Wavelength-Shifting Performance of Polyethylene Naphthalate (PEN) Films in a Liquid Argon Environment

Presented by Dr. Ryan Dorrill (IIT)

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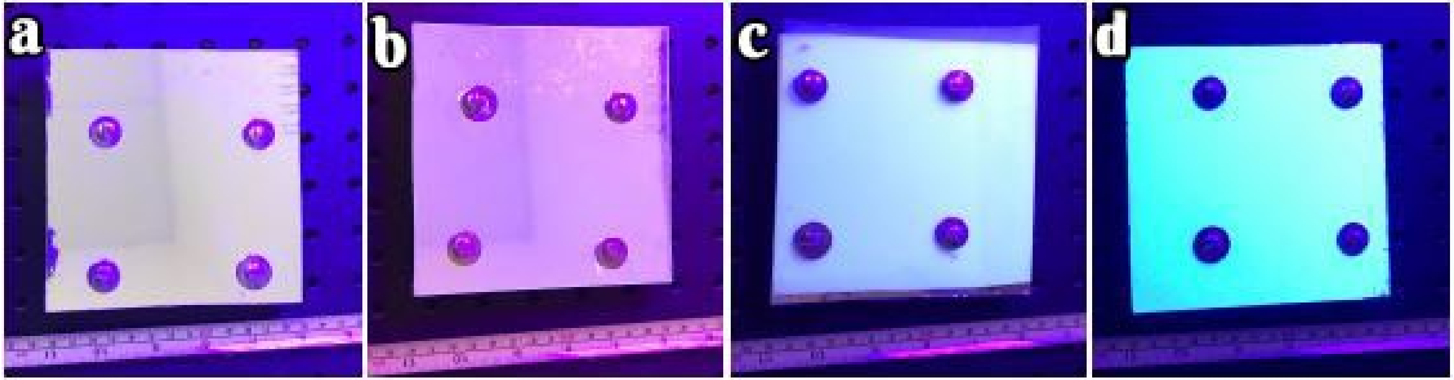

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Wavelength-Shifting Performance of Polyethylene Naphthalate Films in a Liquid Argon Environment

Now submitted to JINST!

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U.S. DEPARTMENT OF ENERGY

https://arxiv.org/abs/2103.03232

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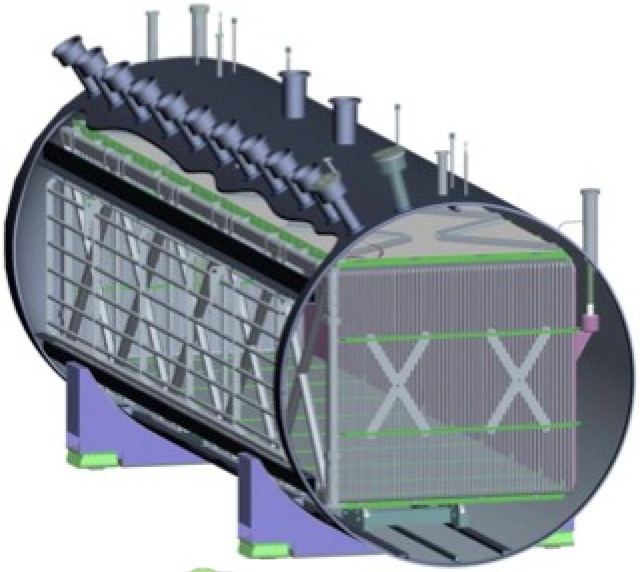
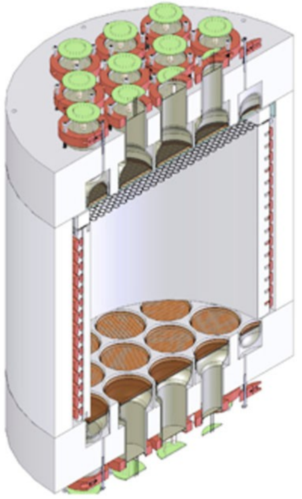
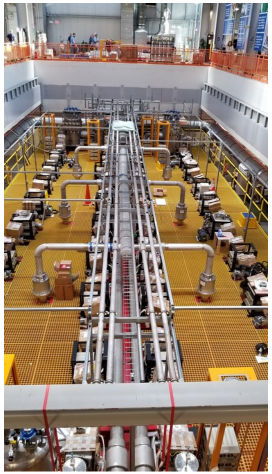
Background: LArTPCs

