Physics at the NuMI Beam

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This contribution to the proceedings of the 2010 NOW Workshop summarises the latest results from the MINOS experiment and talks about the future prospects for the MINERνA and NOνA experiments. Descriptions of the Fermilab NuMI neutrino beam, its performance and future potential as well as that of the associated accelerator complex are also given.

1. Introduction

The Neutrinos at the Main Injector (NuMI) beam at Fermilab produced its first neutrinos in 2005 and a stream of physics results have been forthcoming over the past six years. The MINOS experiment has observed neutrino oscillations at the atmospheric scale with high significance and in doing so made the world's most precise measurement of Δm^2_{atm} along with a host of other results. Starting on 29th September 2009 NuMI ran for six months in dedicated antineutrino mode. MINOS observed a difference in the extracted antineutrino oscillation parameters with respect to neutrinos at the two sigma level and this is now being followed up with a second period of antineutrino data taking that started on 1st November 2010.

The MINERνA neutrino scattering experiment is now constructed and operational in the MINOS underground hall at Fermilab. Detector performance is good and first results are expected in 2011. As part of a test project the ArgoNeuT liquid argon detector collected neutrino data in 2009/10. The Fermilab schedule for the future envisages a long shutdown in 2012 to upgrade the NuMI beam line and various parts of the Fermilab accelerator complex for the long-baseline NOνA experiment, which is currently under construction. The NOνA detectors are designed to optimise the search for electron neutrinos that may appear in the muon neutrino beam as a consequence of a non-zero θ_{13}.

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This article is divided into two main sections: the first discusses the NuMI beam; and the second talks about experiments using the neutrinos.

2. The NuMI Beam

This section gives an overview of how the neutrino beam works and details its operation. Sustained high power accelerator performance is a critical issue for many neutrino experiments as is the feasibility of future operation at powers approaching the megawatt scale. For these reasons a description is given herein of the accelerator complex at Fermilab, particularly from the perspective of the next generation of accelerator neutrino experiments.

The significant milestone of accelerating 10^{21} protons onto the NuMI target was achieved in 2010.

For additional details on the NuMI beam beyond those presented here the reader is referred to [1,2]. Furthermore, Fermilab produces a series of guides that give a nice overview of almost all of the various accelerators and beam lines [3].

2.1. Neutrino Production

Production of neutrinos in the NuMI beam starts just after the 120 GeV protons from the Main Injector (MI) accelerator strike a 2.0 interaction length segmented graphite target. Two magnetic horns operating at 185 kA focus the resulting pions and kaons: when operating in neutrino (antineutrino) mode positive (negative) mesons are focused and the opposite sign defocused. A 675 m long decay pipe, previously evacuated but now filled with helium, gives the mesons and tertiary muons time to decay. A hadron absorber at the end of the decay pipe stops any remaining hadrons leaving only muons and neutrinos. The muons are then removed from the beam by about 250 m of rock, leaving just the neutrinos.

The composition of the NuMI beam when operating in low energy mode and as sampled by the MINOS Near detector is as follows. In neutrino mode the beam comprises of 91.7% ν_μ, 7.0% $\overline{\nu}_\mu$ and 1.3% $\nu_e + \overline{\nu}_e$. In antineutrino mode the composition is 39.9% $\overline{\nu}_\mu$, 58.1% ν_μ and 2.0% $\nu_e + \overline{\nu}_e$, however, these figures are potentially misleading at first glance since the composition is strongly energy dependent (and also off-axis angle dependent). To first order, the magnetic horns are only responsible for the peak in the spectrum and the "high-energy tail" (events above around 10 GeV in low energy running) is actually the same in both neutrino and antineutrino mode. The reason for this is that the mesons producing the high-energy tail travel down the centre of the horns where the magnetic field is zero. In the "focusing peak", below about 6 GeV in low-energy running, the antineutrino beam is dominated by muon antineutrinos.

