“Neutrino Interactions”

Grant Number: DE-SC0009861 (R011065320)

Final Report

To the Department of Energy, office of High Energy Physics

For period 5/1/2013 – 04/30/2015

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October 24, 2016

Introduction

Neutrino group of the University of Tennessee, Knoxville under DOE-HEP grant DE-SC0009861 extended from 5/1/2013 to 04/30/2015 was involved in neutrino physics research. The group included following personnel: faculty **Tom Handler** (Co-PI) and **Yuri Kamyshkov** (PI), research assistant **Athanasios Hatzikoutelis**, graduate students **Eric Flumerfelt**, **Philip Mason**, and **Ben Rybolt**. Our group previously was involved in the neutrino oscillation experiment KamLAND that has received 2016 Breakthrough Prize in Fundamental Physics. Current project period covers continuing participation in two neutrino experiments. One is Double-Chooz nuclear reactor experiment in France where second detector was commissioned with our participation during this period and final series of measurements has been started. Although Double Chooz was a smaller experimental effort than the competitive Daya Bay and RENO experiments, several advantages of Double Chooz make its data valuable for understanding of systematic errors in measurements of neutrino oscillations. Double Chooz was the first experiment among competing three that produced initial result for neutrino angle theta-13 measurement, giving other experiments a chance to improve measured value statistically. Graduate student Ben Rybolt defended his PhD thesis on the results of Double Chooz experiment in 2015. UT group has fulfilled all the construction and analysis commitments to Double Chooz experiment and has withdrawn from the collaboration at the end of the mentioned period to start another research, although reactor neutrino measurements in Double Chooz still continue.

Larger effort of UT neutrino group during this period was devoted to the participation in another DOE-HEP project - NOvA experiment. The 14,000-ton "FAR" neutrino detector was commissioned in northern Minnesota in 2014 together with 300-ton "NEAR" detector located at Fermilab. Following the commissioning of the detectors physics measurement program has started when Fermilab accelerator complex produced the high-intensity neutrino beam through Earth to the detector in Minnesota. UT group contributed to NOvA detector construction and developments in several aspects. Our Research Associate Athanasios Hatzikoutelis was managing (Level 3 manager) the construction of the Detector Control System for NOvA detectors. This work was successfully accomplished in time with the commissioning of the detectors. The group was also involved in the development of the on-line software and study of the signatures of the cosmic ray backgrounds. Eric Flumerfelt and other graduate student Philip Mason were also studying the non-linearity properties of the NOvA liquid scintillator - information that will be essential at the final stages of NOvA data analysis. Philip Mason also studied the response of the FAR NOvA detector to cosmic muons in correlation with Solar flares. E. Flumerfelt and P. Mason successfully defended their PhD in 2015. Also, several undergraduate students were involved in the research projects at UT along with our work on NOvA. One of them, undergraduate student **Cameron Blake Erickson** has defended his undergraduate thesis on the NOvA liquid scintillator studies using for the measurements Compton gamma spectrometer that we built at UT.

Double Chooz Experiment in France

The idea of the Double Chooz (DC) experiment was to measure accurately the shape and the flux of reactor antineutrinos coming from two power stations (Figure 1) at Chooz (France) with two identical detectors (Figure 2) for pursuing the goal of determination of the missing parameter angle θ_{13} of neutrino oscillations. International Collaboration that had proposed and built this experiment involves scientists from several European countries led by France, several groups from US including our University of Tennessee group, and also participants from Japan, Brazil, and Russia. The first "FAR" detector of DC was commissioned in early 2011. NEAR DC detector due to limited availability of construction funds was commissioned with the delay in early 2015. First new result on the measurement of the θ_{13} angle with two reactor cores and only one FAR DC detector [1] was available by the end of 2011. Although with the lower statistical accuracy and based on the results from only one FAR detector, the DC result was first in the competition with the larger Daya Bay[2] and Reno [3] experiments whose data with both Far and Near detectors appeared later in 2012 and were at that time statistically more significant.

Fig 1. Chooz reactor site in France.

