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A Demonstration of Light guides for Light Detection in Liquid Argon TPCs

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Abstract

Liquid Argon (LAr) Time Projection Chambers (TPCs) are a developing technology that is becoming a popular choice for neutrino and dark matter experiments due to the low cost of the LAr as a target material and the high signal efficiency and background rejection that these detectors can achieve. When excited by a passing charged particle created in a neutrino interaction, argon produces scintillation light at 128nm. Several types of systems exist for detecting this light. Most involve shifting the wavelength of the light using Tetraphenyl Butadiene (TPB), resulting in visible light which is detected by a PMT.

I will discuss our work on a new system under development for light detection in LAr which uses acrylic lightguides. The lightguides are coated with a thin film consisting of TPB embedded in polystyrene. This system could provide a solution to some of the issues associated with scaling existing systems for a larger future LAr detector. Though we are only in the preliminary stages of this R&D, we have shown that the results are already sufficient for triggering.

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1. Introduction: LArTPCs

LArTPCs consist of a volume of LAr with an electric field applied across the detector. When a charged particle travels through the LAr, such as those produced in a neutrino interaction, it ionizes the argon atoms. This produces a line of ionization electrons in the wake of the particle, mapping out its track. This “track” of ionization electrons then drifts toward wire planes located along the side of the detector due to the electric field, quickly reaching terminal velocity. The wire planes usually consist of one or more “induction planes”, which measure the ionization electrons by induction, and a collection plane, which collects the ionization electrons. This information allows the dE/dx of the charged particles to be reconstructed, as well as its 3D track (Fig 1). This leads to excellent particle ID of tracks and showers and low energy tracking.

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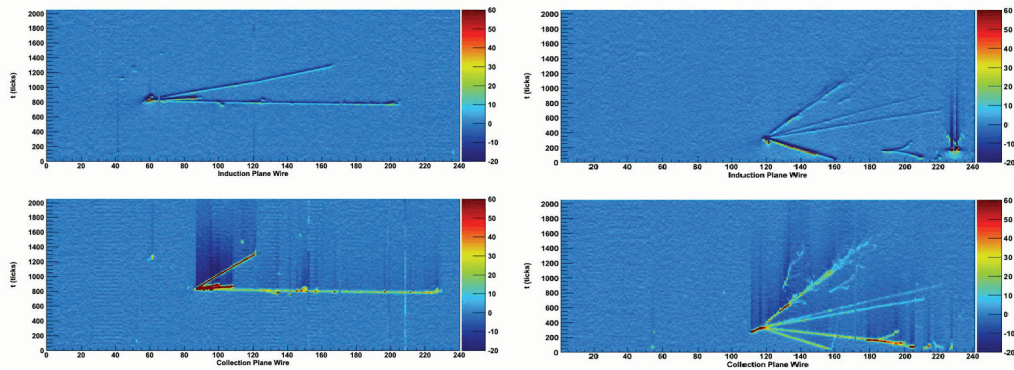


Fig. 1. Examples of event displays from the ArgoNeuT experiment [1]. ArgoNeuT was an R&D project for LArTPCs which measured neutrino cross-sections on argon. It was a 170 L LArTPC located along the NUMI beamline at Fermilab.

2. Light in LAr

2.1. Importance of light collection

While a light detection system is not strictly necessary for the function of a LArTPC, the timing information it provides has many benefits. Since we only know when the ionization electrons reach the wire planes, the drift time introduces an uncertainty into the measurement of the distance from the event to the wire planes. Having the timing information from the light collection system helps to reject background by comparing the neutrino interaction time with the time structure of the beam. It also allows for accurate triggering on interesting non-beam events, such as supernovae neutrino events. This information can also help to correct for charge losses and diffusion which occur during charged drift in measurements of energy deposits.

2.2. LAr scintillation light

Scintillation light can be produced in LAr by two mechanisms [2][3]—a fast scintillation path and a slow scintillation path, taking 6 ns and 1.6 μ s respectively. The fast scintillation path accounts for 25% of the total light and occurs when a charged particle excites an argon atom, leading it to form a singlet state eximer with another argon atom, which then breaks apart into two argon atoms and a 128 nm photon. The slow scintillation accounts for 75% of the light and occurs when the charged particle ionizes the argon atom, allowing it to form a triplet state eximer with another argon atom and an electron. This then becomes a singlet state eximer, as before, and also emits a 128 nm photon. 128 nm light is in the vacuum UV, a range of UV wavelengths unable to propagate through most materials, including air. This means it cannot be seen by photomultiplier tubes (PMTs), as it does not propagate through the glass.

2.3. Wavelength shifting

A prevalent method to detect this light is to use the wavelength shifting material Tetraphenyl Butadiene (TPB). TPB absorbs UV light and emits visible light, peaking at 425 nm (Fig 2), which is a good match to the quantum efficiency of many PMTs. Many existing and upcoming experiments are coating PMTs or plates in front of PMTs with this material. Evaporative coatings of pure TPB have been demonstrated by ref [4] to yield 1.2 visible photons for each incident UV photon.

