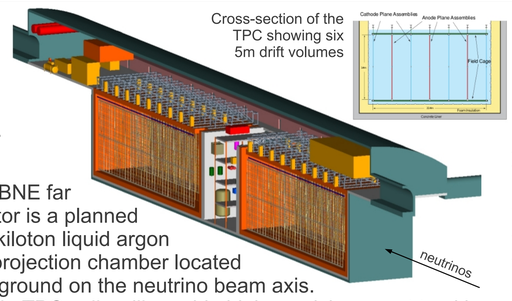
Development of a Photon Detection System in Liquid Argon for the Long-Baseline Neutrino Experiment

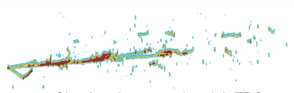
Denver Whittington, Ph.D.
dwwhitti@indiana.edu
for the LBNE Collaboration

The LBNE Far Detector

The Long-Baseline Neutrino Experiment will provide a premier facility for accelerator-based neutrino science. With a neutrino beam generated at Fermilab, a high-precision near detector, and a far detector at the Sanford Underground Research Facility, the experiment's 1300 km baseline will allow world-leading measurements of neutrino parameters such as the CP-violating phase and help resolve the neutrino mass hierarchy. The far detector will also have sensitivity to proton decay and neutrino bursts from galactic supernovae.



Cross-section of the TPC showing six 5m drift volumes



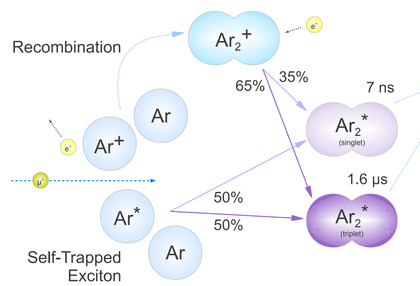
Simulated ν_e event in a LArTPC

The LBNE far detector is a planned multi-kiloton liquid argon time-projection chamber located underground on the neutrino beam axis. Multiple TPC cells will provide high-precision event tracking.

A UV photon detection system will complement the millimeter-scale spatial resolution of the TPC by providing a precise event timing signal from the LAr scintillation to improve background rejection, sensitivity to supernovas, and energy resolution.

Scintillation of Liquid Argon

As a charged particle passes through liquid argon, it excites and ionizes argon atoms. Both recombination and self-trapped excitation lead to an excited Ar_2 molecule. The singlet molecular state decays with a mean lifetime of 7 ns, while the triplet state lifetime is about 1.6 µs. This excited Ar_2^* disassociates to two neutral argon atoms and emits an ultraviolet photon with a wavelength of 128 nm.

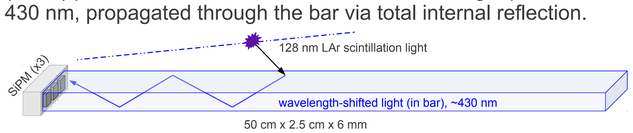


This photon signal tags the event time t_0 for TPC event reconstruction.

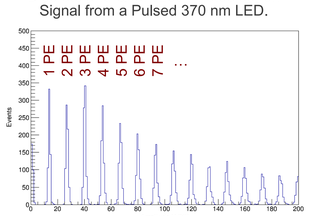
The ratio of contributions from the two components depends on $\beta\gamma$ and can aid in particle identification.

Photon Detector Modules

To facilitate photon detection in the large active volume of the LBNE far detector, the collaboration is exploring designs based on acrylic or polystyrene lightguides imbued with a wavelength shifting compound (TPB or bis-MSB). An array of silicon photomultipliers (SiPM) positioned at the end collects waveshifted light peaked at 430 nm, propagated through the bar via total internal reflection.



Discrete and Quantized Photoelectron Signal from a Pulsed 370 nm LED.



When operated at cryogenic temperatures, the SiPMs exhibit excellent gain and noise characteristics, making resolution of individual photoelectron signals readily possible.

Twenty photon detector modules (10 cm x 50 cm) will be installed inside each anode plane assembly of the far detector TPC. This scalable design yields a large active surface area sensitive to the 128 nm scintillation signal while reducing both the total required photocathode area and the system cost.

Waveguide Designs

Light emitted from the wavelength shifter must be generated inside the lightguide to be contained by total internal reflection. A number of novel designs are being pursued and tested by various groups.