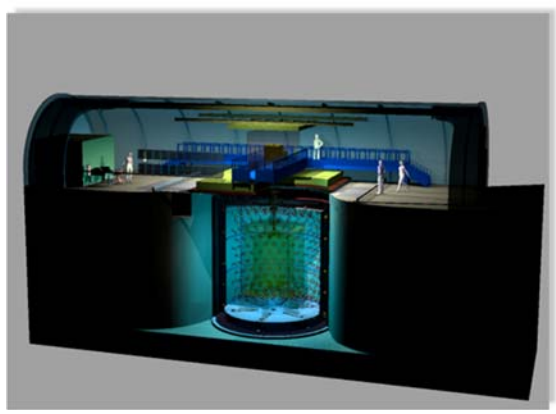

Fig 2. Rendering of Double Chooz Far Lab.

After first publication DC continued reactor measurements with the FAR detector and during 2012-2014 most efforts of the collaboration including UT group, were concentrated on the construction and commissioning of the second NEAR detector, a duplicate of the first FAR detector. Measurements of neutrino flux with two detectors is critically important because two detectors allow excluding the main source of uncertainty in such measurements – calculation from the first principles of the reactor neutrino flux. Although DC was behind the competitors Daya Bay and RENO experiment in the use of two detectors and in overall statistics of neutrino events, the other factors in the detector construction and flux control with small and well understood systematic errors make results of DC very valuable for the field. Recently analysis of the data of about a year of statistics with two operational NEAR and FAR detectors was prepared, reported by collaboration at several seminars and conferences, and are prepared for publication. University of Tennessee didn't participate in these latest DC developments after 2015 since our group discontinued its DC membership and get engaged in another experimental program after finishing all detector construction and commissioning commitments in DC and also after the last UT graduate student Ben Rybolt had prepared and defended his PhD thesis on DC data. Part of the PhD work of Ben Rybolt describes his contribution to the construction of DC PMT system where UT group was engaged in PMT testing at several stages of construction including testing before and after installation in the detector. Figures 3 and 4 below show in-situ testing process and equipment provided by UT for these measurements. This detailed and multiple testing have helped to reveal the PMTs with defects and anomalous behavior (including cables, connectors) and replace them. After finding and replacing 6 PMTs in the final installation of the FAR detector, the rate of failed photo-detectors in installation of 390 10-inch PMTs was 0% compared to 1-2 % typical for the large experiments (e.g. KamLAND, Super-K). Other contribution of Ben Rybolt in the data analysis described in his thesis was the study of performance identity of two detectors including DC-specific effect of the "light noise" and cosmogenic Li-9 background. Interesting contribution made by Ben Rybolt in his thesis was also an idea of using two (or more) detectors like Double Chooz (correspondingly upscaled in mass and at large distance from one another) for the detection of unknown and/or hidden reactors by the rate measurement. This idea might be of interest for the programs sponsored by NNSA.

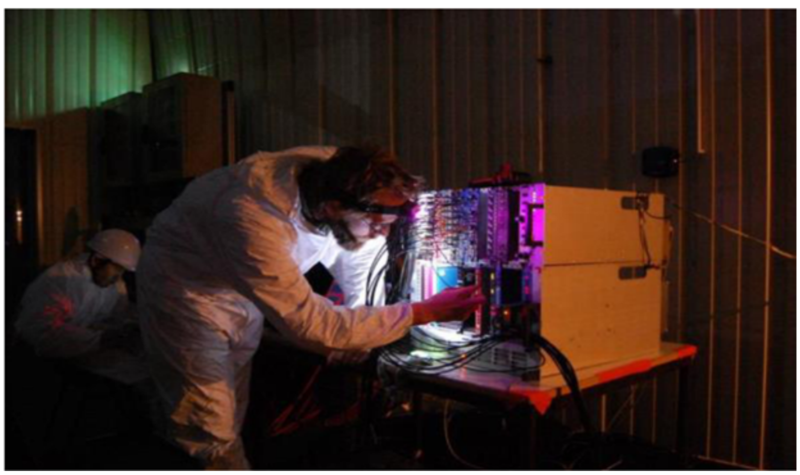

Figure 3. Graduate student B. Rybolt testing PMTs after installation in the NEAR detector.

