Background in LArTPCs

Ariana Hackenburg
Yale University

April 4, 2016

Proposal Summary

In this proposal I am requesting funding for a non-consequtive 3-4 month stay at Fermilab over the period of September 1, 2016 - August 30, 2017. During this time, I will pursue two courses of action. First, I will continue work I have already begun on tool validation and development for analysis of first data. Second, with the use of these completed and validated tools, I will calculate the interaction cross section of the Neutral Current (NC) π^0, one of MicroBooNE's most prominent backgrounds, on Liquid Argon. These investigations will require a lot of detailed, careful work which will be aided and accelerated by direct collaboration with Fermilab research scientists and postdocs. Furthermore, these efforts will benefit the whole experiment, in addition to future users of LArTPC technology (e.g., SBND, DUNE).

Contents

1 Experiment Overview

1.1 MicroBooNE

MicroBooNE, the latest in a series of Booster Beam experiments located at Fermilab, is a Liquid Argon Time Projection Chamber (LArTPC) investigating the low energy excess seen by MiniBooNE. With the high precision reconstruction capabilities of a LArTPC, MicroBooNE will be able to determine with high statistical certainty whether e^{-}'s or γ's caused the anomalous MiniBooNE low energy excess. Of further interest to MicroBooNE, and the subject of this proposal, are neutrino-nucleon interaction cross-sections. Cross sections have accounted for much of the uncertainty in recent results from a variety of neutrino experiments[1] and sensitive measurements by MicroBooNE have the potential to lead to improved nuclear models and rate predictions.

1.2 Liquid Argon Time Projection Chambers

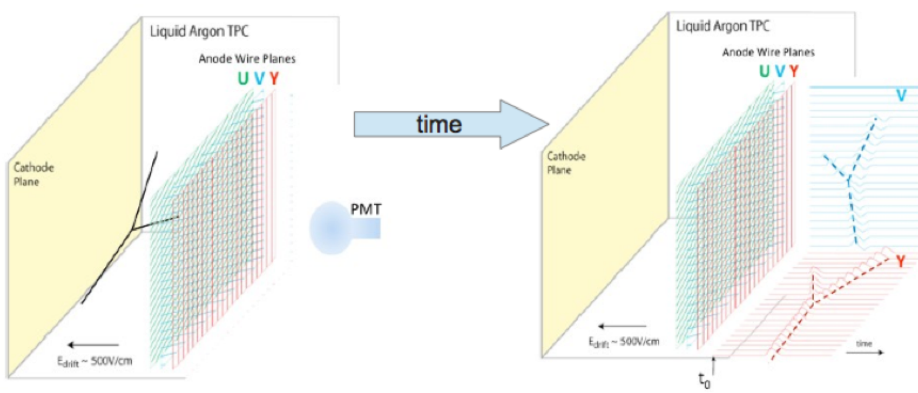

Figure 1: Event readout in a TPC

Liquid Argon Time Projection Chambers (LArTPCs) are ideal detectors for neutrino oscillation experiments with short and long baselines. The benefits of using TPC technology include good calorimetric information and image quality resolution (Figure 2). Readout from multiple wire planes makes the Y and Z coordinates of an interaction accessible, while the drift time, in conjunction with t_0 given by the PMTs, makes the X coordinate. It is important to note that the optical flashes seen by the PMTs play a crucial role in coordinating TPC events with the beam gate (thus establishing t_0 and "X") and mitigating cosmic background, as discussed later. Beyond MicroBooNE, LArTPCs (such as SBND and DUNE) will continue to play a notable role in neutrino oscillation physics, and thus the work done here on MicroBooNE will likely aid future efforts and analyses.