- Liquid Argon (LAr) is an excellent scintillator and LArTPCs are ideal for dark matter and neutrino experiments
  - Argon produces O 10,000 photons/MeV
  - Argon also allows for good charge transport to wires, cathode planes
- However, traditional photodetectors are not sensitive to argon’s 128 nm (UV) scintillation light
  - One possibility: UV light sensors
  - Another: <u>Wavelength-shifting coatings</u>
    - Commonly used: Tetraphenyl butadiene (TPB)





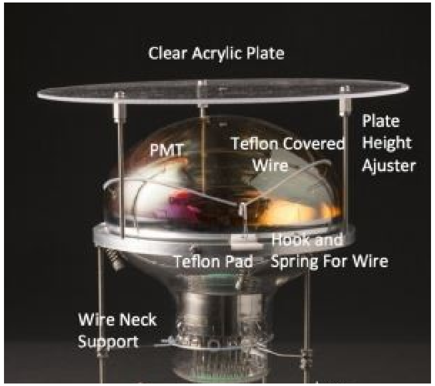


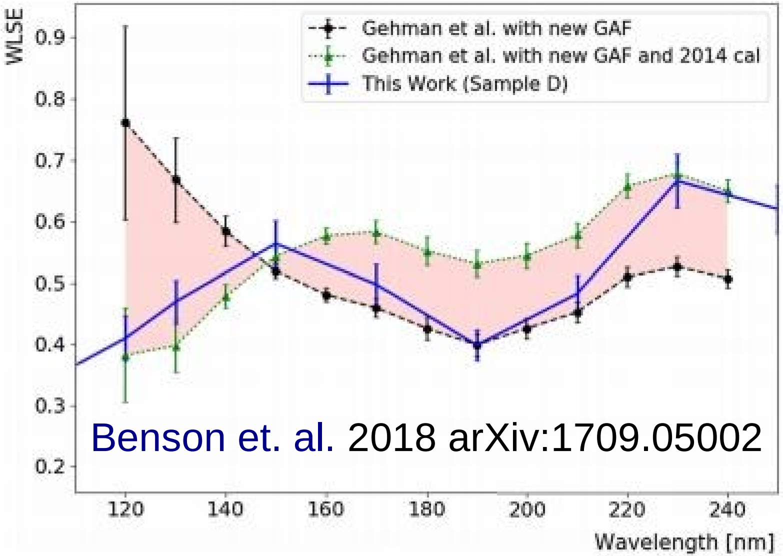
MicroBooNE, DarkSide-50, and ICARUS, all use LAr

Wavelength Shifting (WLS) Coatings

Do we need an alternative to TPB?

- Can be used to coat PMTs, windows, large-area/reflective surfaces
- TPB is currently the "*industry standard*"
  - Demonstrates ~40-50% absolute efficiency
  - However it remains difficult to use:
    - Expensive, usually required vacuum coating on surfaces, and coatings can be delicate
    - Prohibitive for large surface area detectors (e.g. DUNE, future LAr DM detectors)
    - Painted TPB coatings yield less light
- Cheaper, easier alternatives may be desired
    - Polyethylene Naphthalate (PEN) looks promising
      - *Kuzniak et al, Eur. Phys. J. C (2019) 79:291*
      - *Jose Soto Oson, Measurements of the polyethylene naphthalate performance as a wavelength shifter in ProtoDUNE-DP, Neutrino 2020*



