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Probing Neutrino Properties with Long-Baseline Neutrino Beams

Alysia D. Marino
Department of Physics, University of Colorado at Boulder
Boulder, CO 80309-0390
alysia.marino@colorado.edu

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1 Introduction

This is final report on an Early Career Award grant began in April 15, 2010 and concluded on April 14, 2015. Alysia Marino's research is focussed on making precise measurements of neutrino properties using intense accelerator-generated neutrino beams. As a part of this grant, she is collaborating on the Tokai-to-Kamioka (T2K) long-baseline neutrino experiment [6], currently taking data in Japan, and on the Deep Underground Neutrino Experiment (DUNE) design effort for a future Long-Baseline Neutrino Facility (LBNF) in the US.[1] She is also a member of the NA61/SHINE particle production experiment at CERN, but as that effort is supported by other funds, it will not be discussed further here.

T2K was designed to search for the disappearance of muon neutrinos (ν_μ) and the appearance of electron neutrinos (ν_e), using a beam of muon neutrino beam that travels 295 km across Japan towards the Super-Kamiokande detector. In 2011 T2K first reported indications of ν_e appearance [2], a previously unobserved mode of neutrino oscillations. In the past year, T2K has published a combined analysis of ν_μ disappearance and ν_e appearance [1], and began collecting taking data with a beam of anti-neutrinos, instead of neutrinos, to search for hints of violation of the CP symmetry of the universe. The proposed DUNE experiment has similar physics goals to T2K, but will be much more sensitive due to its more massive detectors and new higher-intensity neutrino beam. This effort will be very high-priority particle physics project in the US over the next decade.

2 Personnel

In addition to Marino, this grant has partially supported two postdoctoral researchers and one graduate student. Postdoc Robert Johnson joined the group in August 2010 and departed in September 2013. During his time in the group, Dr. Johnson worked on the replacement of water sensors in the T2K near detector, served as a reconstruction convener for T2K, and worked on simulations of the LBNF beamline. PhD student Tianlu Yuan joined the group in September 2010 and is expected to graduate in the 2015-2016 academic year. His PhD dissertation will be a measurement of the interaction cross section for muon neutrinos with oxygen nuclei in the T2K near detector. Postdoc Jeremy Lopez started in November 2013. He

[1] The DUNE experiment is a reformulation of the former Long-Baseline Neutrino Experiment (LBNE) that was originally discussed in the proposal.

has collaborated with Yuan on his cross section analysis and has a strong role in the T2K near detector calibrations.

Marino and the postdoctoral researchers have also supervised a number of undergraduate students during this grant period who contributed to the group's efforts on T2K or LBNF/DUNE: Christopher Vanek, Craig Pitcher (now in Physics PhD program at UC Irvine), Sebastien Tawa (currently in graduate school at UCSD), Bryan Barnhart (now working for Raytheon), Daniel Poulson, Ben Schlitzer (now in the Physics PhD program at UC Davis), Amanda Steinhebel (who will start graduate school at University of Oregon in the fall), and current undergraduates Camilla Lambrocco and Peter Madigan. Many of these students were supported during the through university funds, but Schlitzer, Barnhart, Poulson, and Madigan were all partially supported by this grant.

3 T2K Effort

3.1 Introduction and Leadership Roles

Marino is active in the off-axis near detector group, particularly the Pi-Zero Detector (P0D), which is a US responsibility on T2K. Since spring 2014, Marino has been one of the conveners of T2K's Cross Section Physics analysis group. Marino is also a convener of the ND280 Computing group, which coordinates the production of simulated events and the reconstruction of the data events in the off-axis near detector. Postdoc Lopez is currently the P0D calibration coordinator. Postdoc Rob Johnson served as a convener of the T2K ND280 Reconstruction group.

Marino chaired the committee that reviewed the T2K beam flux inputs to the summer 2012 oscillation results. The flux information was published [3], and Marino was a member of the paper committee. She also served on the committee that reviewed the 2012 ν_e appearance analysis results [4], and the updated results that included the 2013 dataset [5]. Marino became a member of T2K's Publication Board, which oversees the reviews of all T2K results and publications. Since October 2014 she has been the Chair of this board.