Acrylic or Polystyrene Bars (right)

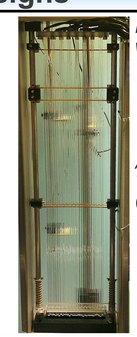
Based on a 1" x 20" lightguide design by MIT, four lightuides are arranged together and read out by 12 SiPMs.

Dip-coating – Acrylic bars are dipped into a solution of TPB, toluene, and acrylic (MIT) or waveshifter and dichloromethane (IU).

Hand-painting – The dip-coating solution is instead applied by hand. (MIT)

Flash-heating – TPB or bis-MSB is spray-coated onto the surface of an acrylic bar, which is then briefly heated to partially melt the surface and imbed the waveshifter. (IU)

Casting – Polystyrene (LBNL) or acrylic (IU) bars are commercially manufactured by casting plastic doped with 1% TPB or bis-MSB.



Polystyrene fibers doped with TPB (left)

32 square fibers are mapped onto 8 SiPMs. A 3 mm fiber width allows four fibers to be mapped to the full active area of each SiPM. (CSU)

Acrylic paddle coated with TPB, with imbedded WLS fiber (blue-to-green) (right)

UV photons are converted at the surface to visible light, captured by a second WLS-doped fiber, and carried to two SiPMs, one located at each end. (LSU)

Blue: directly compared in 2014 TallBo run (see bottom-left of poster)

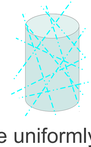
Comparing Designs at the TallBo Facility

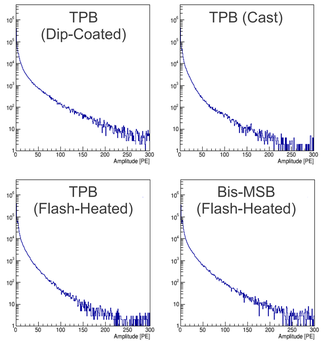
Direct comparisons of various lightguide designs were conducted at the TallBo facility at Fermilab's Proton Assembly Building. The 84" TallBo dewar is filled with ultra high purity liquid argon and maintained by a LN_2 condenser. The dewar's large volume accommodates simultaneous operation of up to 16 different lightguide technologies. Runs in Oct. 2013 and Mar. 2014 have provided valuable feedback on these designs.

Two 8x8 arrays of PMTs from the CREST balloon experiment were positioned on either side of the dewar as a cosmic ray hodoscope. This external trigger provided discrimination between showers and single particles, as well as track selection and reconstruction.

"Free Run" Self-trigger

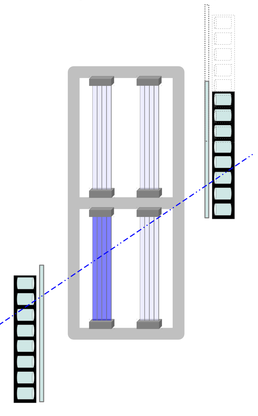
Direct comparisons between bars in different modules was facilitated through special threshold-based self-triggered runs. Over time, the modules are uniformly and evenly illuminated by random cosmic rays passing through the dewar. After a minor correction for effects from the cylindrical dewar geometry, the distribution and rate of light collected by each lightguide is a direct indicator of its overall photon detection efficiency.



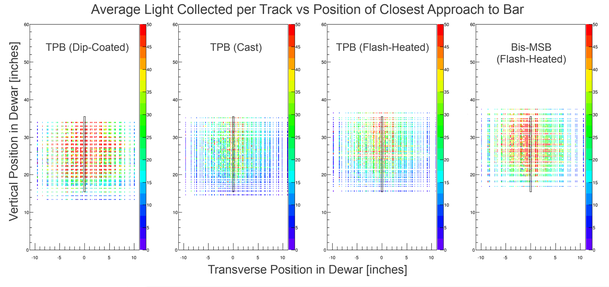


Hodoscope Trigger

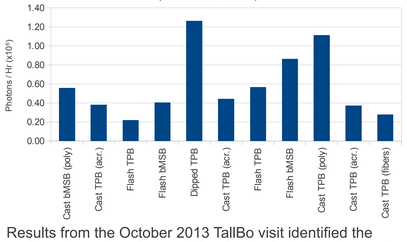
The hodoscope-selected tracks provide direct comparisons between bars in each module, probe efficiency versus track position relative to the modules, and provide a data set of single-particle events for detailed analysis of the liquid argon scintillation. Extraction of absolute photon detection efficiencies is under investigation.