Figure 4. UT test station at DC site.

Major idea of the design in all two-detector reactor antineutrino experiments (including DC, Daya Bay, and RENO) was the use of Gd-loaded scintillator in a well-defined volume thus reducing systematic uncertainty of determination of the target mass. However, significant number of antineutrino interactions in the detector is followed by the neutron capture on hydrogen in a volume larger than volume of the central Gd-loaded scintillator. In early 2013 DC Collaboration accomplished an analysis of event with delayed neutron capture on hydrogen and published independent determination of

θ_{13} mixing angle from this analysis [4]. This analysis was further improved in the recent paper [5] on the hydrogen capture data with the novel background rejection technique. Updated preliminary results of DC from two recent detectors analysis are shown in Figure 5 below [6].

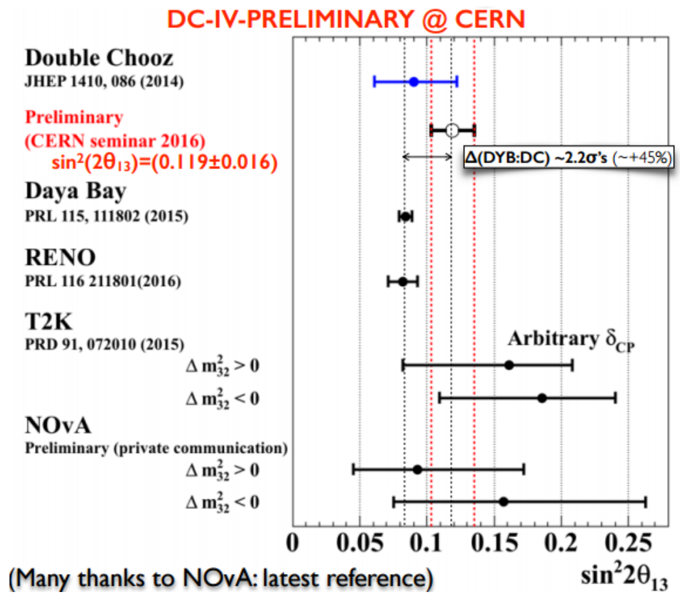

Figure 5. Recent results of Double Chooz measurement of θ13 (2016) compared with the results of other measurements [6]. Due to detailed and serious work on the study of systematics in DC this recent result challenges the values obtained by Daya Bay and RENO experiments.

During the time of operation DC used a unique situation when both cores of Chooz reactors were off for total of 7.5 days. This provided a possibility of accurate measurement of the OFF-reactor background that otherwise would be determined only from the Monte Carlo simulation and interpolation of 1- and 2- reactor data. Such a situation is impossible for Daya Bay and Reno experiments since the numbers of reactor cores in each of these experiments is 6 and few are always on. Other advantages of DC experiment are "iso-rate" location of both detectors in respect to the distance to two reactors, low singles rates due to careful material selection of the detector components, calibration procedure and others. These DC features makes θ_{13} results of DC complementary to Daya Bay and RENO measurements.

UT personnel involved in Double Chooz project during the reported period and supported by DOE/HEP grant included faculty Yuri Kamyshkov; graduate student Ben Rybolt and graduate student Aaron Osborn, who left the project and the University in the middle of period due to family reasons.

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NOνA Experiment at Fermilab

The NOνA experiment is designed to obtain roughly an order of magnitude more precise measurements of both $\nu_\mu \rightarrow \nu_e$ oscillations and ν_μ disappearance through a combination of more detector mass, more beam power yielding large numbers of neutrino interactions, a narrow-band off-axis beam, and fully active detectors with finer longitudinal segmentation.

The NOνA experiment was commissioned in 2014 as a large FAR at Ash River Minnesota and small Near Detector at Fermilab site. Participation in NOνA was the major effort of the UT group during the reported period.

Detector Control Systems (DCS, Slow Controls).