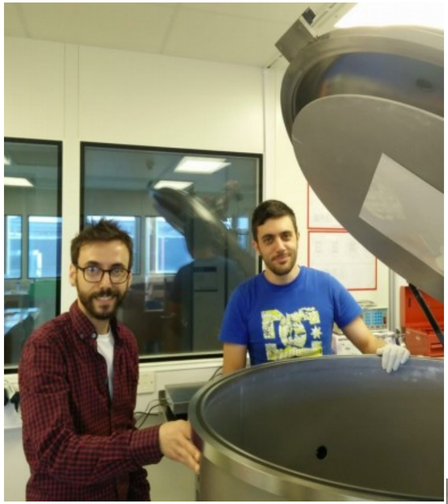


Images: Left – a TPB coated plate w/ PMT for MicroBoone, Right – a PEN bottle, Bottom – TPB efficiency

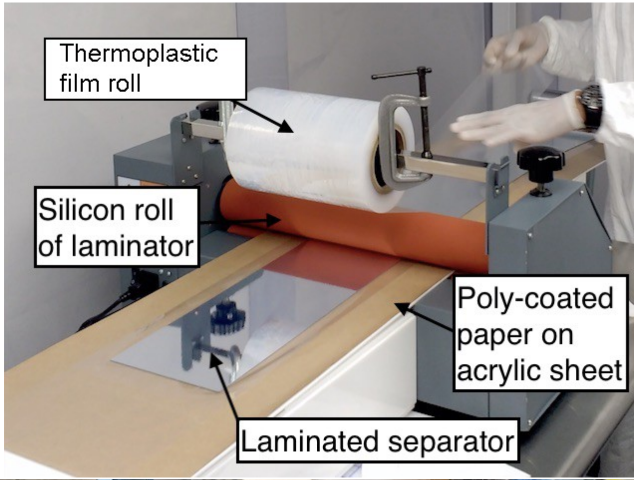
PEN as a Wavelength Shifting (WLS) Coating

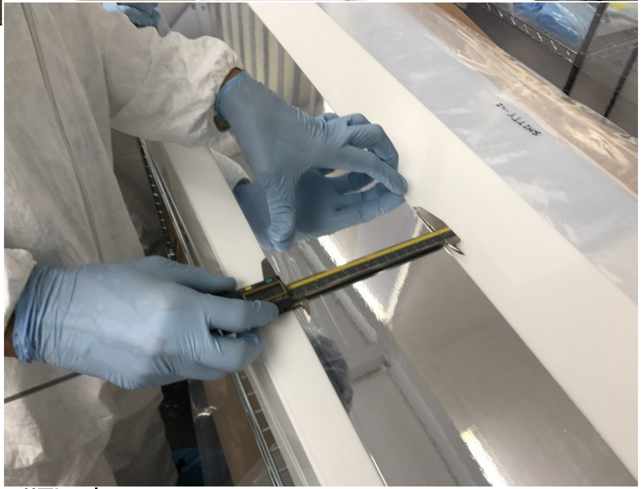
Polyethylene Naphthalate (PEN) offers several advantages:

- Ease of applicability:
  - Reflectors can be prepared with a lamination machine (~$500), as shown at right
  - Fast: ~ meter long panels take < 1 minute
  - Ideal for coating many windows, large surfaces, including behind TPC wire planes, cathode, field cage, etc. to help increase total light detection
  - Coatings are more robust
- PEN can be bought from many vendors off the shelf
  - By contrast, evaporatively coating TPB requires a large dedicated process control system and vacuum conditions, as seen at right



