LArIAT-II Physics Goals & Requirements

Our primary goal is to conduct a study of particle interactions inside a liquid argon TPC with a large event sample, a well characterized and controlled beam, stable operating conditions, and good external particle identification. Testbeam studies of this sort have commonly been performed as technology R&D ventures (DREAM/CERN-RD52 and CALICE are recent examples) and in support of larger experiments at the energy and intensity frontier. The global HEP community is planning to construct one or more large, multi-kiloton liquid argon TPCs to study neutrino oscillations but, to date, no comprehensive testbeam study of LArTPCs has been carried out. We intend to remedy this situation. In detail, we plan to study the following:

Energy Reconstruction

Neutrino interactions produce final states with one or more hadrons and leptons whose energy needs to be measured in order to reconstruct the neutrino energy. We will take data to explore energy reconstruction in a few ways.

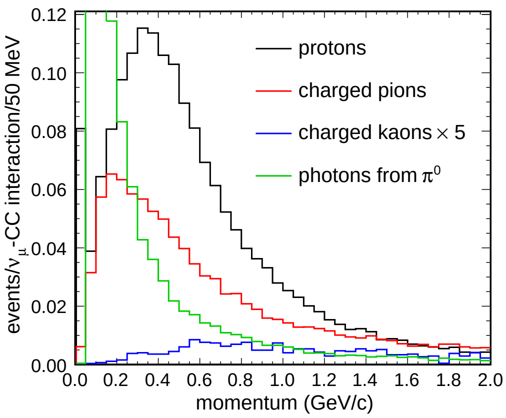
First, we'll explore the viability and performance of "traditional" calorimetry. In this approach, the electrons ionized by charged tracks induce signals in the TPC wire planes that are directly related to the energy of the primary particle. For hadrons, this ionization energy accounts only for a portion of the incident energy, the rest being lost to binding energy as multiple low energy protons and neutrons are liberated from nuclei participating in the cascade. The neutrons may also leave the few meter region around the hadronic interaction and, as their energy decreases, participate in soft interactions not visible to the detector. Finally, pion and muon decays produce neutrinos which are responsible for additional missing energy. Therefore the detector's calorimetric response to hadrons is generally expected to be smaller than the response to electrons and muons. The hadronic shower process is complex and depends on the composition of the calorimeter. Monte Carlo codes have improved much in recent years but still cannot be expected to offer *ab initio* predictions of the calorimetric response with uncertainties at the few % level needed by oscillation experiments. We will want to study the response to incoming electrons, pions and protons with energies in the range interesting for oscillation experiments, roughly 200 MeV–2 GeV as shown in Fig. 1a. We'll quantify energy deposition both along the beam direction and transverse to it and compare the data to MC.

Second, energy deposition in liquid argon also produces scintillation light which can be detected by photosensors placed inside the cryostat. We plan to measure the scintillation based calorimetric response of the TPC, and study how the scintillation and ionization signals can be combined to yield an optimal measurement of particle energies.

Third, LArTPCs are able to observe the fine details of hadronic interactions. We plan to study how well one can augment traditional calorimetry with information about the event topology, such as the kinematics information and identity (pion vs proton) of secondary tracks. In addition, events in which a high energy neutron carries energy away from the interaction point may also be possible to identify via momentum balance. Correcting for that effect could enhance the energy resolution.

Particle Identification

Particle identification is crucial to establish the neutrino flavor in charged current neutrino interactions and distinguish between charged and neutral current interactions. We will study the way in which LArTPCs can distinguish between particle species using a variety of techniques. First, we'll explore the way in which the energy deposition at the start of electromagnetic showers can be used to distinguish electron induced showers and photon induced showers, leveraging the fact