1.3 e^{-}, γ Discrimination

One of MiniBooNE's biggest problems was its inability to distinguish between e^{-} and γ's. Luckily, this discrimination will not be majorly problematic for MicroBooNE, due to its usage

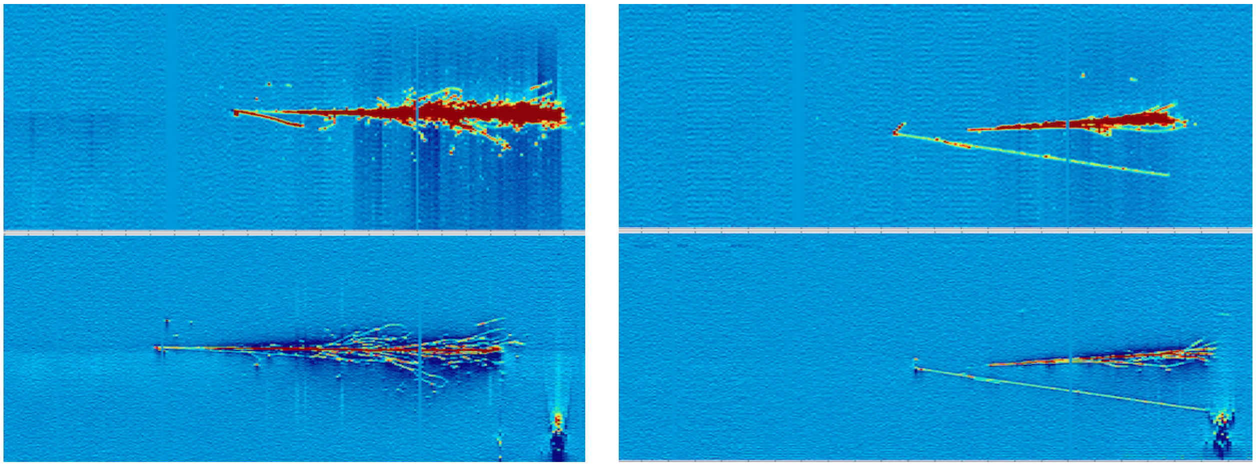

Figure 2: Readout images from the Argoneut detector. The event on the left is a signal ν_e CCQE event, while the event on the right is a background event producing a γ

of a LArTPC. Figure 2 displays two example events from Argoneut in which an e^- and γ were produced respectively. A clear distinction between these two displays is the degree of gap between the start of the showery object and the event vertex. This gap is associated with a neutral particle which cannot be detected directly; this means we only see a γ when it scatters or pair produces to cause an electro-magnetic (EM) shower. In contrast, the gapless e^- EM shower is seen as soon as the e^- is born [1].

An important caveat to this story is that the γ can sometimes pair produce near enough to the vertex of interaction to appear gap-less. This means that using just a topology cut to discriminate between the two can negatively impact the purity of our selected signal sample. To take this into account, we note that the e^- is a minimally ionizing particle (MIP) with a $\frac{dE}{dx}$ of $\sim 2\frac{Mev}{cm}$, while a γ pair produces (2 MIPs, and accounts for $\sim 94\%$ of events above 150 MeV) with a $\frac{dE}{dx}$ of $\sim 4\frac{Mev}{cm}$ [2]. The first few cm of the showering particle will contain this information, and thus allow us to discriminate with high efficiency. A successful example of this discrimination technique is shown for Argoneut (Figure 3).

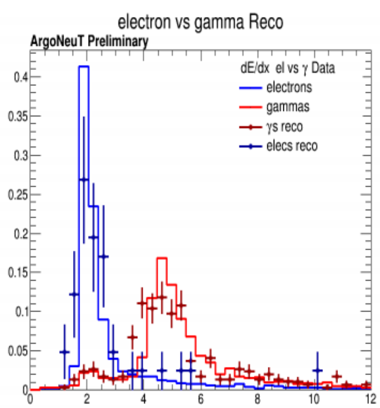

Figure 3: $\frac{dE}{dx}$ separation of electron vs γ [2]

Charged kaon production by atmospheric neutrinos is a background in searches for the proton decay $p \rightarrow K^+\bar{\nu}$. Measurements of neutrino-induced K^+ production are important inputs for current and future proton decay searches at Super-K, Hyper-K and DUNE. The MINERvA neutrino-nucleus cross section experiment at Fermilab uses timing information to isolate a sample of K^+ decay-at-rest events. I will present the first differential cross

[1]Assuming it is above some threshold.

section measurements for both charged- and neutral-current K^+ production by neutrinos, and discuss how these measurements can be used to constrain background predictions for proton decay. I will also show the first experimental evidence for coherent K^+ production by neutrinos.