Top,bot from A. Szelc, Manchester/Edinburgh





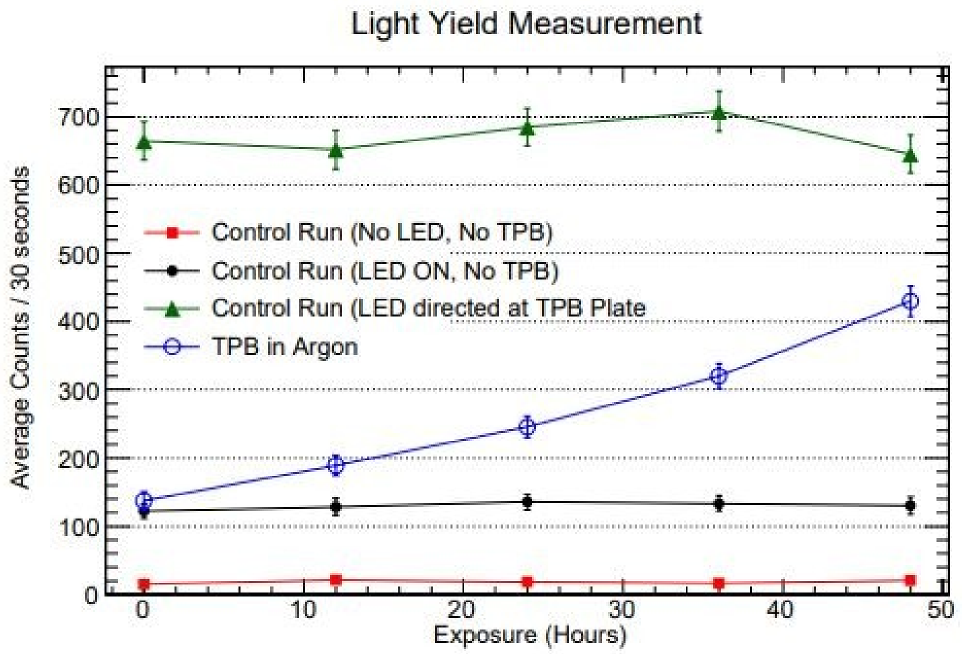
Left: device for evaporatively coating surfaces w/ TPB for SBND. Right: reflectors films being prepared for PROSPECT in IIT's clean room

(*A low mass optical grid for the PROSPECT reactor antineutrino detector, J. Ashenfelter et al 2019 JINST 14 P04014)*

Further Motivation for PEN?

Emanation and Fluorescence of TPB in Liquid Argon

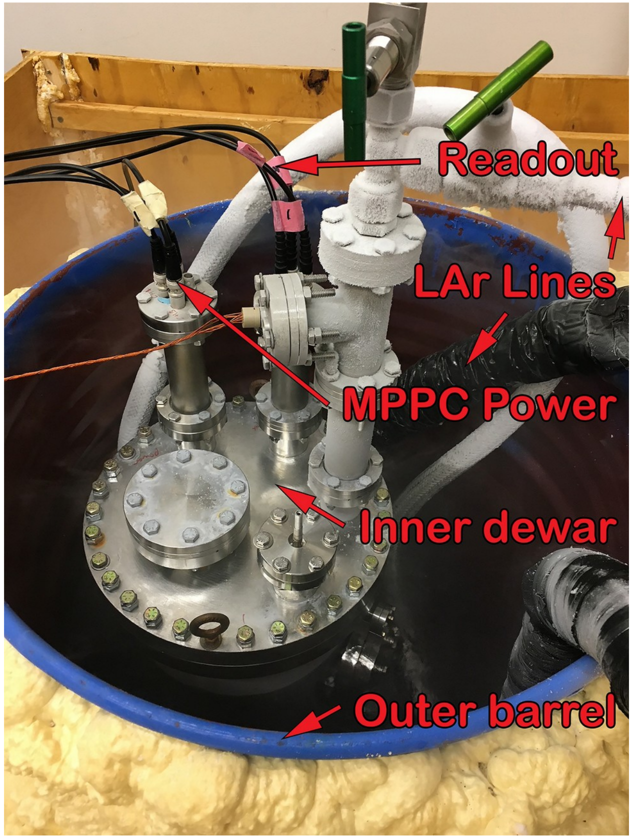
- Measurements in 2019 investigated the stability of TPB:
  - TPB foils, films and coated acrylic lightguides were immersed in argon
  - Uncoated Light detectors were faced away from the TPB surface.
  - Light yields were found to grow over time
  - Molecular sieve measurements also confirmed the presence of TPB in the argon
- **Question: Does PEN exhibit similar behavior? How does its performance compare?**