2.4. MicroBooNE: An example existing light collection system

MicroBooNE is a 170 ton LArTPC which will search for $\nu_\mu \rightarrow \nu_e$ neutrino oscillations using the booster neutrino beam at Fermilab, and will begin taking data in early 2014. It currently has a system of 30 8 inch PMTs with 50% TPB-PS coated plates in front of them behind the wire planes along the side of the detector. This system was designed to be able to trigger on 40 MeV protons from the beam but is capable of triggering on 5 MeV electrons such as those expected to be produced by supernova neutrinos undergoing charged current interactions, with an average of tens of photoelectrons (p.e.) throughout the detector.

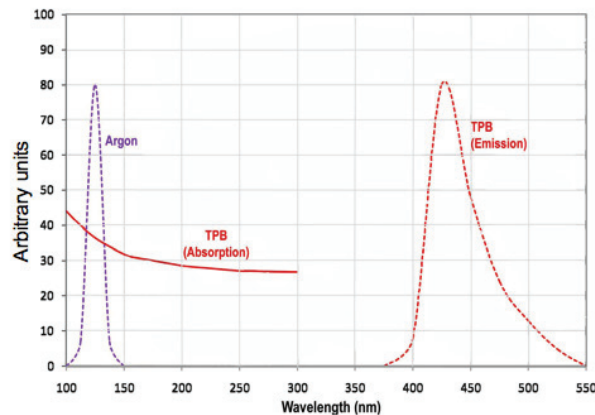


Fig. 2. TPB absorption and emission spectra plotted with the argon scintillation spectrum. The quantum efficiency of our PMTs overlaps nicely with the TPB emission spectrum.

2.5. Scaling up to multi-kiloton detectors

Light detection using PMT assemblies at the edge of the detector volume is successful for smaller LAr detectors, such as those that exist today [5] [6], but this system will face challenges when scaling up LArTPC technology to multi-kiloton detectors. Current designs for future detectors split up the fiducial volume into modules, each with their own set of wire planes and applied field. This is to avoid challenges associated with large electric fields and drifting ionization electrons long distances. In this scenario, light produced in the center modules have a high probability of being lost through processes such as Rayleigh scattering and absorption by impurities on its way to PMTs along the side of the tank. A solution to this problem would be to have a system which can fit in between the wire planes, such as lightguides which can collect light along their surface area and transmit this light to PMTs located outside of the active volume. PMTs in this space would be very cumbersome, taking up a large amount of space. The lightguide system also allows for the PMTs to be placed outside of the electric field, which is important as electric fields will degrade the performance of PMTs.

3. Lightguides

3.1. Design

The lightguides would be curved into a PMT such that light is transmitted adiabatically down them, as shown in figure 3. Our lightguides are constructed from 1" wide by 3/16" thick acrylic bars. In order for the angle of reflection to be such that internal reflection occurs, the light must originate from the end of the lightguide or from within the lightguide, and the surface must be optically smooth. This is achieved by coating the lightguides with a mixture of TPB embedded in acrylic or polystyrene (PS), which is a good index of refraction match to acrylic. In this scenario, light is produced by a TPB molecule embedded in the coating, thus being produced inside the guide. We use a mixture of 25% TPB to 75% PS (we define this as a "25% TPB-PS" mixture), which produces a clear, smooth coating. We apply this coating by dissolving the TPB and PS in toluene, brushing on the solution, and allowing the toluene to evaporate. A complication of this design is that 128 nm light does not penetrate very deeply into PS, so we lose most of the light before it is able to reach a TPB molecule. We measure that a 25% TPB-PS coating converts only 10% as much of the incident light as an evaporative coating. This and the capture efficiency are our main sources of inefficiency relative to a PMT and plate based system, but we can make up for this by having a much greater collection area than that of a PMT alone.

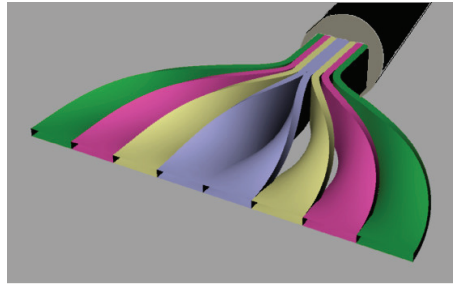
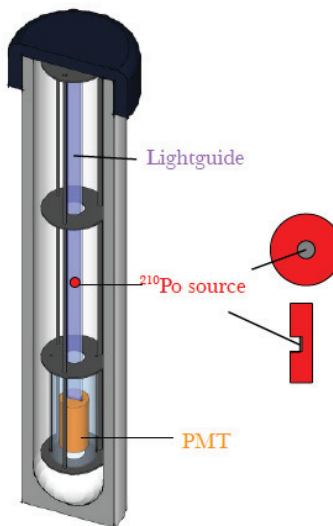


Fig. 3. A paddle composed of 8 lightguides which are bent in a way that causes light to be transmitted adiabatically to the PMT.

