MicroBooNE: Searching for new physics in the neutrino sector with a 100-ton-scale liquid argon TPC

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Abstract. The MicroBooNE experiment, a 170 ton liquid argon TPC, is currently under construction in the Booster Neutrino Beamline at Fermilab. These proceedings describe the MicroBooNE detector, and the experiment’s physics goals, focusing on MicroBooNE’s sensitivity to interpretations of the “low energy excess” observed by the MiniBooNE experiment, as well as its sensitivity to light sterile neutrino oscillations, both as a single detector and in combination with a second kiloton-scale liquid argon TPC in the same beamline.

1. The MicroBooNE Experiment
MicroBooNE serves as a demonstration experiment for the liquid argon time projection chamber (LArTPC) technology, which is being pursued for future large-scale neutrino detectors, such as LBNE [1]. MicroBooNE’s detector size (170/60 metric tons of total/fiducial liquid argon mass) allows for reaching important R&D milestones for a phased program currently being followed in the United States to multi-kiloton scale LArTPC’s, while providing high-statistics neutrino event rates for producing meaningful physics results. The present run plan for MicroBooNE projects data collection commencing in early 2014 and extending over ~2-3 years of running in neutrino mode, for a total of $6.6 \times 10^{20}$ protons on target.

The MicroBooNE detector will be located on surface in the Fermilab Booster Neutrino Beamline (BNB), ~470 m downstream from neutrino production. The neutrino beam is sign-selected to provide a high-purity $\nu_\mu$ (present plan) or $\bar{\nu}_\mu$ beam. Protons with 8 GeV kinetic energy are incident on a beryllium target producing charged mesons. Positively charged mesons are forward-focused (toward the detector) and allowed to decay in a 50 m long decay tunnel, producing primarily a $\nu_\mu$ beam, with a small wrong-sign ($\bar{\nu}_\mu$ and $\bar{\nu}_e$) and intrinsic $\nu_e$ contamination, similar to that in [2].

The detector consists of a rectangular TPC inscribed within a cylindrical cryostat. The TPC forms the primary active detector component. Ionization electrons, produced when charged particles traverse the liquid argon volume contained within the TPC, are drifted toward three sensor wire planes on the beam right side of the TPC, under the influence of a 500 V/cm electric field. The TPC drift length is 2.5 m. The three wire planes are aligned at 90°, +30°, and -30° relative to the neutrino beam direction, so that the induced signals from the drifted ionization charge can be used to map out the three-dimensional trajectories of the charged particles produced, for example, in a neutrino interaction. A PMT array situated behind the TPC wire...
planes acts as a secondary active detector component, and is used to determine the absolute time of each neutrino interaction, by exploiting the scintillation light produced and reaching the PMT’s nearly instantaneously in each interaction. As such, the PMT signals are used to provide a trigger for any 1.6 $\mu$s-wide neutrino beam pulse which contains an interaction. The light collection system consists of 30 8-inch Hamamatsu low-temperature PMT’s and transparent plates coated on one side with wavelength-shifter for efficient scintillation light (produced in the UV range) detection.

The MicroBooNE TPC signals from the 8256 wires are read out by cold CMOS pre-amplifiers, shaped with a $\sim$1$\mu$s peaking time, digitized at 2 MHz with 12-bit resolution, and permanently stored after lossless data compression involving Huffman coding. The PMT signals from the 30 PMT’s are shaped with a 60 ns rise time, and digitized at 64 MHz. This fast digitization allows event timing determination with high resolution, and provides trigger conditions for reading out frames of interests from the TPC, such as in the case of beam events, calibration, etc. Continuous TPC readout is also available in one-hour cycles, albeit with some data reduction (not losslessly). The continuous stream provides an opportunity for supernova neutrino searches and rare event studies with MicroBooNE.

2. MicroBooNE’s Goals

2.1. R&D

MicroBooNE’s R&D goals include the demonstration of efficient electron/photon particle identification and differentiation; tests of liquid argon purity levels in a large, non-evacuated detector; the development and demonstration of operation of high channel-count cold electronics; and demonstration of the ability to efficiently collect beam-off data for nucleon decay background studies. Simultaneously, MicroBooNE will contribute to the development of data analysis tools to handle reconstruction of large data samples, and provide a cost scaling model for larger future LArTPC detectors.

2.2. Physics

The primary physics goals of MicroBooNE can be categorized under two main areas: neutrino cross section measurements, and investigation of the MiniBooNE “low energy excess” [3]. Secondary physics goals include searches for new physics such as short-baseline neutrino oscillations, and “R&D physics” such as measurements of cosmogenic backgrounds for nucleon number violating processes, and supernova neutrino detection.

The BNB energy range spans energies from 100 MeV to 3 GeV, which overlaps with those of T2K [4], NOvA [5] and LBNE. MicroBooNE is therefore able to perform a suite of neutrino cross section measurements of interest to next-generation neutrino oscillation experiments, including charged-current quasi-elastic (CCQE) scattering on argon, which is the most relevant interaction in that energy range. Sufficient understanding and knowledge of the CCQE cross section is crucial in the canceling of flux systematics in various oscillation search techniques. MicroBooNE will be able to study neutrino interactions in exquisite detail. The detector has high efficiency down to low energies (40 MeV proton), and together with energy and position resolution it can exploit resolution of activity at the interaction vertex to observe nuclear debris and constrain nuclear effects, which contribute to the CCQE cross section uncertainty. Additionally, MicroBooNE will be able to contribute to measurements of coherent/resonant pion production, and possibly electron neutrino cross section measurements. Rare channels such as neutral-current kaon production and charged-current kaon production may also be accessible, given sufficient statistics, thus contributing to neutrino meson production measurements, which have received increasing interest following recent MiniBooNE measurements.
3. Sensitivity to New Physics

3.1. MiniBooNE Low Energy Excess

MicroBooNE’s expected excellent electron versus photon differentiation capabilities, and its high electron detection efficiency, provide advantages over MiniBooNE for further studies of the MiniBooNE low energy excess. The excess seen in MiniBooNE in neutrino running in reconstructed neutrino energies of 200-475 MeV has a 3σ significance and is consistent with either single electron production or single photon production via neutrino scattering on carbon.