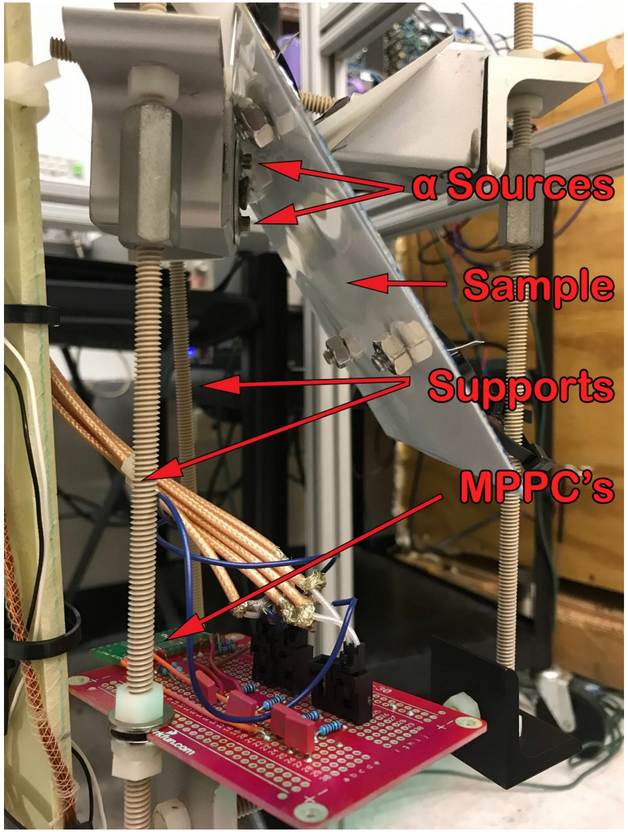


J. Asaadi et al 2019 JINST 14 P02021, arXiv:1804.00011

Comparing PEN's WLS Efficiency to TPB: Experimental Setup

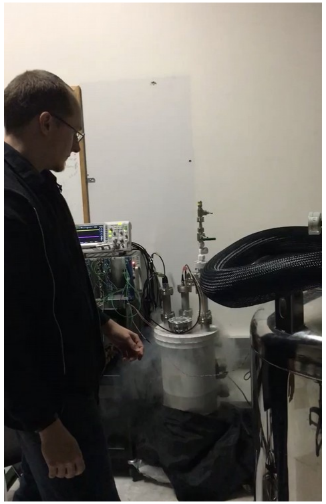
- Samples attached to a reflective ESR backing, immersed in liquid argon
- Hamamatsu MPPCs used to observe light
  - Readout into NIM discriminator, counting modules
- Alpha sources used to create scintillation light in the Lar
  - UV LED sometimes used to crosscheck rates as well
- Three grades of PEN tested alongside TPB
  - Samples also compared to a bare reflector film

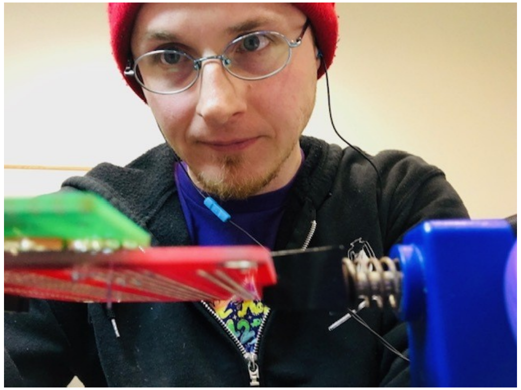




Data-taking Procedure

- Observe count rates in electronics with a sample in, but MPPC's off to verify 0 count rates
  - Follow up with MPPCs powered, no source present to estimate dark counts
  - Observe counts over 30s intervals, take a short ~15s break, and repeat 10 times to calculate an average and standard deviation for each trial
  - Average rate: 51.4, StDev: 6.75, Range: 43.8
    - Range used as uncertainty in single-hit dark count contributions for future runs
- Empty liquid argon, refill, and insert ^{241}Am alpha sources
  - Repeat the 10-part trial every 1-2 hours, for five trials over 6-8 hours
- Empty system, repeat with a new sample – for 6 total samples