The contribution of the UT group in NO𝜈A Detector Controls (DCS) started in late 2010 when Dr. Hatzikoutelis took over as the L3 manager of WBS 2.7.4 within the "NO𝜈A Electronics and DAQ" subproject. Dr. Hatzikoutelis was also the designer of the system and one of its developers for both hardware and software. He delivered the DCS for the FAR Detector in October of 2013 as was our agreed commitment to the project. Dr. Hatzikoutelis was requested by NO𝜈A project to continue managing of the DCS as he has been the sole expert of the full scope of DCS hardware and software. Since then he has delivered the DCS of the Near Detector on May 2014 and assisted in the commissioning operations by ensuring the good operation of the DCS that monitored the status of the detector in real time and being the point of contact for all problems of DCS and the interpretation of detector problems from DCS reports. At later time Dr. Hatzikoutelis continues his involvement in DCS as the co-convener of the "Detector Experts" group in the collaboration organization chart.

NO𝜈A Detector Control System

The Detector Controls include all hardware signals for control or monitor that are not used directly for data taking. For NO𝝂A that is all the signals and configuration parameters from the electronics that are installed "On Board" the detector, like the Front-end-boards (FEB), and all devices that support the detector operation around the detector like the power supplies and the environmental monitoring.

NO𝜈A DCS has met with several challenges from the beginning of Dr. Hatzikoutelis' involvement. Figure 1 shows the diversity of the subsystem technologies it has to communicate in order to monitor the detectors. This variation is partially caused by the abandonment of the project for the 2 years before UTK involvement, when the various subsystem technologies matured independently and diversely from each other. Furthermore the initial design underestimated the resources needed. It was naively thought of as a minor part of DAQ development. In order to catch-up with the aggressive scheduling of installation and instrumentation of the Far Detector, Dr. Hatzikoutelis had to assume multiple roles such as manager, team leader, designer, developer, hardware prototyping and installation, etc., roles that he has been asked to continue also at the later time. For the development of the system he enlisted engineers, scientists and techs from various departments at Fermilab and outside companies.

Under this pressure to stay off the “critical path” of the schedule but also design the DCS to be flexible as all control systems suffer from “scope creep” (i.e. adding more services during development as the operators discover new unpredicted needs) Dr. Hatzikoutelis had to make several innovations. The most notable has been his choice of using a hybrid controls technology from two very different systems that had very specific capabilities, appropriate for specific subsystems covered by NOνA DCS. This has been noticed by the Fermilab directorate that it was suggested that this hybrid system could become the standard for the controls in future experiments at Fermilab.

With his newly designed system we have managed to meet every milestone in the development of the NOνA detectors building the DCS in phases that matched the needs at each level of the detector development stages; like the NDOS prototype runs in mid of 2011, the first instrumentation of the first Far detector blocks in Fall of 2012, the full system in October 2013, up to recently the final and most advanced control system upgrade for the needs of the Far detector retrofitting effort in September 2014. In general the decisive contribution of the UTK group in the NOνA DCS has been critical for the project’s success.

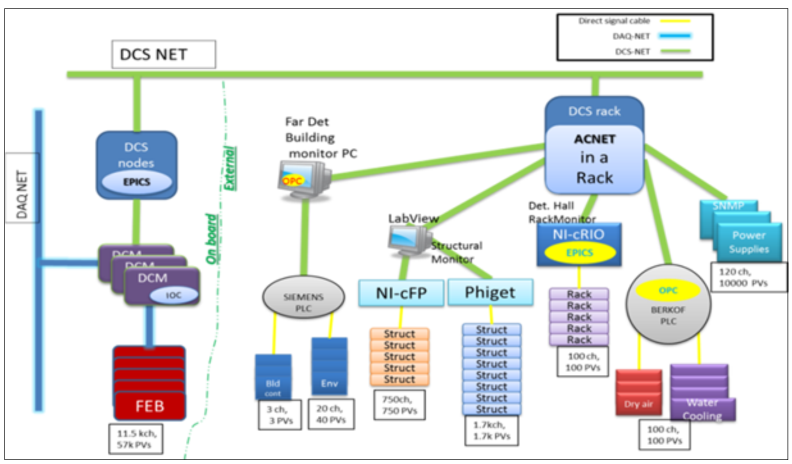

Figure 1. The layout of the NOνA Far detector controls systems. From bottom upwards we see the various hardware devices being monitored and/or controlled. Upward from that the variety of readout technologies that NOνA DCS has to integrate, while at the very top the DCS computing is represented with the DCS nodes/rack where the DCS software reside.

