Conventional Neutrino Beam Experiments: Present and Future Generations

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Abstract. There are currently four conventional neutrino beams produced around the world serving a total of six different neutrino experiments devoted to a broad range of physics. In this article we discuss the current generation of experiments served by those beamlines, future plans for those beamlines, and plans for yet newer facilities, with a focus on lessons the current generation of experiments can pass on to future generations.

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INTRODUCTION

The field of neutrino oscillation physics is currently taking more protons from accelerators than any other field in particle physics. Given the low oscillation probabilities that are being sought and the requirement that neutrinos travel some distance between production and detection, the demands of neutrino experiments on accelerators have never been higher.

The current and near term generations of neutrino experiments served by the four currently operating beamlines have the goal of establishing the foundations for the oscillation framework. OPERA and ICARUS have the goal of confirming that the muon neutrinos are in fact oscillating into tau neutrinos at the atmospheric mass splitting. MINOS is currently making the most precise measurements of the atmospheric mass splitting that will be necessary to ultimately measure CP violation in the neutrino sector.

Before any long distance searches for CP violation can be conclusive, the field must improve its knowledge of neutrino interactions and the processes that comprise future backgrounds and signals, which is the purview of MINERvA. Finally, the LSND neutrino signature[1] must be better understood and MiniBooNE is working to do this. The size of the last unmeasured mixing angle θ_{13}, now being explored by T2K, will play a large role in determining the size of the effort required to get to the ultimate goal of CP violation in the neutrino sector.

The next generation of neutrino experiments is not far behind. As of this writing the NOvA experiment, whose goal is also to search for electron neutrino appearance from a muon neutrino beam, has started testing and checkout of its near detector using the NuMI beamline, while the far detector is under construction[2]. The MicroBooNE experiment is in the planning and approval stages but will be poised to extend the Liquid Argon TPC technology to low energy neutrinos, and to extend the physics reach of the Booster Neutrino Beamline by improving the search for short baseline electron neutrino appearance in a muon neutrino beam.

The next to next generation of experiments has the tall order of understanding the mass hierarchy in the neutrino sector and looking for CP violation. This generation will need to be informed not only of the size of the last mixing angle but also the precise ways that these signals will arise in their detectors.

CURRENT GENERATION OF NEUTRINO EXPERIMENTS

Neutrino Beamlines

All of the currently operating neutrino beamlines have a similar layout: the primary proton beam strikes a target producing pions and kaons. Those particles are focused by a horn-based system, consisting of one, two, or even three magnetic horns. Then a long decay volume follows, whose length is dictated by both the focused pion energy and the primary physics goals of the experiment: electron neutrino search experiments tend to have shorter decay volumes to minimize the electron neutrino background coming from muon decays, while the muon neutrino disappearance and tau appearance experiments have longer decay volumes to maximize muon neutrino production.

Booster Neutrino Beamline

The Booster Neutrino Beamline (BNB) began operations in 2004 and produces neutrinos using an incident proton beam of 8GeV from the Fermilab Booster. The beamline uses a beryllium target and a single focusing horn, and the decay pipe is relatively short to minimize the intrinsic electron neutrino content of the beam. The resulting neutrino beam spans a relatively broad range in energy, and is peaked at roughly 1.4 GeV. There are enclosures in the beamline for both the SciBooNE detector and the MiniBooNE detector.

This beamline has been operation for the longest of the beamlines discussed here. The current horn has worked for over 6 years and as of this writing has been pulsed more than 275 million times[3].

Neutrinos at the Main Injector

The Neutrinos at the Main Injector (NuMI) beamline began operations in 2005 and is produced using 120GeV protons from Fermilab's Main Injector. The protons are incident on a graphite target just upstream of the two-horn focusing system.

TABLE 1. This table summarizes the defining characteristics of the current and near term neutrino experiments.