The NuMI beam was designed to be tunable. The most dramatic effect on the energy spectrum comes from moving the position of the target relative to the first magnetic horn. The vast majority of NuMI running has been with the target deep inside the first horn to produce a spectrum that peaks as low as possible at 3 GeV. At the other extreme, about 2% of NuMI running has been with the target pulled 2.5 m back out of the horn to give a neutrino spectrum that peaks at 10 GeV. Data with other special beam configurations have also been taken for short periods: including horn currents of ±15 kA and several intermediate target positions. It is also possible to change the separation of the two horns but to date this has not happened since it would take of order a month to implement: the horns have always been placed in the configuration that gives the greatest flux at low energies.

For future NOνA running the plan is to move the horns further apart to a so called "medium energy" position. Combining this with the target pulled back out of the first horn by 1 m optimises the neutrino flux at low energies for NOνA's 14 mrad off-axis detector position. On-axis the beam will peak at around 7 GeV, which is relevant for MINERνA and other experiments operating in the MINOS Near detector underground hall at Fermilab.

2.2. The Fermilab Accelerator Complex: Present and Future

An overview of the accelerator complex, very much from the neutrino physicists point of view is given here. A particular focus of this section is on the two key factors that dominate the NuMI beam upgrade from the current 320 kW operation to the planned future operation at 700 kW. These are:

- Using every proton batch from the MI for neutrino production.
- Eliminating the time it takes to fill the MI before acceleration begins.

The chain of acceleration steps from the start all the way to the NuMI target is as follows: the 750 keV H^- ion source; the 400 MeV H^- ion linac; the 8 GeV "Booster" proton synchrotron and lastly the 120 GeV "Main Injector" proton synchrotron. This article will focus primarily on the Booster and MI steps.

The Booster operates at 15 Hz, which means it takes 1/15th of a second to both fill the ring and then accelerate protons to 8 GeV. The circumference of the Booster is approximately 1/7th that of the MI. With spaces between them, six batches of protons from the Booster fill the circumference of the MI ring. However, in 2007 a new MI operational mode called slip-stacking was brought into operation for NuMI. When slip-stacking, initially five batches of protons are injected from the Booster into the MI. Then into the remaining gap a bunch is injected and slowly moved, or "slipped", around the ring relative to the other five bunches until it lines up with an existing bunch. This process is repeated a further four times, then the last (11th) bunch just fills the remaining gap. When the Tevatron is running two of the eleven batches are used to make antiprotons and nine are used for to make neutrinos. During regular operation there are short periods when anti-proton production does not need to occur and during those times the NuMI beam intensity increases by a factor of 11/9. Similarly, should the Tevatron be shut down for maintenance then the NuMI beam benefits. At the time of writing, the mechanics of extracting the two slip-stacked batches onto the antiproton production target while leaving the remaining nine batches in the MI makes inserting a 12th batch problematic. However, in future, when the Tevatron is no longer operating it will be possible to run the MI with 12 batches all going to NuMI thus giving a factor of $12/9 = 1.3$ intensity gain compared to present operation.

At present the protons from the Booster are transferred directly into the MI. At 15 Hz, filling the MI with eleven batches thus takes about $1/15 \times 11 = 0.73$ seconds. The time taken to accelerate the protons from 8 to 120 GeV is about 1.5 seconds giving an overall duty cycle of 2.2 seconds. There are clearly two ways to improve the overall performance: reduce the acceleration time and reduce the filling time. In 2012 some improvements to the MI, including increasing the number of RF stations from eighteen to twenty and installing new quadrapole transformers will reduce the acceleration time by 0.15 seconds. However, the really major improvement will come from reducing the MI filling time from 0.7 seconds to 11 microseconds. This will be achieved by parallelising the production of protons and their acceleration.

In the same tunnel that houses the MI synchrotron there is an 8 GeV fixed field storage ring called the “Recycler”, which at present is used to store antiprotons after they are produced but before they are injected into the Tevatron. Once the Tevatron shuts down it is relatively straightforward to adapt the Recycler so that it accepts 8 GeV protons straight from the Booster. Thus while the MI is accelerating protons to 120 GeV the Recycler will be filling and slip-stacking the next set: transferring the protons from Recycler to MI takes a single turn (one revolution of protons in the ring), which is a negligible 11 microseconds. These relatively straightforward improvements to the duty cycle of the MI will mean 2.2 seconds is reduced to 1.3 seconds, thus delivering a factor of 1.7 times more power.