“On Board” DCS

The “OnBoard” DCS monitors the status of electronics that are installed on board the detectors, specifically the front-end-boards (FEB) and the state of the Avalanche Photodiodes (APD). The base system was delivered in Oct 2013 and was upgraded to provide to the operators fine control on each one of the 12,000 FEB on the Far detector and the 600 on the Near as it was requested when the need for the retrofit and the time scale of this effort was estimated. The “On Board” DCS for the Near Detector was provided to the project in May 2014.

“External DCS” technologies

This part of DCS monitors and controls the power supplies, the environmental sensors, the electronics racks, and the dry-gas and cooling systems of the NOνA detectors. It totals monitoring

~12,000 sensor signals, and controlling 183 power channels between the low and high voltage modules of the near and far detectors together. It is a distributed system adapted from the FNAL accelerator controls (ACNET) framework with the capability of accessing a wide variety of communication protocols from hardware subsystems. Dr. Hatzikoutelis lead a team of 7 ACNET engineers who assembled the suite of open-source and proprietary s/w applications into a portable form that made it possible for the first time to be moved and operated outside the confines of the Fermilab. The first version was deployed at the far detector in the Ash River site in September 2012 with the final one delivered in the summer of 2013.

DAQ Systems

UT graduate student Eric Flumerfelt was awarded a URA Visiting Scholars Fellowship, which allowed him to move to Fermilab in order to work with the DAQ Software group. This work has included becoming an on-call DAQ Expert, becoming an overall DAQ Software expert, creating scripts and programs to monitor the health of the DAQ system, responsibility for DAQ Servers, and software fixes and troubleshooting. In addition to this, Eric has become the official point-of-contact between the NOνA Experiment and Fermilab's Scientific Server Support group. The NOνA DAQ Software group had been in need of a general troubleshooter, someone who understood the system in its entirety and was able to implement patches to the software to resolve issues quickly. Eric has taken on this responsibility and also has worked on improving the user interfaces for several of the DAQ applications.

With the NOνA Near Detector nearing completion in early 2014, it has become necessary to create a DAQ cluster to run this detector. Eric has been working on reconfiguring several of the NDOS DAQ machines to serve in this new role, and then supplement these with several new machines from the next NOνA computing purchase. He has developed expertise in installing and maintaining the NOνA DAQ Software, as well as maintaining the configurations necessary for the correct operation of the DAQ computing cluster.

Liquid Scintillator Non-Linearity

Energy calibration in NOνA is performed with the cosmic muons, however the response to the electrons required for observation of $\nu_\mu \rightarrow \nu_e$ appearance can be affected by non-linearity of the energy scale since most of electrons in e-m shower are low-energy particles affected by the quenching effect in the liquid scintillator (LS) through higher dE/dx energy losses. In addition, Cherenkov radiation produced by the electrons mostly in invisible UV range of wavelengths, that per se is a non-linear process vs energy, can be absorbed and re-emitted by the scintillator components in the visible range, thus, giving rise to additional non-linearity of the scintillator. Combined effect of LS non-linearity can lead to 10-15% shift in the energy scale calibrated with muons. This correction can be measured by laboratory methods with the samples of LS. These measurements were performed at UT with Compton γ-spectrometer and with UV vacuum monochromator. These measurements are now completed and reported to Collaboration. These also were experimental parts described in details in the PhD work of our graduate students Eric Flumerfelt (Compton spectrometer measurements) and Philip Mason (UV vacuum monochromator).

