

The ArgoNeuT Experiment

Andrzej M. Szelc for the ArgoNeuT Collaboration

Yale University, Physics Department, New Haven, CT 06511, USA

Abstract. The ArgoNeuT (Argon Neutrino Test) Experiment ran on the NuMI beam line at the Fermi National Accelerator Laboratory, from Sep 2009 to Feb 2010. It is the first stage of the US R&D effort on using Liquid Argon Time Projection Chambers (LArTPCs) as neutrino detectors. ArgoNeuT has collected thousands of beam neutrino events in the 0.1 -10 GeV energy range during its run and, apart from fulfilling its R&D goals, is now publishing physics results, including the first measurement of the inclusive muon neutrino charged current differential cross sections on argon. These proceedings will present these results, together with the perspectives for ongoing and future analyses, as well as ideas for running the detector in a test beam of charged particles.

Keywords: LArTPC, neutrino, ArgoNeuT, LArIAT

INTRODUCTION

In recent years the need for precision measurement in the field of neutrino physics has been growing, as the observables that are left to be measured are becoming more and more elusive. For this reason, liquid argon is recently becoming the go-to technology in neutrino experiments. Noble liquids in general exhibit properties that make them an interesting choice in measuring weak interaction physics, due to their high scintillation and ionization yields and relatively large density. Argon is the natural choice when considering larger detectors, because of its abundance in the atmosphere and therefore moderate price. The lack of free protons in argon means that nuclear effects have to be taken into account when analyzing data, which can be challenging but also provide insight into nuclear effects.

The LArTPC and the US R&D Program

The Liquid Argon Time Projection Chamber (LArTPC), proposed by C. Rubbia [1] and pioneered by the ICARUS collaboration[2], aims to take advantage of the qualities of liquid argon as a detector medium. The principle of operation is shown in fig. 1 - an energy deposition caused by a charged particle traversing the medium results in scintillation light and ionization electrons. In a LArTPC, the free electrons are drifted towards the anode in a uniform electric field where they are registered on wires in multiple (at least two) planes, due to electromagnetic induction and collection of the electrons on the last plane of wires. Because the wires in different planes are at an angle with respect to each other, identifying the channels in different planes where a charge deposit has been registered gives the position reconstruction in the Y and Z coordinates, while the drift time provides the X coordinate completing the full 3D reconstruction of an event. Measuring the quantity of the deposited charge provides calorimetric information.

The LArTPC, given its ability for simultaneous precise 3D and calorimetric reconstruction of particle interactions is an extremely interesting detector technology and is being developed in the framework of the US LArTPC R&D program, which connects physics goals, like the sterile neutrino search [3], and technology development milestones that will lead to a multi-kiloton long-baseline neutrino experiment [4]. ArgoNeuT was the first LArTPC placed in a neutrino beam in the framework of this program. Its goals included measuring the CC cross-sections in the 1-5 GeV range, examining the effects of Final State Interactions (FSI), testing the Particle ID capabilities of the LArTPC, especially the e/γ separation crucial for future neutrino experiments, and finally to develop automated reconstruction techniques that could be used by subsequent experiments.

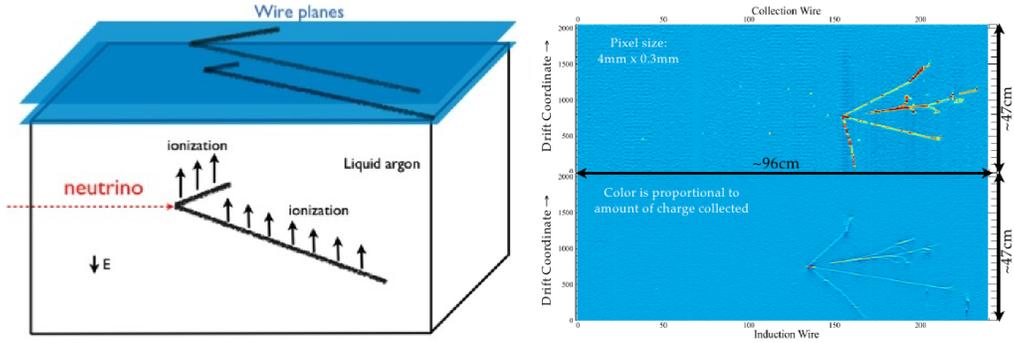


FIGURE 1. The LArTPC concept: Charged particles leave a trail of ionization electrons in their wake. The electrons are then drifted towards the anode wire planes in the uniform electric field. The electrons pass the first wire planes inducing a signal due to electromagnetic induction to be collected on the final, collection wire plane (left). A typical ArgoNeuT event (right).