3.2 T2K Hardware

In summer 2010 Marino's group undertook an upgrade to the water monitoring system in the P0D subdetector. The P0D contains 50 water bladders that can be filled and drained with water in order to understand differences

between neutrino interactions on carbon (which makes up much of the near detector) and oxygen (on which the majority of the neutrino interactions in the far water Cherenkov detector occur). The water level in these bladders must be carefully monitored for detector safety, and also to determine the uniformity of the distribution of the water throughout the subdetector. Aided by postdoc Rob Johnson, and summer undergraduate Chris Vanek, fifty water depth sensors (half of the total) were tested, calibrated, and packaged at the University of Colorado. In late summer 2010 Johnson lead their installation in the near detector. Since then group members, including Yuan and Lopez, have participated in the the maintenance, and repair of the water systems in the P0D. Lopez is also responsible for determining many of the P0D's calibration constants and coordinating the calibration efforts.

3.3 T2K Computing

Since 2011, Marino's group has been responsible for the production and reconstruction of T2K near detector Monte Carlo events, specifically the files that use the Genie neutrino generator to simulate neutrino interactions. As a service to the collaboration from the US group, beam events are simulated at the level of 15-30 times the data statistics, using the High Energy computing cluster at the University of Colorado. Additional specialized samples were generated as well.

3.4 ν_μ Analysis

Johnson, Yuan, and now Lopez are looking at ν_μ events originating in the P0D, which houses much of the mass in the active volume of the near detector. Working in collaboration with Walter Toki and his group at Colorado State University, Johnson and Yuan selected samples of ν_μ candidates events in the P0D and first TPC and compared the event rate in data to the expected rate as a function of the muon momentum [7]. In 2012-2013 undergraduate Bryan Barnhart searched for $\bar{\nu}_\mu$ events in the P0D in the neutrino data for his honors thesis, and he observed a rate consistent with predictions.

Since then the group has focussed more specifically on charged-current quasi-elastic (CCQE) events, where a neutrino interacts with neutron in a nucleus, yielding a proton and a muon, with no additional particles. Data samples have been taken both when the P0D water bladders contained water and when they were empty. Since the far detector is composed of water, it will be important to extract the ν_μ signal on water by carefully subtracting

the signal seen in these two datasets (taking into account changes in the detector efficiencies, etc.). For Yuan's thesis, he is using data taken in both modes to extract the CCQE cross section for muon neutrinos on oxygen.

4 LBNF/DUNE Effort

Marino and her group are interested in constraining the uncertainty on the neutrino flux for the new neutrino beam proposed for Fermilab's LBNF. This includes a combination of proposed ex situ measurements with the NA61/SHINE experiment (which are not in the scope of this proposal), and in situ measurements of muons produced in the LBNF beamline with the neutrinos. The muon detectors would be located just downstream of the absorber and use the exiting muons to monitor the beam profile and stability, and place a constraint on the absolute neutrino flux at high energies.

4.1 Prototype DUNE Detectors

Marino's group has developed a conceptual design for the DUNE muon detectors using a threshold gas Cherenkov detector to measure the muon spectrum. Undergraduate Craig Pitcher simulated this design for his honors thesis. A small prototype detector was assembled at Colorado by undergrads Schlitzer and Madigan and is operating with cosmic rays to verify the Cherenkov nature of the signal. In collaboration with LANL, a larger prototype has been deployed in the existing NuMI neutrino beam line at Fermilab and this preliminary data is being examined by Madigan and Lopez.

4.2 Beam Simulations

Postdoc Johnson was active in the development of the new Geant4-based LBNF beam simulation software, g4LBNE. Working with Paul Lebrun at Fermilab, Rob helped with the release of a new version (v3) of the software with significant changes to the geometry specifications. Working with Johnson and Marino, undergrads Steinhebel, Poulson, and Lambrocco have used this software to predict the muon flux after the absorber and study the impact of misalignments of the beam line elements on the neutrino flux.

5 Conclusion

Throughout this Early Career Award, Alysia Marino at the University of Colorado constructed a research program with her group that centers on

investigating neutrino properties in the near detector of the T2K accelerator neutrino experiment. They have also designed and constructed prototype muon detectors to better understand the neutrino beam for the future DUNE experiment the US. This group will continue to contribute to the analysis of T2K data while focussing increasingly on future projects like DUNE.