Overall, the power of the NuMI beam will be upgraded from 320 kW to 700 kW by making the relatively straightforward changes described above. In summary, the number of batches will increase from 9 to 12 giving a factor of 1.3 increase in power; and additionally the reduction in the MI cycle time will give a factor of 1.7. These two factors are multiplicative thus giving the overall factor of 2.2 required to reach 700 kW.

The time scale for implementing the upgrades to the accelerator complex is strongly coupled to the Tevatron's schedule. On 27th August 2010 the Fermilab Physics Advisory Committee strongly recommended a three year extension of the Tevatron operation to 2014 [4]. This was followed on 26th October 2010 by a report from the P5 subpanel of HEPAP [5], which made two recommendations: firstly, to proceed with the three-year Tevatron extension provided additional resources can be found by the funding agencies; and secondly, that Fermilab make a strong effort to minimise the effect on NOνA. The provision of extra funding is dependent on the US President's proposed budget, which at the time of writing was not published.

In the scenario of NOνA running in parallel with the Tevatron the NuMI beam power would be limited to 400 kW. The Tevatron requires use of the Recycler thus the large reduction in duty cycle that comes from parallelising the accumulation of 8 GeV slip-stacked protons and their acceleration to 120 GeV would not be attainable.

3. The Experiments

A number of experiments have used the NuMI beam since it produced its first neutrinos in 2005 and there are experiments that plan to study NuMI neutrinos until near the end of this decade. These experiments can be divided into two groups: long-baseline neutrino oscillation experiments with a remote detector and experiments performed entirely on-site at Fermilab.

3.1. Long-baseline Neutrino Oscillation Experiments

The long-baseline neutrino oscillation experiment currently running at Fermilab is MINOS for which the NuMI beam was initially constructed. The second generation experiment, NOνA, is currently under construction. These experiments follow the same basic principle of making a relative measurement between two similar detectors. In both cases a Near detector at Fermilab measures the NuMI beam composition, energy spectrum and backgrounds to various neutrino event categories; a Far detector is then used to search for oscillations. To allow the neutrinos time to oscillate the MINOS (NOνA) Far detector is located 735 km (810 km) from the NuMI target. MINOS is situated along the central axis of the beam while NOνA is situated 14 mrad off-axis where the flux of low energy neutrinos is increased and the high energy tail is substantially reduced (enhancing the oscillation signal to background ratio).

3.1.1. MINOS

Several new MINOS results were released in 2010 [6] using data from an increased exposure of 7.25×10^{20} protons on target (POT), double that previously published [7–10]. An updated disappearance analysis of muon neutrino charged current events gave a preliminary result of $\Delta m^2_{atm} = 2.35^{+0.11}_{-0.08} \times 10^{-3}$ eV^2 vs. $\sin^2(2\theta) > 0.91$ at 90% C.L. The contour in Figure 1 shows the allowed region as a function of Δm^2_{atm} vs. $\sin^2(2\theta)$ overlaid with other precision measurements.

Data from an exposure of 1.71×10^{20} POT was collected with NuMI operating in dedicated antineutrino mode. MINOS consequently made the first direct observation of muon antineutrino disappearance. With this exposure 155 events were predicted to be observed in the Far detector muon antineutrino sample assuming no oscillations. Only 97 events were observed, disfavouring the null oscillation hypothesis for antineutrinos at 6.3 σ. Figure 2 shows the observed Far detector antineutrino energy spectrum along with the best oscillation fit and the no-oscillations prediction. Unexpectedly, some ten-