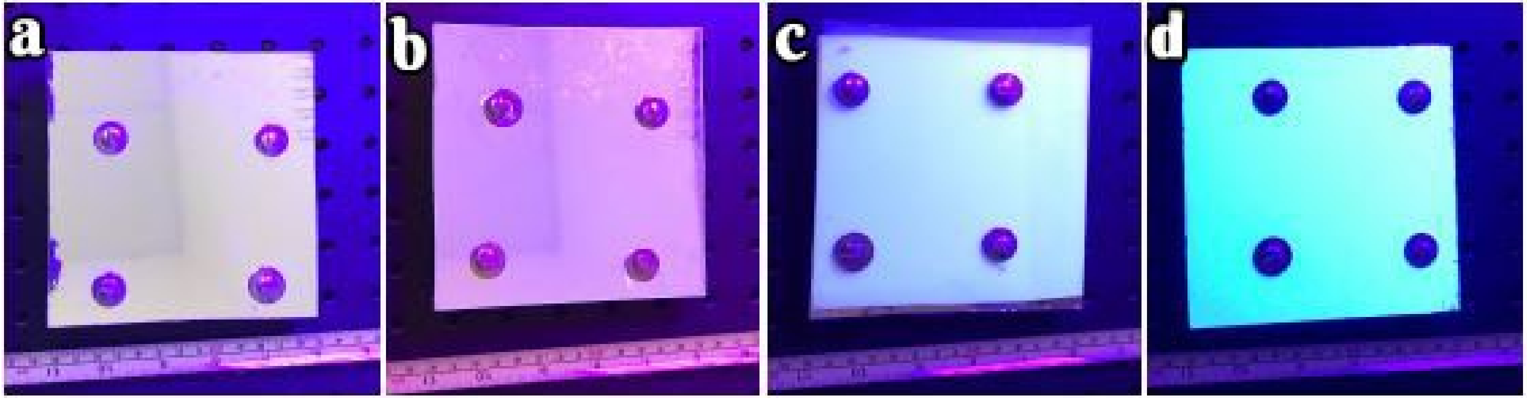


Date of Data Taking	Mean Counts	Statistical Error
Feb 11,2020	41.36	1.0
Feb 13,2020	36.5	1.9
Feb 21,2020	38.8	3.0
July 13,2020	52.98	2.6
July 20,2020	58.56	2.7
July 24,2020	80.3	2.3
Feb 5, 2021	52.3	2.2

Above: dark count rates

Samples Tested

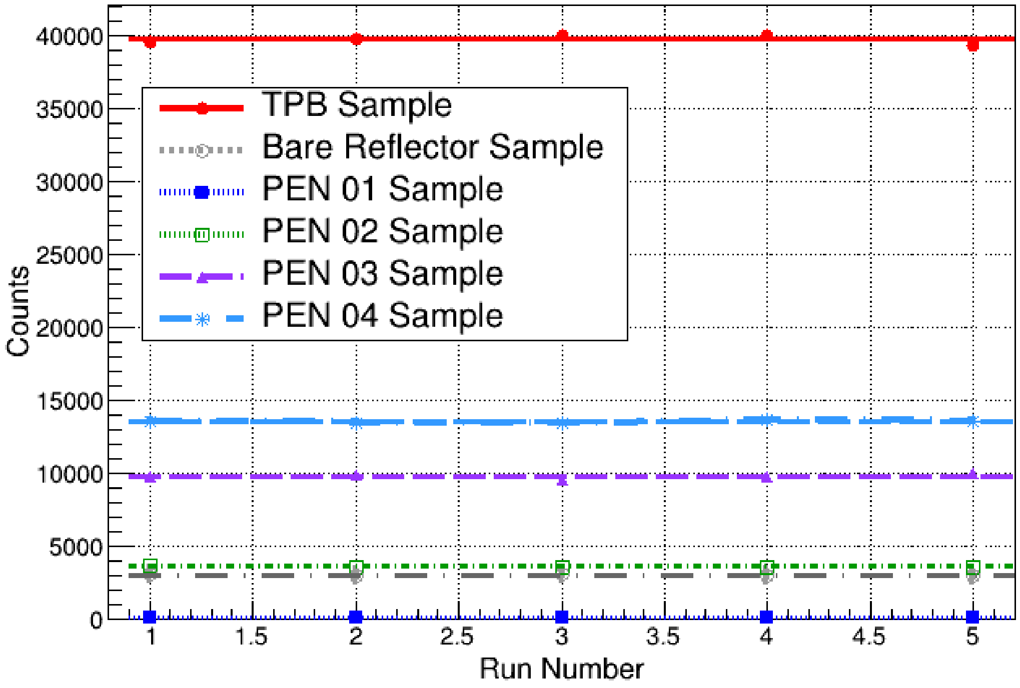
Data Sample	Origin	Trade Name	Thickness	Properties
PEN01	Piedmont	Teonex Q65FA	0.125m	Ultra-clear
PEN02	ORNL	Teonex TN-8065S	1.5mm	Low crystallinity, clear
PEN03	Millipore Sigma	Teonex Q53	0.125mm	Biaxially oriented, hazy
PEN04	Goodfellow	Teonex Q53	0.125mm	Biaxially oriented, hazy
TPB	Manchester Univ.	-	0.003mm	Evaporatively deposited
Bare	-	-	-	No WLS layer applied