References

[1] "Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with 6.6E20 protons on target, Abe, K. *et al.* (T2K Collaboration), Phys. Rev. D **91** 072010 (2015)

[2] "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam", Abe, K. *et al.* (T2K Collaboration), Phys. Rev. Lett. **107**, 041801 (2011)

[3] K. Abe *et al.* [T2K Collaboration], "The T2K Neutrino Flux Prediction," Phys. Rev. D **87**, 012001 (2013)

[4] "Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam,"K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **88**, no. 3, 032002 (2013)

[5] "Observation of Electron Neutrino Appearance Muon Neutrino Beam", Abe, K. *et al.* (T2K Collaboration), Phys. Rev. Lett. **112**, 061802 (2014)

[6] "The T2K Experiment", Abe, K. *et al.* (T2K Collaboration) Nucl. Instrum. Meth. A **659**, 106 (2011).

[7] "Analysis of ν_μ Charged Current Inclusive Events in the P0D in Runs 1+2+3+4", T. Campbell , A. Clifton, R. Das, R. A. Johnson , A. D. Marino, E. Reinherz-Aronis, W. Toki, and T. Yuan, T2K Technical Note 80

6 Appendix: Publications and Presentations

6.1 Published Refereed Papers

1. K. Abe *et al.* [T2K Collaboration], "The T2K Experiment, Nucl. Instrum. Meth. A **659**, 106 (2011)

2. K. Abe *et al.* [T2K Collaboration], "Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam," Phys. Rev. Lett. **107**, 041801 (2011)

3. K. Abe *et al.* [T2K Collaboration], "Measurements of the T2K neutrino beam properties using the INGRID on-axis near detector," Nucl. Instrum. Meth. A **694**, 211 (2012)

4. S. Assylbekov, *et al.*, "The T2K ND280 Off-Axis Pi-Zero Detector," Nucl. Instrum. Meth. A **686**, 48 (2012)

5. K. Abe *et al.* [T2K Collaboration], "First Muon-Neutrino Disappearance Study with an Off-Axis Beam," Phys. Rev. D **85**, 031103 (2012)

6. S. Bhadra *et al.*, "Optical Transition Radiation Monitor for the T2K Experiment," Nucl. Instrum. Meth. A **703**, 45 (2013)

7. N. Abgrall *et al.* [NA61/SHINE Collaboration], "Pion emission from the T2K replica target: method, results and application," Nucl. Instrum. Meth. A **701**, 99 (2013)

8. K. Abe *et al.* [T2K Collaboration], "T2K neutrino flux prediction," Phys. Rev. D **87**, no. 1, 012001 (2013)

9. K. Abe *et al.* [T2K Collaboration], "Measurement of the inclusive ν_μ charged current cross section on carbon in the near detector of the T2K experiment," Phys. Rev. D **87**, no. 9, 092003 (2013)

10. K. Abe *et al.* [T2K Collaboration], "Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam," Phys. Rev. D **88**, no. 3, 032002 (2013)

11. K. Abe *et al.* [T2K Collaboration], "Measurement of Neutrino Oscillation Parameters from Muon Neutrino Disappearance with an Off-axis Beam," Phys. Rev. Lett. **111**, no. 21, 211803 (2013)

12. K. Abe *et al.* [T2K Collaboration], "Observation of Electron Neutrino Appearance in a Muon Neutrino Beam," Phys. Rev. Lett. **112**, 061802 (2014)

13. K. Abe *et al.* [T2K Collaboration], "Precise Measurement of the Neutrino Mixing Parameter $\theta_{23}$from Muon Neutrino Disappearance in an Off-Axis Beam," Phys. Rev. Lett. **112**, no. 18, 181801 (2014)

14. K. Abe *et al.* [T2K Collaboration], "Measurement of the intrinsic electron neutrino component in the T2K neutrino beam with the ND280 detector," Phys. Rev. D **89**, no. 9, 092003 (2014)

15. K. Abe *et al.* [T2K Collaboration], "Measurement of the neutrino-oxygen neutral-current interaction cross section by observing nuclear de-excitation γ rays," Phys. Rev. D **90**, no. 7, 072012 (2014)

16. K. Abe *et al.* [T2K Collaboration], "Measurement of the inclusive ν_μ charged current cross section on iron and hydrocarbon in the T2K on-axis neutrino beam," Phys. Rev. D **90**, no. 5, 052010 (2014)