Average Light Collected per Track vs Position of Closest Approach to Bar

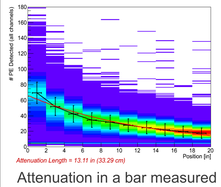


Total Photons Collected per Hour (SiPM Average)
(Waveforms > 10 PE)

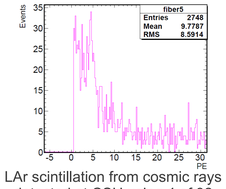


Results from the October 2013 TallBo visit identified the preferred quantity of waveshifter for the flash-heating method. The most promising designs to emerge from the March 2014 tests were acrylic dip-coated with TPB and polystyrene cast with TPB (above). In each run, relative performance in the free run data agrees with observations from hodoscope-triggered tracks.

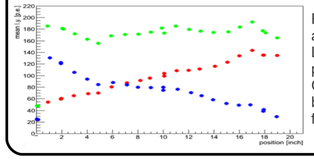
Testing at Home Institutions



Attenuation in a bar measured at IU using an alpha source.



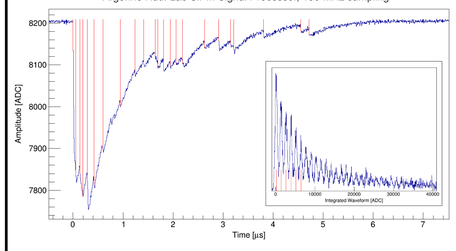
LAr scintillation from cosmic rays detected at CSU using 4 of 32 TPB-doped polystyrene fibers.



Readout of signals from an alpha source by the LSU paddle module, performed at CSU. Combining signals from both ends compensates for attenuation in the fiber.

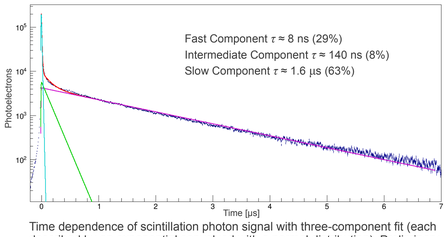
Scintillation Signal Structure

Example Waveform with Tagged Photoelectron signals
Argonne Natl. Lab SiPM Signal Processor, 150 MHz sampling



With the fast response of the SiPMs and the high-resolution sampling of the custom data acquisition electronics built by Argonne National Lab, fine details in the time structure of the scintillation signal are easily resolved. The SiPM response to photoelectrons is linear, meaning the signal strength can be easily converted into a measure of detected photons.

A sample of single-track events selected from the TallBo data using the hodoscope trigger shows the liquid argon response to minimally-ionizing muons. The fast and slow scintillation components are easily resolved after deconvolving each waveform with an SiPM response function and accumulating events.



Time dependence of scintillation photon signal with three-component fit (each described by an exponential convolved with a normal distribution). Preliminary analysis finds agreement of the fast and slow components with reported lifetimes and relative contributions, as well as an intermediate component observed in various experiments, possibly instrumental in nature.

Special Thanks to Everyone Involved

- Indiana U.
  - Stuart Mufson, Jim Musser, Mark Gebhard, Brice Adams, Mike Lang, Brian Baugh, Paul Smith, Brian Baptista, Bryan Martin, John Urheim, Jonathon Lowery
- MIT
  - Janet Conrad, Matt Toups, Ben Jones, Len Bugel
- Colorado State U.
  - Norm Buchanan, Dave Warner, Ryan Wasserman, Dylan Adams, Jay Jablonski, Tom Cummings, Forrest Craft, Andrea Shacklock
- LBNL – Victor Gehman, Richard Kadel
- Louisiana State U. – Thomas Kutter
- Argonne Natl. Lab
  - Gary Drake, Patrick De Lurgio, Andrew Kreps, Michael Oberling, John T. Anderson, Zelimir Djurcic, Himansu Sahoo, Victor Guarino
- Fermilab
  - Brian Rebel, Stephen Pordes, Marvin Johnson, Ron Davis, Bill Miner