3.2. Test setup

A schematic of our test setup is shown in figure 4. A ^{210}Po source is positioned 5mm from the lightguide and emits 5.3 MeV alpha particles. Alpha particles travel 50 μm in LAr and produce scintillation light as described in section 2.2. Photons produced along the path of the alpha particle may excite a TPB molecule in the wavelength shifting coating which emits an optical photon into the lightguide, ultimately producing a signal in the PMT. Both fast and slow scintillation light components may be emitted by the argon. A sample PMT pulse is shown in figure 5. A clear early light peak can be seen, and is quantized by the number of photoelectrons (p.e.) in the pulse. Late light can also be seen and usually appears as single p.e. pulses, due to its longer time constant with respect to the pulse width. The collected sample of late light pulses serves as the p.e. conversion calibration. This calibration method also agrees with a fit to equally spaced gaussians to the prompt scintillation light pulse heights (approximating a poisson distribution around each number of p.e.). We evaluate the sensitivity of the system using only the early light in our calculations and results, as this is what we will be able to trigger on. Any observed late light may be used at a later time, which would give higher light yields.



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Fig. 4. An illustration of the test stand used for lightguide testing. Light is produced from argon scintillation by alpha particles emitted from a ^{210}Po disk source.

3.3. Results

A full discussion of the results of this talk can be found in [7]. As of that time, we used a 25% TPB-PS coating on extruded acrylic bars purchased from McMaster Carr. The coating is not completely uniform, so

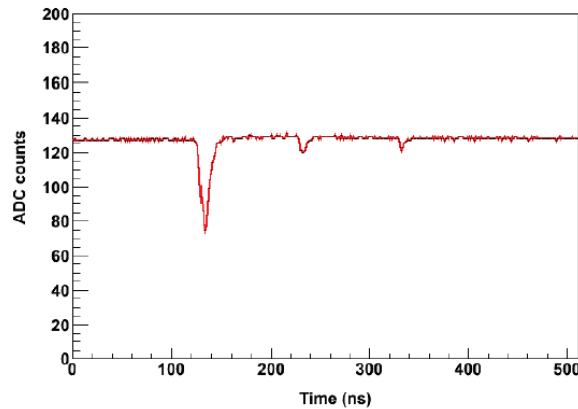


Fig. 5. A sample PMT pulse collected from our setup. Both prompt and late pulses are clearly visible.

we do see some variations in light response due to this lack of uniformity. We measure the efficiency of our coating to be about 10% that of an evaporative coating. We also lose efficiency due to the capture efficiency of light in the guide, and the quantum efficiency of the PMTs. Taking these into account, and only counting the early scintillation light, we calculate the expected light yield to be 10 p.e. per alpha particle. We measure an average of 8 p.e. per alpha particle. In order to understand these results, we take MicroBooNE (Section 2.4) as an example. With these results, we would need 27 m long paddles (8 lightguides curving into a 2 inch PMT) to detect a 40 MeV proton in the MicroBooNE detector, which is definitely feasible. We define a trigger as observing at least 5 p.e. in total. It would take 650 of these paddles to trigger on the 5 MeV electron, so more work needs to be done on this R&D for it to be a viable option for triggering on supernovae events, but this system would be sufficient for studying beam events in a MicroBooNE-like detector.

3.4. Recent Developments

Recently, we have changed our coating method. We have switched to using UV transmitting acrylic instead of PS for our coating in which to embed the TPB. We also switched to cast acrylic instead of extruded acrylic, for greater optical clarity and improved attenuation length, for our actual bars. We were not anticipating this change to have much of an impact, as it does not appear that the UV transmitting acrylic would allow 128 nm light to pass upon inspection of its transmission curve. However, we do indeed see an improvement, as we acquire a factor of 4 more light with these new lightguides, for a total of 35 p.e. per alpha particle

4. Conclusion

We have already improved the response of our original lightguides by a factor of 4 and are still testing new ideas for further improvements. For example, we are looking into a method using co-extrusion which may lead to a more uniform coating and possibly a smoother surface. We are also working on improving the attenuation length of our lightguides, which will greatly impact the effective surface area per PMT.

We will test our system in the spring of 2012 with a demonstration detector (Fig 6). It will consist of 6 paddles, each with 8 lightguides curving into an R7725-mod PMT, running vertically along the sides of the detector. We will demonstrate that we can see Michel electrons and measure the muon lifetime in argon. We have shown that this system is sufficient for triggering on beam events in LArTPCs, and with a few further developments, we will hopefully be able to trigger on lower energy events as well.

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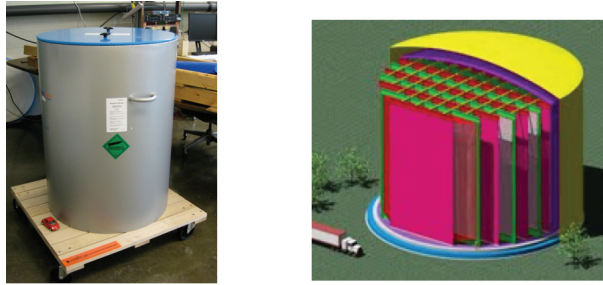


Fig. 6. The dewar which will become our demonstration detector alongside a model of a next generation multi-kiloton LAr detector.

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