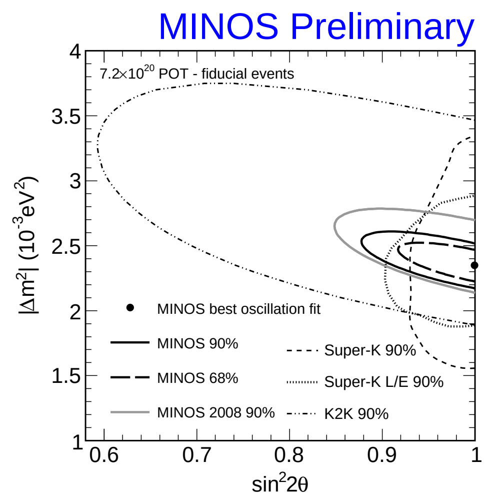

Figure 1. MINOS contours showing the allowed region as a function of Δm^2_{atm} vs. $\sin^2(2\theta)$. Results from other experiments are shown [11–13].

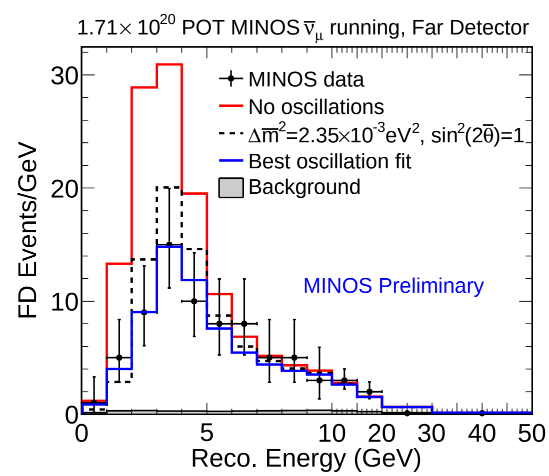

Figure 2. MINOS Far detector energy spectrum of selected muon antineutrino charged current events.

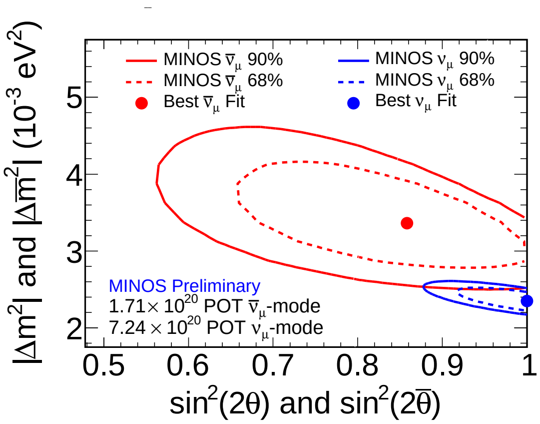

Figure 3. MINOS contours showing the allowed region as a function of $\Delta\overline{m}^2_{atm}$ and Δm^2_{atm} vs. $\sin^2(2\overline{\theta})$ and $\sin^2(2\theta)$.

sion was observed between the extracted oscillation parameters for antineutrinos compared to neutrinos at the 2 σ level. The preliminary results give the extracted antineutrino oscillation parameters as $\Delta\overline{m}^2_{atm} = 3.36^{+0.45}_{-0.40} \times 10^{-3}$ eV^2 and $\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$ at 90% C.L. Figure 3 shows the allowed region as a function of $\Delta\overline{m}^2_{atm}$ and Δm^2_{atm} vs. $\sin^2(2\overline{\theta})$ and $\sin^2(2\theta)$. This result is being followed up, and on 1st November 2010 NuMI started a second run in dedicated antineutrino mode. It is expected that the duration of this run will be about 8 months and that results will be available in summer 2011.

Also in 2010 MINOS reported new limits on the unknown third mixing angle, θ_{13}, via a search for electron neutrino appearance in the muon neutrino beam [14]. The number of events predicted to be selected in the Far detector with electron neutrino characteristics was 49.1 ± 7.0(stat.) $\pm$ 2.7(syst.). In the data 54 events were observed, which is 0.7 σ higher than expected with $\theta_{13} = 0$. The limit set on the value of θ_{13} is a function of four other oscillation parameters. In the normal mass hierarchy with $\delta_{CP} = 0$ and using MINOS best fit values for Δm^2_{atm} and $\sin^2(2\theta)$ a limit of $\sin^2(2\theta_{13}) < 0.12$ at 90% C.L. is set.