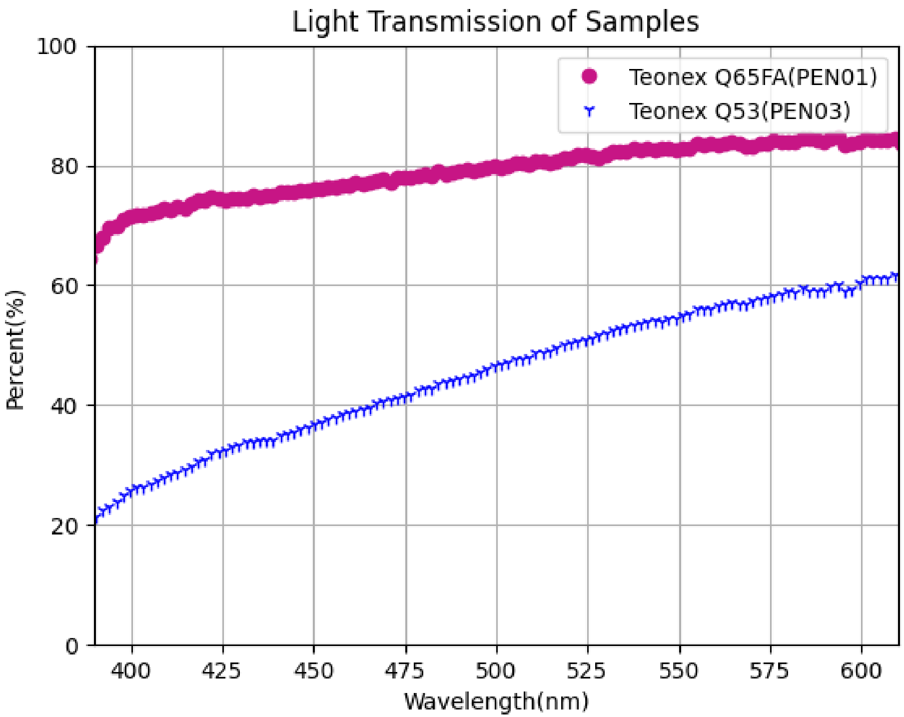
The bare reflector (a), PEN01 (b), PEN04(c), and TPB (d). Note PEN04’s hazy appearance compared to PEN01.