2 Proposal

Below I detail the proposed activities and explain why Fermilab is the best place for me to carry them out.

2.1 Understanding NC π^0 Background

In order to investigate MiniBooNE's low energy excess and to complete its flagship ν_e appearance anlysis, MicroBooNE first needs to have a well-characterized background. Studies have shown [6] that NC π^0 events are one of MicroBooNE's primary backgrounds (Figure 4a). Part of this proposal is thus to measure the inclusive NC π^0 interaction cross section on Liquid Argon, where "inclusive" indicates all interactions which conclude with a single π^0 and no other mesons (example event in Figure 4b). This condition of inclusiveness purposefully includes all final state interactions (FSI) in order to both decrease model dependent uncertainties and to limit this study to production we can feasibly see in the detector. While simply described, this task is actually a series of tasks, and requires the use of some tools which are incompletely developed. A considerable amount of work, the majority of which will occur in collaboration with people stationed at Fermilab, will need to be done to bring these tools up to speed.

It is worth noting that only a handful of such π^0 cross section measurements exist today, some examples of which are K2K, SciBooNE and MiniBooNE [4][5][3]. Thus, this analysis will also add an important data point to a small sample of measurements.

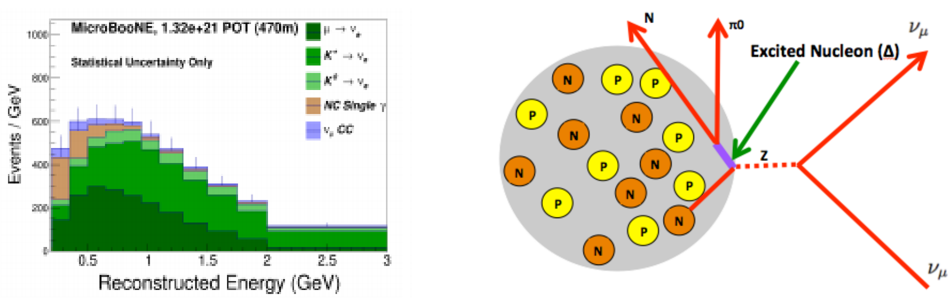

Figure 4: (a)Rate predictions at MicroBooNE for POT 1.32E21; (b) Example Inclusive NC π^0 event

2.2 Reconstruction Efforts

Automating reconstruction is crucial for both MicroBooNE analyses and the new generation of LArTPCs which will rack in more than a million neutrino events per year. While track (μ, π^+, π^-, etc.) reconstruction has existed for some time, electromatic shower reconstruction (e^-, γ) is an unfinished product (different topologies of "track" and "shower" shown in Figure 2). High quality shower reconstruction is crucial. We need the 3D shower angle to calculate "dx" in $\frac{dE}{dx}$ and to discriminate effectively between e^- and γ's as discussed above (this will allow us to resolve MiniBooNE's anomaly). Shower reconstruction currently works as follows: "hits" from MicroBooNE's 3 wire readout planes are clustered (per plane) by first preliminary and then more sophisticated algorithms. These "clusters" are then matched across the planes to reconstruct 3D showers and assign event characterization based on log likelihood calculations. While the actual reconstruction of the shower has been shown to work well on perfectly clustered information, it falters when either stage of clustering (preliminary/sophisticated) is bad (Figure 5a). Recently, I began an effort with several people stationed at Fermilab to investigate the potential of image processing software tools (OpenCV) to reconstruct showers. We have made rapid progress (Figure 5b), but there is a lot of work that needs to be done before these tools can be useful for everyone. The majority of people working on reconstruction improvement are based at Fermilab.