Single electron production could simply be contributed by $\nu_e$ or $\bar{\nu}_e$ in the beam interacting via charged-current scattering, in which case the excess could be the result of a mis-estimated $\nu_e$ or $\bar{\nu}_e$ background, or the result of $\nu_\mu \rightarrow \nu_e$ oscillations at high $\Delta m^2$, which have also been proposed as an interpretation of the anomalous LSND excess [6]. A dedicated oscillation search in MiniBooNE finds the excess shape incompatible with oscillations of that type [3]. Single photon production can be mediated by resonant $\Delta$ production in neutrino-nucleus scattering followed by $\Delta$ radiative decay. That particular contribution however has been constrained by in situ measurements of $\Delta$ production followed by the cleanly identifiable $\pi^0$ production and decay in MiniBooNE. Other photon interpretations have been suggested as explanations, and remain plausible, including anomaly-mediated photon production [7].

MicroBooNE is expected to resolve the MiniBooNE low energy excess as either electron-like or photon-like, with a signal statistical significance of 5.7σ or 4.1σ, respectively. The increased sensitivity relative to MiniBooNE results from a two-fold increase in overall $\nu_e$ efficiency, combined with a high $e/\gamma$ differentiation, which further reduces single-photon, neutral-current-induced backgrounds in the reconstructed $\nu_e$ sample. Increased sensitivity is possible by extending the analysis down to tens of MeV.

3.2. Light Sterile Neutrino Oscillations

Having the properties of a near-ideal single-electron detector, MicroBooNE has sensitivity to new physics which would manifest via $\nu_e$ or $\bar{\nu}_e$ appearance, such as light sterile neutrino oscillations. Despite being a factor of five times smaller than MiniBooNE, the improved detection and particle identification of MicroBooNE leads to comparable sensitivity to MiniBooNE’s, for similar beam running. MicroBooNE’s sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillations is shown in Fig. 1 (left), contrasted to the LSND allowed $\sin^2 2\theta$ and $\Delta m^2$ parameters from a corresponding $\nu_\mu \rightarrow \nu_e$ search.

4. Sensitivity Studies Beyond the Present MicroBooNE Plan

The physics goals discussed in the previous sections are part of the approved and presently planned MicroBooNE running. The following section presents an example path for MicroBooNE Phase II running, with a second, larger LArTPC (LarLAr) detector in the BNB. This second LArTPC is assumed to have a 1 kton total liquid argon mass, and be located at 700 m from the BNB proton target. Possible two-detector configurations for MicroBooNE and LarLAr in the BNB include: (a) MicroBooNE at 470 m (present location) and LarLAr at 700 m; (b) MicroBooNE at 200 m and LarLAr at 700 m; and (c) MicroBooNE at 200 m and LarLAr at 470 m (present MicroBooNE location).

Figure 1 (right) illustrates the sensitivity to sterile neutrino oscillations assuming a combined MicroBooNE and LarLAr running for a total of $6.6 \times 10^{20}$POT in neutrino mode. A near/far comparison provides increased sensitivity to LSND-like oscillations, with a potential coverage of the LSND allowed region at 5σ, assuming two-neutrino oscillations. The estimated sensitivity is independent of MicroBooNE’s location in the neutrino beam (200 m or 470 m). Note that the curves assume no systematic uncertainties.

Corresponding sensitivity curves are shown for potential antineutrino running in Fig. 1 (middle). Because of reduced statistics, the coverage of the LSND allowed region is reduced...
to less than $5\sigma$; however, extended antineutrino running could be possible and would improve the combined sensitivity.

![Figure 1](image1.png)

**Figure 1.** Left: MicroBooNE-only sensitivity to two-neutrino oscillations, corresponding to $6.6 \times 10^{20}$ POT in neutrino mode running. Right and Middle: MicroBooNE and LarLAr combined sensitivities to two-neutrino oscillations, corresponding to $6.6 \times 10^{20}$ POT in neutrino mode and antineutrino mode running, respectively. The two-detector configuration assumed is (a) MicroBooNE at 470 m and LarLAr at 700 m.

5. Summary

MicroBooNE, a 100-ton-scale LArTPC experiment is now beginning detector construction. It is expected to be operational and commencing data collection in the Fermilab BNB (at the 470 m location) in 2014. It aims to reach valuable R&D goals for future-generation, large-scale LArTPCs, and well-defined and motivated physics goals, spanning neutrino cross sections, light sterile neutrino oscillations, studies of nucleon number violating processes and backgrounds, direct tests of the MiniBooNE low energy excess, and supernova neutrino detection. In addition, if offers the possibility of an enhanced neutrino physics program at the Fermilab BNB in combination with a second, $\sim 1$ kton LArTPC detector.

References

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