17. K. Abe *et al.* [T2K Collaboration], "Measurement of the Inclusive Electron Neutrino Charged Current Cross Section on Carbon with the T2K Near Detector," Phys. Rev. Lett. **113**, no. 24, 241803 (2014)

18. K. Abe *et al.* [T2K Collaboration], "Neutrino oscillation physics potential of the T2K experiment," PTEP **2015**, no. 4, 043C01 (2015)

19. K. Abe *et al.* [T2K Collaboration], "Search for short baseline ν_e disappearance with the T2K near detector," Phys. Rev. D **91**, no. 5, 051102 (2015)

20. K. Abe *et al.* [T2K Collaboration], "Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with $6.6\text{x}10^{20}$ protons on target," Phys. Rev. D **91**, no. 7, 072010 (2015)

21. K. Abe *et al.* [T2K Collaboration], "Measurement of the ν_μ charged current quasielastic cross section on carbon with the T2K on-axis neutrino beam," Phys. Rev. D **91**, no. 11, 112002 (2015)

22. K. Abe *et al.* [T2K Collaboration], "Measurement of the Electron Neutrino Charged-current Interaction Rate on Water with the T2K ND280 pi-zero Detector," Phys. Rev. D **91**, 112010 (2015)

6.2 Conference Presentations

1. J. Lopez,"Measurement of the ν_μ Charged Current Quasielastic Scattering Cross Section on Water with the T2K Off-Axis Near Detector", talk at APS DPF meeting, Ann Arbor, MI, August 4-8, 2015

2. T. Yuan, "A Measurement of the ν_μ Charged Current Quasielastic Cross-section on Water with T2K's Near Detector ", APS April Meeting, Baltimore, MD, April 11-14, 2015

3. A. D. Marino, "Muon Monitors for the Long-Baseline Neutrino Experiment", Poster at Neutrino 2014: 26th International Conference on Neutrino Physics and Astrophysics, Boston, MA, June 2-7, 2014

4. T. Yuan, "Towards Measuring the NuMu Charged Current Quasielastic Cross Section on Water using T2K's Near Detector", Poster at Neutrino 2014: 26th International Conference on Neutrino Physics and Astrophysics, Boston, MA, June 2-7, 2014

5. A. D. Marino, "Long-Baseline Neutrino Results", Talk at PIC 2014: 34th International Physics in Collision Symposium, Bloomington, IN, Sept 16-20, 2014

6. A. D. Marino,"Prospects for Improvements in Neutrino Flux Understanding", Talk at NuINT 2014: 9th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region, Surrey, UK, May 19-24, 2014

7. A. D. Marino,"Hadroproduction Experiments: Impact on T2K/LBNE", Talk at LBNE Scientific Workshop, Sante Fe, NM, April 25-26, 2014

8. B. Barnhart, "Charged-Current Anti-Muon Neutrino Events in the Near Detector at T2K", Talk at Annual Meeting of the Four Corners Section of the APS, Denver, CO, October 18-19, 2013

9. R. A. Johnson, "Inclusive Charged-Current ν_μ Analysis of the Pi-Zero Detector at T2K", Talk at APS April meeting, Atlanta, GA, March 31-April 2, 2012

10. A. D. Marino,"Overview of neutrino mixing results from accelerator-based neutrino experiments",Talk at Eleventh Conference at the Intersections of Particle and Nuclear Physics (CIPANP), St. Petersburg, FL, May 29-June 3, 2012

11. A. D. Marino, "Recent Results from the T2K Experiment", Talk at Annual Meeting of the Four Corners Section of the APS, Socorro, NM, October 26-27, 2012

12. A. D. Marino. "Recent Results from T2K", Talk at Workshop on Flux Measurement and Determination in the Intensity Frontier Era Neutrino Beams, Pittsburgh, PA, December 6-8, 2012

13. C. Pitcher,"Preliminary Design of the Gas Cherenkov Muon Monitors for LBNE", Talk at Annual Meeting of the APS Four Corners Section, University of Arizona, Tucson, AZ, October 21-22, 2011

14. A. D. Marino,"Run 1 and 2 Results from T2K", Talk at INFO'11 Conference, Santa Fe, July 18, 2011