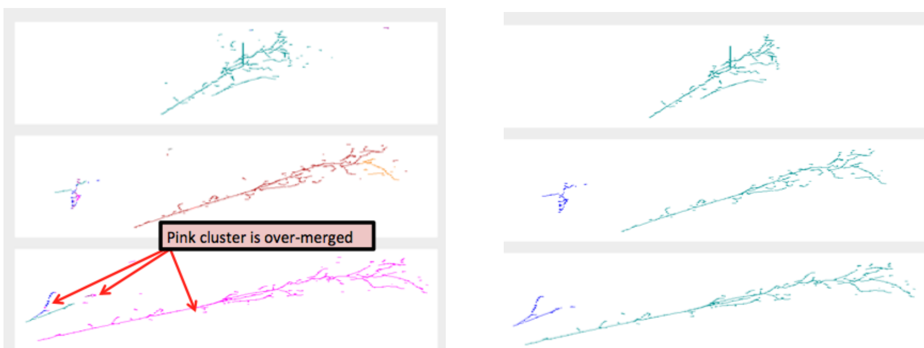

Figure 5: The 3 planes of hit-readout for MC π^0's using two different clustering schemes. Note, we only need 2 good planes to do shower reconstruction. (a) Current default clustering used by MicroBooNE, before any additional clustering has been carried out–note that at this preliminary stage, we have already over clustered. (b) Clustering on same event using OpenCV.

2.3 Cosmic Background

MicroBooNE, a surface dweller, is subject to constant bombardment by cosmic radiation from the upper atmosphere. Quantitatively, this bombardment amounts to 5 kHz, or 8 cosmics per MicroBooNE's 2.2 ms drift window. As mentioned earlier, scintillation light seen by the PMTs plays a large role in determining the t_0, or time of occurence with respect to the beam trigger, of an event. However, this timing information is only useful to us if we're able to combine it efficiently with reconstructed TPC information. This track to light matching ("flash matching") is crucial to the mitigation of our high cosmic rate, and the successful completion of most MicroBooNE analyses. I am currently working in conjunction with Fermilab postdocs and students to both improve and implement flash matching. Thus far, we have shown that it works on MC and in simple reco scenarios (eg, single μ samples). There is much validation still to be done before we can use this tool.

2.4 Potential for Further Studies

On a final note, we can potentially extend the depths of the study described above to investigate in more depth the underlying physics of exclusive channel production of π^0. The exclusive channels of neutral current π^0 production are the coherent and incoherent channels. In coherent π^0 production, the neutrino interacts with the whole neucleus to produce a π^0 (Equation 1). In constrast, a neutrino with a bit more momentum can interact with a neucleon or constituent quark (Equation 2) and cause incoherent π^0 production. The latter interactions occur more prevalently at higher momentum transfers, and have the potential to produce very messy event displays (particularly in the case of quark excitation). A measurement such as this also requires us to invoke an FSI model, particularly for an incoherent measurement; for every π^0 we see, we need to account for those which were absorbed or exchanged in the nucleus, and thus not seen in the detector. Despite this necessary model assumption, the results of this study may offer us, and future neutrino experiments, a more complete picture of the physics occurring in our detector.

$$\nu_\mu A \to \nu_\mu \pi^0 A \tag{1}$$

$$\nu_\mu N \to \nu_\mu \pi^0 N \tag{2}$$

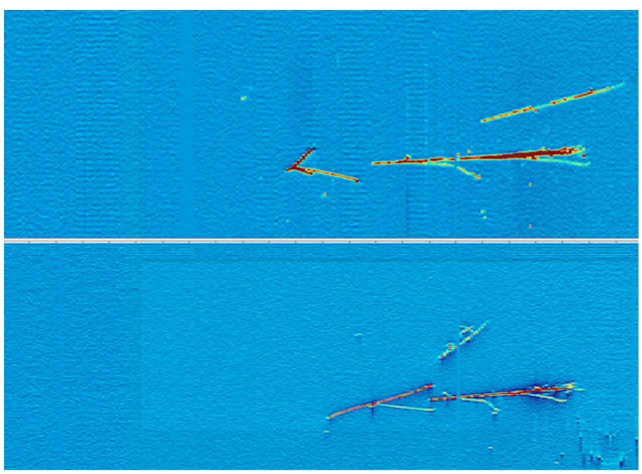

Figure 6: NC π^0 candidate found in Argoneut data

References

[1] MiniBooNE Collaboration. "The Neutrino Flux prediction at MiniBooNE." Phys. Rev. D. (2008): n. page. Print.