Additional new results include: a search for a sidereal modulation in the MINOS Far detector neutrino rate that set new limits on the parameters in the Standard-Model Extension theory [15]; further improvements to the limits on sterile neutrinos via the search for a deficit in the rate of neutral current events in the Far detector [16]; substantial improvements on previous experiments' measurements of neutrino and antineutrino inclusive charged-current cross sections from using the millions of events in the Near detector [17]; seasonal variations in cosmic rays [18]; observation of sudden stratospheric warmings with cosmic rays [19]; comparison of the Near and Far detector readout systems at a test beam [20].

3.1.2. NOνA

A detailed description of the NOνA experiment is given elsewhere in these proceedings [21]. Currently, NOνA is under construction and expects to start taking data with the first Far detector modules in mid-2012 before completion in mid-2013. The innovative detectors are of the so called "totally active scintillator detector" (TASD) design. Liquid scintillator will comprise 70% of the detectors' mass and the longitudinal sampling will be 0.2 radiation lengths giving excellent muon-electron separation and π^0 rejection capability. The Far detector's mass will be 14 ktons (or 18 ktons if funding permits). This huge detector will be a rectangular cuboid, measuring $15.7 \times 15.7 \times 67$ m^3 and consisting of 930 planes. The NOνA Near detector will have the same granularity but a smaller mass of 222 tons.

A major physics goals is the search for θ_{13} with a sensitivity down to $\sin^2(2\theta_{13}) < 0.01$. Should the value of $\sin^2(2\theta_{13})$ be above about 0.05 then NOνA will potentially be able to exploit its longer baseline and resolve the neutrino mass hierarchy.

3.2. Experiments located on the Fermilab site

The MINOS underground hall at Fermilab currently hosts the MINERνA experiment (situated in front of MINOS) and previously ArgoNeuT and PEANUT were also located there. An extension, off to one side of the hall, will be constructed for the NOνA Near detector.

3.2.1. MINERνA

MINERνA is a dedicated neutrino scattering experiment that aims to map out and study the physics of the neutrino-nucleus interaction in the 0.5 to 20 GeV region. Construction of the MINERνA detector is complete except for the water and helium targets. The detector has a fine-grained tracking calorimeter and uses the MINOS Near detector as a muon spectrometer. The first data set was collected at the end of 2009 with NuMI operating in antineutrino mode, which was followed by neutrino data in 2010 and then further antineutrinos. Many analyses of the data are underway with everything on track for a useful and interesting set of measurements in the near future. For further details see [22,23].

3.2.2. ArgoNeuT and PEANUT

ArgoNeuT was a test project to operate a liquid argon TPC (LArTPC) in a neutrino beam with the goals of: gaining experience of building and running a LArTPC; accumulating neutrino and antineutrino events; developing simulation and reconstruction for LArTPCs; and comparing data to MC [24]. For further details see [25]. PEANUT was a small ν-interaction experiment that used nuclear emulsions and scintillator detectors to measure low energy ν cross sections [26].

4. Conclusion

Much exciting physics has been accomplished using neutrinos from the NuMI beam over the last six years, with MINOS as the flagship experiment. Highlights include: the world's most precise measurement of $\Delta m^2_{atm} = 2.35^{+0.11}_{-0.08} \times 10^{-3}$ eV^2; new limits on θ_{13} via a search for electron neutrino appearance; and the first direct observation of muon antineutrino disappearance.

The second phase of NuMI operation is getting underway: MINERνA is currently taking neutrino scattering data; and the NOνA detectors' construction is progressing rapidly. A straightforward upgrade of the NuMI beam from 320 to 700 kW is scheduled for 2012 (400 kW if the Tevatron run extension goes ahead). It's an exciting future for physics at the NuMI beam. Stay tuned!

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