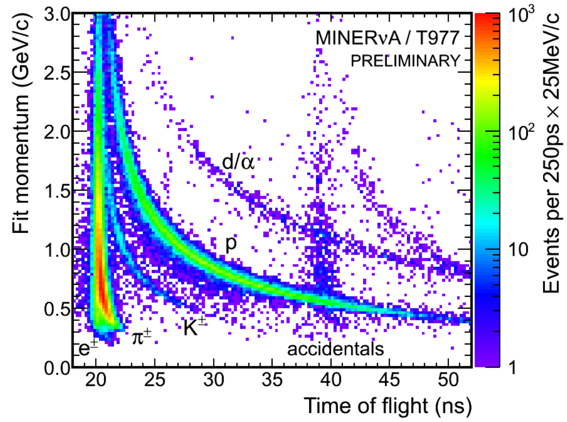


Figure 1: (a) Particle spectra created in neutrino interactions in the NuMI low energy beam, similar to the planned beam from Fermilab to Homestake. (b) The PID capabilities and momentum coverage achieved in T977, the MINERvA beam test which ran in the Fermilab meson test area.

that photon showers begin with $\gamma \to e^+e^{-1}$. Second, we'll study how well dE/dx can be used to distinguish electrons, pions, kaons and protons over the full range of energies relevant to oscillation experiments. Third, we'll study the way in which particle interaction and decay topologies may be used to augment the dE/dx information, allowing one to recognize neutral pions, the $\pi \to \mu \to e$ decay chain, pion absorption (sensitive to the charge sign), and other topologies.

Hadronic Cross-sections

The elastic and inelastic cross-sections for pion and proton scattering off argon are not well known and, aside from being interesting in their own right, are closely related to the final state interactions (FSI) that neutrino produced hadrons experience. The interactions cause uncertainties when reconstructing the neutrino flavor and energy. Modern neutrino interaction codes, such as GENIE, use hadron nucleus data directly in parametrized "hA" models of FSI and also to judge the accuracy of cascade based "hN" models [1]. We propose to measure the total and reaction cross-sections for incident pions and protons as a function of energy from 200 MeV to 2 GeV. We also propose to measure the multiplicity of charged and neutral pions and protons produced in these interactions to distinguish different scattering channels and study pion absorption. Finally, neutrino induced coherent pion production $\nu A \to \nu' \pi^0 A$ is a background to ν_e charged current interactions, possibly limiting measurements of θ_{13}, the mass hierarchy and the CP phase. Models for neutrino induced coherent pion production rely on knowledge of the $\pi^\pm A \to \pi^\pm A$ scattering cross-section as a function of energy transfer t at low energy transfers. We propose to measure $d\sigma/dt$ for incident pions across the energy range accessible in our experiment.

Other Measurements

The physics program will require us to precisely calibrate the detector, understanding and correcting for wire to wire variations in response, the attenuation of charge over the drift direction, non-uniformity of the electric field, and any time dependent effects. We'll also need to understand the absolute ionization and scintillation yields per MeV of deposited energy, and the manner in which electron-ion recombination and quenching can decrease those yields. These calibration measurements will be done with a combination of beam muons, cosmic ray muons and Michel electrons.

[1] This is also a goal of the first phase of LArIAT.

Finally, since the detector will operate on the surface we will be able to understand the impact that cosmic ray pileup is likely to play in larger TPCs, like the one planned for LBNE. Moreover, the tunable test beam intensity will allow us to explore pileup issues relevant for LArTPC near detector for oscillation experiments.

Detector Requirements

The TPC must be large enough to offer good longitudinal and transverse containment for hadronic cascades, at least in the lower portion of the 200 MeV-2 GeV energy range, the portion most important for oscillations. The TPC must also be small enough to fit into an affordable cryostat with a flanged lid. The readout granularity should be comparable or better than that envisioned for upcoming oscillation experiments such as MicroBooNE and LBNE. Those experiments have three readout views, $0°, \pm 60°$ with a 3 mm pitch in the case of MicroBooNE and $0°, \pm 45°$ with a 5 mm pitch for LBNE. The readout electronics must assure that the signal/noise ratio is similar or superior to those experiments. Finally, the detector must have a cost that isn't too large.