[2] Szlec, A. M. "Recent Results from ArgoNeuT and Status of MicroBooNE." Proceedings from Neutrino 2014. (2014): n. page. Print.

[3] Anderson, Colin. "Measurement of Muon Neutrino and AntiNeutrino Induced Single Neutral Pion Production Cross Section." Thesis. (2011): n. page. Print.

[4] Nakayama, S., et al. "Measurement of single π^0 production in neutral current neutrino interactions with water by a 1.3 GeV wide band muon neutrino beam." Phys. Lett. B. 619.255-262 (2004): n. page. Print.

[5] Kurimoto, Y., et al "Measurement of inclusive neutral current 0 production on carbon in a few-GeV neutrino beam." Phys. Rev. D. 81. (2010): n. page. Print.

[6] Acciari, R., Adams, C., et al. (2015). A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam. ArXiv:1503.01520.

3 Budget

I plan to make 5 trips to Fermilab from September 2016 - August 2017 (explained further in biosketch). These trips will total approximately 3 non-consequitive months:

October 2016 : 2 weeks
December 2016-Janury 2017 : 4 weeks
March 2017 : 2 weeks
June - July 2017 : 4 weeks
July - August 2017 : 3-4 weeks

Note: The salary requested below is equivalent to a Yale physics graduate student stipend.

Description	Cost
Airfare + Transport to Airport	$400/trip (x5 trips)
Rental Car	$500/month (x3 months)
Lodging	$500/month (x3 months)
Salary	$2781/month (x3 months)
Total	$13,343

4 BioSketch

My name is Ariana Hackenburg and I am a 4th year graduate physics student at Yale University. I work primarily on MicroBooNE, secondarily on SBND, under the advisement of Bonnie Fleming.

I began my path to physics at Rutgers University working for Ron Ransome on Minerva. Over the 3 school years I worked on Minerva, I completed a variety of tasks ranging from fixing light leaky photomultiplier tubes to analyzing event displays. For my senior thesis, I wrote a series of routines in C++ and root to model neutrino-nucleon interactions at various energies, angles and distances. During the summers, I got to work with Daya Bay, Neutrino Factory Muon Collider, and (what was at the time) LBNE with Dr Minfang Yeh, Dr. Juan Gallardo, and Dr. Mary Bishai respectively.

During my first year as a graduate student, I worked under Dr. Dan McKinsey on PIXeY. PIXeY is a Xenon time projection chamber that tracks the origin of gamma radiation, for example, loose nuclear materials. While on PIXeY I built (with Dr. Ethan Bernard) a wire-readout board that would enable us to achieve high resolution of interaction positions in our detector. Now on MicroBooNE, my roles have been diverse and several fold. I have maintained the MicroBooNE geometry file, done an extensive cosmic rate study, worked to understand light collection and its combination with TPC information, and helped to develop various reconstruction algorithms (in nearly all cases, in collaboration with those at Fermilab). Now with first MicroBooNE data, I will also be able to grow as an analyzer.

Teaching has played an important role throughout the duration of my PhD. The graduate physics program at Yale requires us to teach for our first 2 years; however, the option to continue teaching beyond this time(in addition to full time research) is open to us. This unique opportunity has allowed me to gain valuable teaching experience for the past 2 years in parallel to my PhD work. Because I teach during the year, it is only possible for me to travel to Fermilab over undergraduate breaks (fall, winter, spring break and summer recess) Shared knowledge and clear communication are crucial for doing good science; teaching will continue to play a valuable role in my physics career. The URA would enable me to continue teaching while doing valuable research in collaboration with scientists at Fermilab.

Throughout my time in graduate school, I have also managed to keep a strong hold on my interests outside of physics. I have played flute for Yale's concert band and for one of Yale's opera companies (currently rehearsing L'Etoile), am captain of the intramural physics frisbee team (The Ultraviolet Catastrophes), and play for an intramural softball team. In my past visits to Fermilab, I have frisbee'd on the Village fields, played guitar with some of the Village musicians, and joined the Big Bangers softball team on the field and off for some fun times.