Experiment	Primary Motivation	Beam Power (kW)	Detector	Baseline (km)	Neutrino Energy (GeV)	Integrated POT as of 10/2010
MiniBooNE	ν_e appearance	30 (Max)	Oil Cerenkov	0.5	0.7 (Wide)	15×10^{20}
MINOS	ν_μ disappearance	350	Steel Scintillator	734	3.5 (Wide)	11×10^{20}
OPERA			Lead/Emulsion	730	25 (Wide)	8×10^{19}
ICARUS	ν_τ appearance	500	Liquid Argon TPC	730	25 (Wide)	2×10^{19}
MINERvA	ν interactions	350	Scintillator	1.0	3.5 and 6	12×10^{19}
T2K	ν_e appearance	750 (100 so far)	Water Cerenkov	295	0.70 (Narrow)	3.4×10^{19}
NOvA	ν_e appearance	700	Scintillator	810	2.0 (Narrow)	-
MicroBooNE	ν_e appearance	30	Liquid Argon TPC	0.5	0.7 (Wide)	-

The design of the target is such that it can be placed at different distances relative to the horns, which produces neutrino beams of very different peak energies. The bulk of the running with NuMI so far has been in what is called the low energy setting, which produces a broad energy spectrum peaked at 3.5 GeV. Alternate target positions are be used for special runs to better understand and constrain the flux of produced neutrinos. There is currently one near detector enclosure which is large enough to house both the MINOS near detector and the MINERvA detector, and there are plans underway for excavating another enclosure for the NOvA near detector. There are also four alcoves that have been excavated for muon monitors, three of which are currently instrumented to provide spill by spill measures of the relative muon rate and for additional flux studies.

The NuMI beamline has been operating for over five years, over which time the target has had to be replaced four times[4]. The two horns have each been replaced once. The beamline monitoring system has been extremely effective in checking for problems associated with the target and horns, perhaps even more than was envisioned at the time it was constructed.

CERN to Gran Sasso

The CERN to Gran Sasso beamline uses 400GeV protons on a graphite target and a two-horn focusing system to produce a high energy neutrino beam centered at about 25GeV to send to the Gran Sasso Laboratory. There are two enclosures for muon monitors to ensure efficient production of neutrinos in the beamline. The neutrino energy must be high enough so that any tau neutrinos which appear in the beam some 730km away in Gran Sasso are high enough in energy to overcome the mass suppression associated with a tau neutrino charged current event. The CNGS beamline has had to overcome problems associated with the horns, radiation shielding of the beamline electronics, and tritium in the cooling water, but the beamline is operating stably now and has integrated over 2.5×10^{19} protons on target in this year alone[5].

Tokai to Kamiokande

The neutrino beam at J-PARC is made from 40 GeV protons striking a graphite target that is part of a three-horn focusing system. This neutrino beamline is designed for the highest proton power of all the currently operating neutrino beams at 770 kW. The peak on-axis neutrino energy is at 2 GeV, but both the far detector is at an angle of 2.5 degrees with respect to the beamline axis and therefore see a much lower and narrower neutrino energy spectrum. The peak off axis energy is at about 600 MeV. There is a single enclosure for muon monitoring containing two different monitoring technologies, and a near detector enclosure that houses both on and off axis detectors.

The T2K neutrino beam has been in operation since January 2010, and as of the NuFact10 conference the beamline was just resuming operations after a summer shutdown to repair kicker magnets. The magnets were showing instability when the proton power was at 100 kW and as a result the proton spot was moving at an unacceptable level on the target. The new magnets that have been installed have passed functionality tests and are currently in use[6].

Neutrino Detectors

There are now several different neutrino detectors operating in conventional neutrino beams. These proceedings will give a brief description of all detectors but give more details on those detectors that have reached significant milestones in the past year.

MiniBooNE and MINOS

MiniBooNE uses 800 tons of mineral oil instrumented with phototubes to detect the Cerenkov light. In the past few years MiniBooNE has improved its reconstruction techniques and can now identify charged current events where a neutral pion was also produced by looking at three-ring events[7]. Also, MiniBooNE has developed a special charged pion tag that makes use of the decay chain from pion to muon to electron[8].

MINOS uses two detectors, one near (1kton) and one far (5.4kton), that are comprised of alternating planes of 2.54cm thick steel plates and 1.0cm thick planes comprised of solid scintillator bars with alternating views for tracking[9]. There is a coil through each detector to create on average a 1.1Tesla field in the fiducial region of each detector. MINOS is optimized to distinguish between the presence and absence of a final state muon, and has also been able to identify on a statistical basis the presence of neutral current and electron neutrino charged current interactions.