MC studies indicate that a TPC 3.0 m long and $2.0 \times 2.0\,\mathrm{m}^2$ wide is large enough to offer sufficient containment and small enough to fit within an affordable cryostat. The TPC should have a 3 mm pitch and three views so that it can study event topologies in a way that is relevant to the upcoming experiments. We plan to flexibly read the TPC out with approximately 2000 electronics channels designed for MicroBooNE. Those electronics feature an amplifier/shaper circuit which operates at liquid argon temperature inside the cryostat and have a signal to noise that is more than sufficient for our needs. We will adapt the cold electronics boards so that we can read out two views for the full 3 m length or three views for a 2 m length. The capacitance of the wires and the amplifier noise will be small enough to allow us to gang two wires on one channel to better model the LBNE readout and to trade TPC size for granularity. Using the MicroBooNE electronics allows us to quickly start this project while leveraging existing R&D efforts and expenditures.

Dataset, Beam Conditions and Instrumentation

The next generation of oscillation experiments will make precision measurements of $\nu_\mu \to \nu_e$ transitions, extracting mixing parameters by fitting neutrino energy distributions. These experiments should not be fundamentally limited by uncertainties in the energy scale or particle identification capabilities of the TPC and the way in with the MC simulates those characteristics. Therefore, we propose a significant exposure consisting of multiple beam energies and with a sample at each that is large enough to yield a 1% measurement of the mean calorimetric response to $e^\pm, \pi^\pm$ and p. We propose taking data in 100 MeV/c steps between 200 MeV/c and 1 GeV/c, followed by 200 MeV/c steps from 1 GeV/c to 2 GeV/c. This is 14 different beam settings, with 50k events at each setting, for a total of 700k events. We will also want to acquire some kaon events but expect that the kaon rate is suppressed relative to the pions by about 2 orders of magnitude, with an even smaller rate at few hundred MeV energies (see Fig. 1b). Also, pion/kaon separation by time of flight will become difficult at higher energies. We would be satisfied with a yield of a few thousand kaon events for the datapoints between 600 MeV/c and 1400 GeV/c.

In an LArTPC, the position of tracks along the drift direction is determined from the time of the pulses on the wire plane relative to an initial time t_0 determined from scintillation light, a beam spill signal, or external beam counters. Ionized electrons drift at 1.5 m/ms in liquid argon and we would like to build a detector in which the drift distance is 2 m. Therefore, clean events will consist of a single particle triggering the detector and limited additional activity within $\pm[3]ms$. This will require work to reduce the beam rate and shield the detector appropriately. Even so, we expect a non-negligible halo which should be actively detected with a veto wall upstream of the cryostat. The wall will need small scintillator counters upstream and downstream to mark the clean events in which the particle is poised to enter the detector through a narrow evacuated exclusion in the front face of the cryostat, rather than through the steel of the cryostat flange. The scintillator counters need to be read out with a multi-channel digitizer or other device capable of distinguishing multiple events in a time window of a few tens of nanoseconds because the beam will likely have a micro-structure, based on the MINERvA/T977 experience. The signals from that digitizer should be used to form an active trigger of the readout electronics.

The momentum of the testbeam particles should be known to about 1%, likely by measuring their trajectories using wire planes upstream and downstream of dipole magnets. It may be necessary to collimate the beam and focus it with quadrupoles upstream and downstream of the bending section. Good momentum resolution may also require limiting energy loss by helium bags or evacuated beam pipes.

Testbeam particles must be identified with good efficiency and small backgrounds. This can be accomplished by a system consisting of 3 time of flight (TOF) counters with the upstream counter providing a common start, and two "stop" measurements, one just upstream of the cryostat, the other at an intermediate position. The system should have a resolution of approximately 100-150 ps, achievable with plastic scintillator counters or with new large area pico-second photo detectors (LAPPDs). A Cherenkov counter will be needed to identify electrons. The Cherenkov and TOF counters should also be passed into the digitizer for use in the trigger logic. The TOF signals will need to be fanned out to a time to digital converter which would be enabled by the trigger.

References

[1] S. Dytman and A. Meyer, AIP Conf.Proc. **1405**, 213 (2011).