THE ARGONEUT DETECTOR

The inner cryostat of the ArgoNeuT detector contained 500 liters of liquid argon, of which $\simeq 170$ liters were in the active volume inside the TPC. A vacuum of 10^{-4} mbar held between the inner and outer cryostats kept the heat-load down to $\simeq 120 - 160$ W, which allowed using a 330 W off the shelf CryoCooler to maintain the liquid argon at its boiling temperature of 87 K. Purity from electronegative contaminants, e.g. O_2 and H_2O , which can attach drifting ionization electrons and weaken the charge signal on the wires, was obtained by recirculating the gas argon through regenerable filters developed at Fermilab [5]. This system, shown in Fig. 2, allowed obtaining the necessary purity of about $\simeq 700 \mu s$ but would probably be insufficient for a larger detector, where a liquid argon recirculation system is necessary.

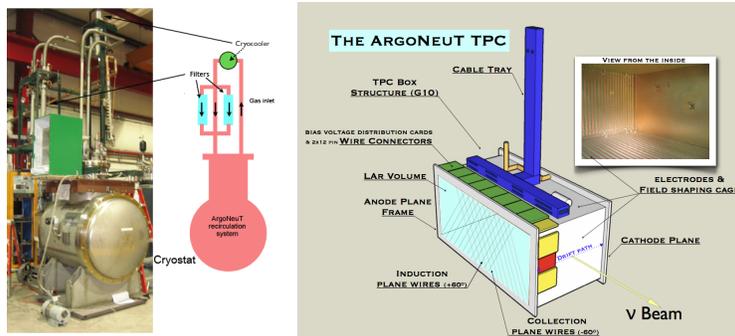


FIGURE 2. The ArgoNeuT Cryogenics system (left) and the ArgoNeuT TPC (right).

The anode wire planes in the TPC were at a ± 30 degree angle from vertical and the spacing between adjacent wires was 4 mm. To read out the 480 channels from the 2 wire planes warm electronics were used, which means that the preamplifier was located outside of the cryostat. Most new experiments are now shifting towards using cold CMOS style electronics, instead of the warm JFET style used in ArgoNeuT, since it raises the signal to noise ratio and makes it easier to drive signals for longer distances, which is necessary in larger scale experiments. A more detailed description of the electronics used in the ArgoNeuT and the whole detector can be found in [6].

The ArgoNeuT Physics Run

During its physics run ArgoNeuT was positioned in the MINOS Near Detector (MINOS ND) hall, just upstream of MINOS ND on the NuMI Beam line. The NuMI beamline is a relatively high energy beam line, with a mean energy of $< 4.3 >$ GeV [7]. In the anti-neutrino mode, the content of ν_μ neutrinos is actually higher than that of $\bar{\nu}_\mu$ s which dominate only at lower energies.

ArgoNeuT operated in the beamline for 5 months and was able to acquire 1.35×10^{20} POT mainly in $\bar{\nu}_\mu$ mode. During this whole period it ran in remote, shiftless operation, with $\simeq 95\%$ uptime. The main cause of down-time was a failure of the off-the-shelf cryo-cooler.

One of the most important parameters during operation was the electron lifetime, which is a measure of electronegative impurities in the liquid argon. The purity of the argon during the run is shown in Fig. 3. The purity obtained in ArgoNeuT was satisfactory, but one of the lessons learned during running and operation was that certain materials, e.g. G10 can cause problems for the purity if they are left to outgas above the liquid phase. The Material Test Stand at Fermilab[8] and LAPD [9] are continuing a more focused research program on the effects of different materials in liquid argon and maintaining sufficient purity in larger detectors.

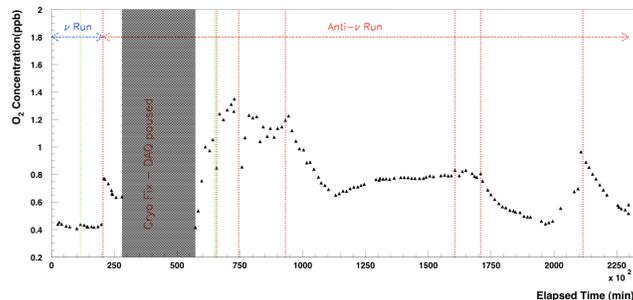


FIGURE 3. The O_2 contamination of liquid argon during the physics run of ArgoNeuT, obtained by measuring the electron lifetime.