OPERA

OPERA uses 300 micron thick sheets of emulsion interspersed with 1mm thick lead sheets that are assembled into bricks which are then stacked to form walls of very sensitive (but time-integrating) target material of total mass 1.8 ktons. Downstream of each wall of bricks are tracking detectors that are read out after each spill and analyzed. When tracks point back to a specific brick, that brick is removed from the wall and then scanned to look for tau decays. These decays are visible by the presence of a kink in the track that is due to the missing energy taken by the neutrino in the tau decay.

Because the analysis requires a kink in the track, backgrounds from other neutrino interactions are extremely low, with the largest background coming from charm decays. The OPERA experiment collected 5391 events in the 2008-2009 run, and found in those events a total of 1921 neutrino vertices. A decay search was performed on 1088 events, and a tau neutrino candidate passing all cuts was found out of this first run, which represents 35% of the total exposure accumulated in 2008-2009. Assuming a mass squared splitting of $2.3x10^{-3}eV^2$ and full mixing, 0.5 tau neutrino charged current events were expected, and substantially less background. There were also six electron neutrino candidates found out of 800 located vertices. As of the NuFact10 conference OPERA had collected roughly 35% of its total exposure[10].

ICARUS

ICARUS uses 950 tons (600 fiducial) of liquid argon instrumented with some 54000 wires to produce a time projection chamber that gives bubble-chamber like images of neutrino interactions on argon. The wires have a 3 mm pitch and there is a 1.5 m drift distance between the successive wire planes. Because argon also scintillates there are 74 phototubes that are used to collect the scintillation light. Although ICARUS cannot provide event by event classification of tau neutrino interactions, the detector can statistically separate tau neutrino charged current events from other events by looking at variables related to the total missing energy and momentum in the event, and the amount of electromagnetic energy in the event (which would come in signal events from tau decays to electrons).

ICARUS started operations this year in the CNGS beamline and has started demonstrated that the detector is functioning well and can identify muon neutrino charged current events, hardonic and electromagnetic showers, and secondary vertices[11].

MINERvA

MINERvA is unique among new experiments operating this year in that it is the first new experiment completely dedicated and optimized to study neutrino interactions on several different nuclei. The MINERvA detector consists of finely segmented scintillator planes that surround several different passive nuclear targets as well as a totally active target region comprised of scintillator read out by multi-anode phototubes. The targets currently in the detector are of carbon, lead, and iron. Additional targets of water and liquid helium under construction. The detector is surrounded by electromagnetic and hadronic calorimetry to ensure event containment, and can make use of the MINOS Near detector for some muon reconstruction[12].

MINERvA started operations this year, after running for several months with a partially complete detector in antineutrino mode in the fall of 2009. The detector is functioning well and event reconstruction is well underway.

T2K

T2K uses the Super-Kamiokande water Cerenkov detector as its far detector, which has been described in detail in many other works[13]. The near detector complex located 280 downstream of the target consists of several different fine-grained detectors at an off axis location similar to the far detector, and a more coarse-grained on-axis detector that extends across many meters and serves to measure the neutrino beam center. The fine grained detectors are in a 0.2 Tesla magnetic field, and have side calorimeters for event containment.

The various parts of the near detector focus on different goals: the scintillator-based P0D detector is optimized to study electromagnetic final states produced when neutrinos interact in water. The Fine Grained Detector (FGD) downstream of the P0D consists of scintillator and water targets followed by Time Projection Chambers for very precise tracking of multi-particle final states[14].

This year T2K saw its first neutrino interactions, and has been commissioned and is currently operating smoothly. Events have been recorded in all of the different target regions of the detector and analysis is underway. This year also signals the recording of the first events from the J-PARC beamline at the Super-Kamiokande detector.