Compton Spectrometer

The Compton Spectrometer with Germanium detector and advanced electronics was constructed at UT by our group. Following the spectrometer and software commissioning calibration runs were performed allowing the Monte Carlo model to catch up to the same sophistication as the physical experiment. In addition to graduate student Eric Flumerfelt, two undergraduate assistants (Blake Erikson and Laura Gunderson) worked on this experiment. A lot of efforts of research team was in understanding the systematics of measurements particularly on electronics side where detectors with different time constants (slow Ge and fast NOvA liquid scintillator with PMT) were used. Results of measurements are described in the collaboration document posted at DocDB and need to be integrated into the NOvA reconstruction algorithms, through Monte Carlo procedure allowing for much more accurate energy reconstruction for electromagnetic showers than is possible with the muon-based energy calibration.

UV Monochromator

NOvA's liquid scintillator exhibits a nonlinear energy response that causes an excess in the estimation of electromagnetic shower energies. This is observed for high dE/dx, as seen in the tail of an electromagnetic shower. The two phenomena responsible for this nonlinear energy response are Birk's quenching and UV Cherenkov reemission. The latter component, the UV reemission, has been studied by graduate student Philip Mason. A NOvA extrusion, identical to the ones used in NOvA except for its length (shortened for practicality and to reduce attenuation) was used with two wavelength shifting fibers instead of one (to improve light output by increasing the likelihood of light capture). Using a McPherson UV monochromator, a deuterium lamp, a calibrated Si diode to establish the wavelength-dependent flux, and a PMT to detect light transmitted by the WLS fibers, the energy response of the scintillator measured over a range of photon energies. These data are included in the PhD thesis prepared by Philip Mason. These data will provide re-emission factor for determination of the contribution of UV Cherenkov photon emission to the light emission. This measurement was also a research project for two UT undergraduate students Kristen Bead and Lajos Magocs. Using UT monochromator Philip Mason has also measured the scintillator's light yield directly, without the wavelength shifting fibers, for a NIM article on NOνA scintillator with the colleague Stuart Mufson of Indiana University and others.

NOvA Physics Analysis

Since during the reported period NOvA neutrino data were not yet available for analyses UT group was involved in the exploration of additional physics that could be included in the NOvA scope as well as physics obtained from the detector prototypes. Several possibilities were considered/evaluated here. Some of that physics will be included in the future proposals of UT group related to NOvA detectors.

NLWCp searches part.

The UTK group is one of the main group that supported and promoted the NLWCp "New Light Weakly-Coupled particles" studies with NOνA detectors through Dr. Hatzikoutelis who is leading this physics investigations as his primary physics interest. He has been involved in the NLWCp community since a Workshop on Neutrinos at the Spallation Neutron Source (see [1]). It was due to Dr. Hatzikoutelis' work on NLWCp with the NOνA detectors that the NOνA experiment was included in the IF5 working group in the IF workshop held at Argonne (see [2]) as well as the community summer study report of the IF (see [3]). Finally, Dr. Hatzikoutelis' research proposals have also been included in the Project-X book, recently published by FNAL (see [4]).

An investigation of the NOνA Near Detector capabilities to detect signatures from such NLWCp, through simulation, is being done. We have been using the NOνA offline analysis software developed to investigate the sensitivity of the NOvA Near Detector to detect these signatures in a model agnostic investigation. Regardless, these studies are well motivated from several models of hidden sectors (HS). These HS are postulated to be made of a "mediator" and a "dark matter" particle type. The mediator couples very weakly to the standard model particles and therefore, could be created in setups that produce high intensity neutrino beams, like the Fermilab's NUMI that the NOνA experiment uses. For examples of such models, see reference [5] and other references from [3]. The signatures of such an interaction in the NOνA near detector would be similar to neutral current events with single electron tracks or di-lepton events from NLWCp decay. Additionally, if the NLWCp is a heavy or sterile neutrino, then the signature may be photons of a wide range of energies. For this analysis, the UTK group was leading a team of four NOνA collaboration members within the "Exotics" analysis group. Their work so far has been presented in the International Conference on Mathematical Modeling in Physical Sciences (IC-MSQUARE) in Prague in Sept 1, 2013. In reference [6], the members of this team are mentioned as co-authors.