PHYSICS RESULTS

The LArSOFT Software Package

One of the goals of ArgoNeuT was to develop automatic reconstruction procedures for future neutrino experiments. This is being done in the framework of the LArSOFT software package [10], which is being developed as a detector agnostic software package usable by any LArTPC experiment. The idea of LArSOFT is to divide analysis tasks and stages into modules, therefore making the analysis process highly customizable for the end-user. ArgoNeuT has been at the forefront of developing algorithms to be used in liquid argon. The capability of most ArgoNeuT analyses is boosted by the presence of the magnetized MINOS Near Detector which provides charge and momentum reconstruction of exiting muons impossible to obtain in ArgoNeuT itself due to its small size.

Completed Analyses

Even though the ArgoNeuT detector was designed as an R&D effort it was able to produce physics results. These include the first ever measurement of the ν_μ Charged Current inclusive cross-section on argon [11]. A second analysis was aimed at understanding the calorimetric capabilities of the LArTPC by attempting a full reconstruction of through-going muons coming mostly from neutrino interactions in the rock before the detector. As shown in Fig. 4 the distribution of energy depositions by the tracks is perfectly consistent with a Landau distribution [12].

On-Going Analyses

The data acquired during the running of ArgoNeuT is still being analyzed and new results will be published soon. One of the areas of the measurements are the studies multi-proton events in the context of the Charged Current $0 \pi + N$ proton cross-section [13] and the nuclear effects including Final State Interactions (FSI) observed in this sample [14]. Both of these studies have been presented at this conference.

Other studies, that are nearing completion are the measurements of the ν_μ and $\bar{\nu}_\mu$ CC-inclusive cross-section using the Anti-Neutrino running data. Due to the composition of the NuMI beam and the charge determination using the magnetized MINOS ND this data set will allow measuring the cross-section in both the neutrino and anti-neutrino channels. It is worth noting that the neutrino energy spectrum in the anti neutrino mode running is significantly higher than that of the neutrino mode running and the sample of events is significantly bigger.

The excellent resolution of the ArgoNeuT LArTPC allows us to study even more complicated topologies. One example is looking for hyperon production, by identifying the gap between the primary and secondary vertex where the resonance decays. The combination of the resolution with the calorimetric capabilities of the detector allows studying the dE/dx separation of electron- and gamma-induced electromagnetic showers. This separation is extremely important for future experiments as it gives a handle on the capabilities of the Neutral Current (NC) π^0 background and ArgoNeuT will be able to provide a first data-based estimate of its level.

Apart from studying beam events, the data acquired with ArgoNeuT will allow constraining properties of liquid argon itself, which will be crucial to understanding the results of future experiments. One of such parameters is the recombination efficiency of ionization electrons. The recombination probability depends on the energy deposition per track length dE/dx and is often described using the Birks' parametrization [15]. Measurements of the parameters of this model have up to now used rather small samples of events and so are imprecise at higher energies [16]. ArgoNeuT has a significant sample of protons and so will be able to measure these values more precisely.

THE FUTURE

ArgoNeuT was only the first step in the US LArTPC R&D program. The liquid argon technology is being actively developed and the immediate next step is MicroBooNE which will use the excellent PID capabilities of argon to resolve the so-called MiniBooNE excess. Next steps include LArI, which will aim to resolve the anti-neutrino MiniBooNE and LSND anomalies and LBNE which is aimed at measuring the neutrino mass-hierarchy and CP-violation in the neutrino sector using a multi kiloton liquid argon detector. For a more thorough discussion of future neutrino experiments see [17].

The LArIAT Detector

The growing acceptance of the LArTPC as a detector of choice for neutrino physics has put emphasis on the need for a proper calibration of this technology. Using a beam of charged particles with a known momentum would allow to refine our understanding of particle identification capabilities both for tracks and electromagnetic showers, shower energy resolution and recombination parameters. Measuring these values should significantly lower systematic errors and improve the predictions of all the future LArTPC detectors.

LArIAT is a project whose objective is the calibration of single tracks and collective topologies and the characterization of their response at a range of energies relevant for future experiments (MicroBooNE, LBNE, etc.). Its first phase