THE NEXT GENERATION

The NOvA experiment will use liquid scintillator-based detectors (one near and one far) to search for electron neutrino appearance in a muon neutrino beam at a baseline of 810 km. The experiment is currently in the construction phase: the far detector building and is progressing, and the near detector is currently being commissioned 107 mrad from the NuMI beamline before being installed in its final location. The NOvA near detector sees a relatively narrow 2 GeV muon neutrino peak there coming from kaon decays, as well as a broad 1 GeV electron neutrino peak coming from three-body decays in the beamline. This will be the first chance to verify that the detector performs as expected[2].

The MicroBooNE experiment is designed to both extend the reach of the Booster Neutrino Beam electron neutrino search, and to understand new possible designs for a liquid argon TPC that would be suitable for large scale detectors. By measuring the liquid argon TPC performance at low energies and high statistics this experiment will serve as an important benchmark for not just the cryostat design, but also the TPC technology which is proposed for several future low energy neutrino experiments. Two characteristics that make MircoBooNE a prototype for future hundred kiloton devices are the long drift length between wire planes (2.5 m maximum) and the goal of achieving acceptable argon purity without having to pump the cryostat down to vacuum[15].

THE GENERATION BEYOND

While the field is pursuing these complimentary efforts towards determining if the last unknown mixing angle is larger than zero, there are yet more ambitious plans that are in the making. These plans are necessary to be able to determine the neutrino mass hierarchy and to probe CP violation. These are much more challenging goals and as such will require substantially more proton power and detector mass than is currently available.

Two strategies are being considered to achieve these goals: one is to use a broad band beam of neutrinos so that both the first and second oscillation maxima are visible in the appearance channel. The matter and CP-violating effects are very different between the first and second maxima and accessing both simultaneously will help untangle those effects. The challenge with this type of beam is being able to model the backgrounds to these channels down to very low energies. The second strategy is to use a narrow band beam that focuses only on the first oscillation maximum, similar to what T2K and NOvA are currently pursuing but with higher statistics. The strategies under consideration depend on many factors, including geography and already existing resources such as underground mines or already existing high power accelerators.

The LBNE experiment proposes to build a new beamline at Fermilab that will send a wide energy beam peaked at 2.4 GeV to the Deep Underground Science and Engineering Lab (DUSEL) for a baseline of 1290 km. There are also plans to extend the reach of the neutrino beam at J-PARC by building additional far detectors that are even larger than the Super-Kamiokande detector. Three options being considered are Korea, Okinoshima Island (which would be on axis) and adding a much larger detector very close to Super-Kamiokande to focus on the first maximum. There are also considerations of a new low energy conventional beam that would send neutrinos to Frejus or elsewhere, which would be a broad band neutrino beam. See reference [16] for a more complete overview of these options.

THE GENERATION BEYOND

There are many lessons that the current generation of neutrino experiments can teach the next generations. The first lesson is that the ramp up in proton power may not go as quickly as planned. The current conventional beamlines are taking huge steps in intensity past previous neutrino beams and because of this, new problems arise which invariably delay operations. For example, the NuMI beamline ran on average at twice as high an intensity in the second two years of operation compared to the first two years of operation[4]. The CNGS beamline had to overcome difficulties for the first two years before hitting the high intensities that it is currently enjoying[5]. A corrolary to this first lesson is that radiation shielding needs are usually greater and more complex than originally envisioned.

The next lesson is that the event rates you originally planned when you designed the experiment may not hold out to be correct. For example, the NuMI event rates in the high energy region was up to 40% higher than predicted by the available hadron production models[17]. Finally, the cross sections assumed when an experiment is proposed are uncertain. For example, when the MINOS experiment first predicted the electron neutrino backgrounds at the near detector, they predicted 20% more events than what was actually seen in the data[18]—this lead to a re-evaluation of the neutral pion production in hadronic showers. Also, both MiniBooNE and SciBooNE are seeing higher quasi-elastic cross sections than were originally expected[19].

In summary, this has been an extremely exciting year for conventional neutrino beam operations. T2K, ICARUS, and MINERvA have all seen beam on their fully installed detectors for the first time. OPERA has found the first tau neutrino candidate. The NOvA Near Detector has been assembled and is taking data in a 2 GeV neutrino beam. The following year promises to be equally busy and exciting for conventional neutrino beam experiments.

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