Sterile Neutrino Search

We are working on understanding what a sterile neutrino signal will look like in the NOvA Near Detector. Nuclear reactor flux predictions suggest a deficit seen for $\bar{\nu}_e$ by reactor-based neutrino experiments. One possible explanation for this deficit is a heavy "sterile" or non-interacting neutrino, which flavored neutrinos may oscillate into over very short baselines. Since the Near Detector sits at an L/E value of about 0.6 m/MeV, it is sensitive region for a sterile neutrino search. (A reactor experiment would have to be within a few meters of the reactor core to achieve similar values of L/E.) Simulations of the neutrino signal from the NuMI beam have produced initial sensitivity curves for a "perfect" NOvA experiment, and integration of systematic errors into this simulation was also pursued. Plans for a full spectral analysis has been made, as one overall effect of the sterile neutrino oscillations would be an enhancement of high-energy events and a depression of low-energy events. Beam line models are notoriously inaccurate, but a spectral analysis would be free from some of the larger uncertainties present in rate-only analyses. Unique aspect of this study is that NEAR NOvA might be sensitive to the disappearance of ν_μ into sterile state.

Extensive Cosmic Ray Showers

Since the Far Detector has only 3.7 m.w.e. of overburden, large cosmic ray showers are seen in the Far Detector. These showers are part of the total energy trigger. Extensive cosmic ray showers are seen by other experiments that utilize detectors that are spread over large surface areas, with large spacing between the detectors. Therefore they have the ability to "see" the whole shower. The NOvA

Far Detector, though it does not have a wide surface area, have a fine grain to it. This then allows us to examine the shower lateral energy depositions in much greater detail than that can be accomplished by other experiments. The UTK group has installed several software shower packages, Aires and CORSIKA, which will be used to simulate shower development through the atmosphere. The resultant showers, ground level could then be projected unto the Far Detector. Algorithms needs to be developed that will correlate what is seen, shower shape and energy, in the Far Detector with the shower simulations to determine the shower energy, the particle that initiated the shower, and shower direction in celestial coordinates. Recently the Telescope Array experiment published a paper [7] concerning an anisotropy of cosmic rays with energies greater than 57 Eev. It is hoped that we can contribute further to such types of analyses,

UT personnel involved in NOvA project during the reported period and supported by DOE/HEP grant included faculty Thomas Handler 100% (Co-PI), Yuri Kamyshkov 50% (PI); Athanasios Hatzikoutelis 100% (Research Assistant Professor), graduate students: Philip Mason, and Eric Flumerfelt.

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PhD theses supported by grant

1. Ben Thomas Rybolt, "Toward a Precision Measurement of the Theta_13 Mixing Angle with the Double Chooz Detectors", PhD Thesis, University of Tennessee, Defended in May 2016.
2. Eric Flumerfelt, "Absolute Scale Energy Calibration and Background Evaluation for the NOvA Experiment at Fermilab", PhD Thesis, FERMILAB-THESIS-2015-15, University of Tennessee, Defended in August 2015.
3. Philip James Mason, "Solar Modulation of the Cosmic Ray Intensity and the Measurement of the Cerenkov Reemission in NOvA's Liquid Scintillator", PhD Thesis, University of Tennessee, Defended in December 2015.
4. Cameron Blake Erickson, "Non-linearity Measurement of Liquid Scintillator for NOvA neutrino Experiment with UT Compton Gamma Spectrometer", senior thesis to fulfill Honors Mathematics requirement, University of Tennessee, Defended in July 2016.

Group Personnel

During the reported period following UT personnel were people were part of the project (in parentheses shown level of support from the project funds):

P.I. Professor Yuri Kamyshkov (50% Double Chooz, 50% NOvA);
Co-PI Professor Tom Handler (100% NOvA);
Athanasios Hatzikoutelis (100% NOvA);
Graduate student Eric Flumerfelt (100% NOvA);
Graduate student Philip Mason (100% NOvA);
Graduate student Ben Rybolt (100% Double Chooz);
Undergraduate student Cameron Blake Erickson (115 hours);
Also several other graduate and undergraduate students were partially supported participating in the measurements at UT and in software developments.
Graduate student Aaron Osborn initially supported for Double Chooz experiment had to leave graduate program at UT in the middle of the period for family reasons.

Funds.

At the end of the reported period all grand funds have been spend.