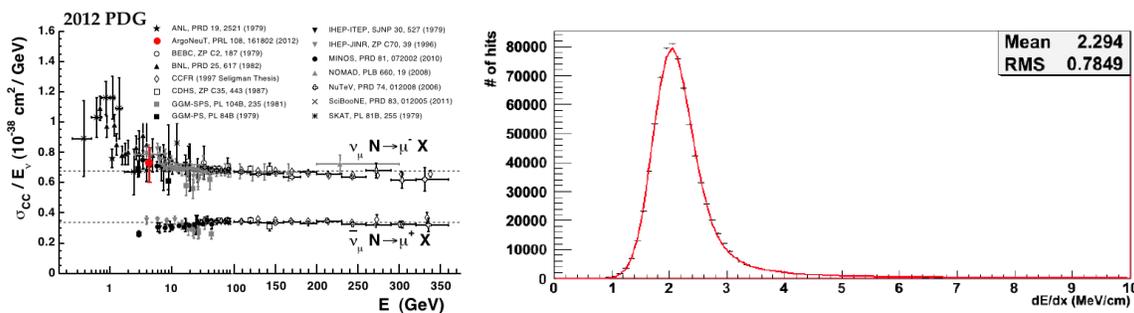


FIGURE 4. The CC inclusive cross-section measured by ArgoNeuT compared with other experiments (left). The distribution of the dE/dx energy depositions of through-going muons reconstructed in the ArgoNeuT TPC overlaid with a Landau curve, showing the calorimetric reconstruction capabilities of the detector (right).

will use the repurposed ArgoNeuT TPC placed on a beam of charged particles in the Fermilab Test Beam Facility (FTBF). The experiment will use the tertiary (low momentum) beam developed by the MINERVA collaboration [18], which provides protons, pions, electrons and muons.

To run in the TestBeam facility the ArgoNeuT cryogenic system will be modified by adding a recirculation system in liquid and modifying the front flange to minimize the amount of material the charged particles have to travel through before arriving in the TPC. The detector will now also be equipped with a light readout system, which will aim to use scintillation light for calorimetric reconstruction.

The first phase of LArIAT is scheduled to run in the fall of 2013 and its results will inform the design of a larger, second phase detector which will be geared towards measuring the containment and energy reconstruction of hadronic and electromagnetic showers.

CONCLUSIONS

ArgoNeuT was the First LArTPC in a neutrino beam in the United States. It has provided important know-how which will be used by subsequent LArTPC experiments. It was able to acquire the first neutrino data in the GeV region in liquid argon. Even though it was designed as a primarily R&D project, it was able to provide physics results. The data acquired during the run is still being analyzed and more results will come in the near future. After its physics run on the neutrino beam line, the ArgoNeuT detector will be refurbished as LArIAT to run on a beam of charged particles, which will allow calibrating many important parameters of the LArTPC technology.

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REFERENCES

1. C. Rubbia, *CERN-EP/77-08* (1977).
2. ICARUS Collaboration, *Nucl. Instrum. Meth. in Phys. Res.*, **A 527**, (2004) 329.
3. MicroBooNE Collaboration, H. Chen et. al., *Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines: MicroBooNE*, FERMILAB-PROPOSAL-0974.
4. LBNE Collaboration, T. Akiri et. al., *The 2010 Interim Report of the Long-Baseline Neutrino Experiment Collaboration Physics Working Groups*, arXiv:1110.6249.
5. A. Curioni et al., *Nucl. Instrum. and Meth. in Phys. Res.* **A 605** (2009), 306.
6. C Anderson et al., *JINST* **7 P10019** (2012); arXiv:1205.6747 [physics.ins-det]
7. K. Anderson et. al., *The NuMI Facility Technical Design Report*, FERMILAB-DESIGN-1998-01.
8. B. Rebel et al., *Results from the Fermilab Materials Test Stand and Status of the Liquid Argon Purity Demonstrator*, FERMILAB-CONF-10-692-PPD.
9. B Rebel et al., *J. Phys.: Conf. Ser.* **308** 012023 (2011)
10. E. Church (for the LArSoft Collaboration), *LArSoft: A Software Package for Liquid Argon Time Proportional Drift Chambers*, To be published in *J. Phys. Conf. Ser.* (2013).
11. ArgoNeuT Collaboration, *Phys. Rev. Lett.* **108** (2012), 161802 (and arXiv:1111.0103 [hep-ex]).
12. ArgoNeuT Collaboration, *JINST* **7 P10020** , (2012); arXiv:1205.6702 [physics.ins-det].
13. Kinga Partyka, *These Proceedings*.
14. Ornella Palamara, *These Proceedings*.
15. J. Birks, *Theory and Practice of Scintillation Counting*, Pergamon Press, 1964.
16. ICARUS Collaboration, *Nucl. Instrum. and Meth. in Phys. Res.* **A 523** (2004), 275.
17. Georgia Karagiorgi, *These Proceedings*.
18. R. Gran. *Test Beam Calibration of the MINERvA Detector Components* , FERMILAB-PROPOSAL-0977