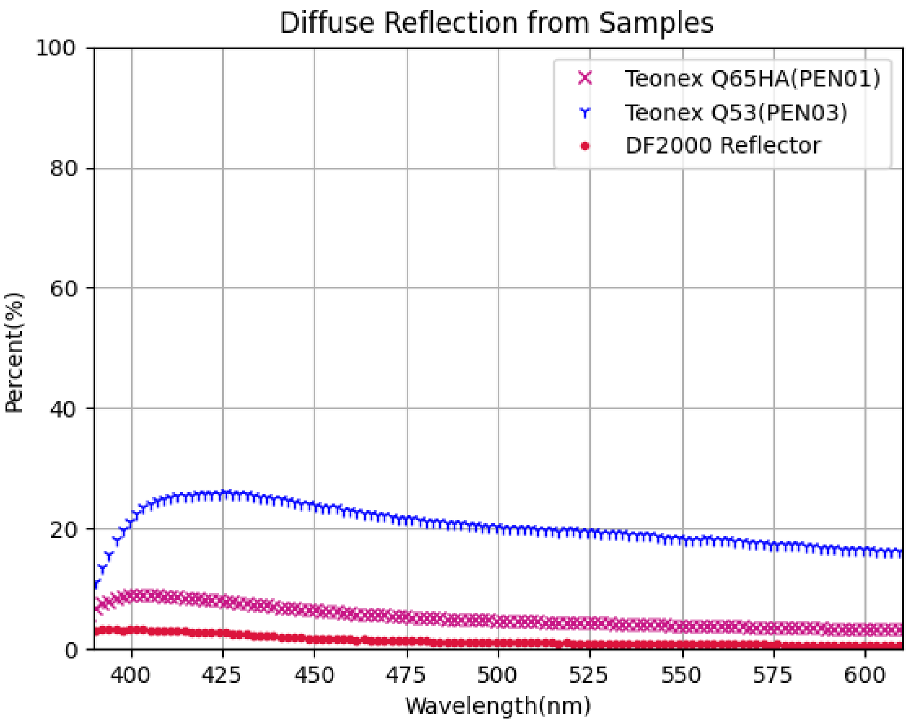
WLS Efficiency Results

- **Light collection ~ ⅓ as high as evaporatively coated TPB films**
- But samples had varying performance:
  - PEN01: 0.4% ± 0.2% TPB
  - PEN02: 9.1% ± 3.6%
  - PEN03: 24.7% ± 0.8%
  - PEN04: **34.0% ± 1.1%**
- Why such varying performance? Several possibilities:
  - **Physical, optical properties of samples**
    - Hazy, diffuse PEN samples (PEN03&04) performed better than optically clear samples (PEN 01&02)
    - But PEN03 and PEN04 are the same material
  - **Coupling of samples to reflector backing**
  - Age, handling, UV exposure



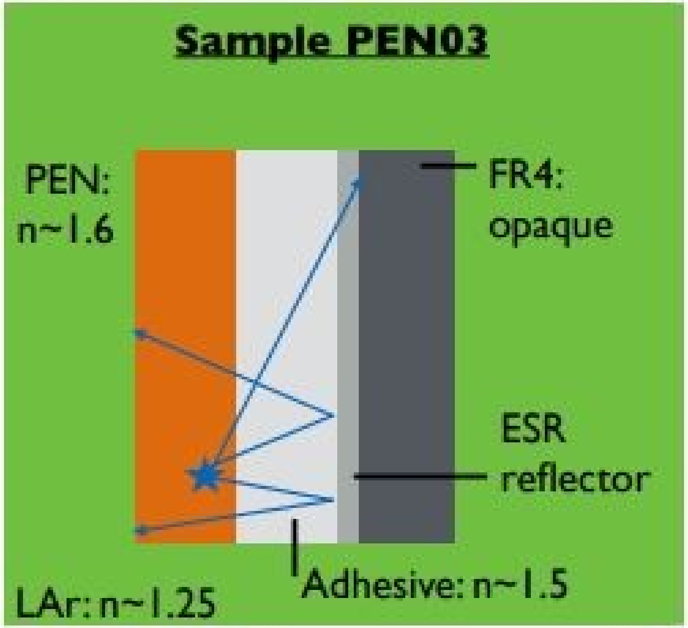
Variation in Optical Properties Of PEN Samples

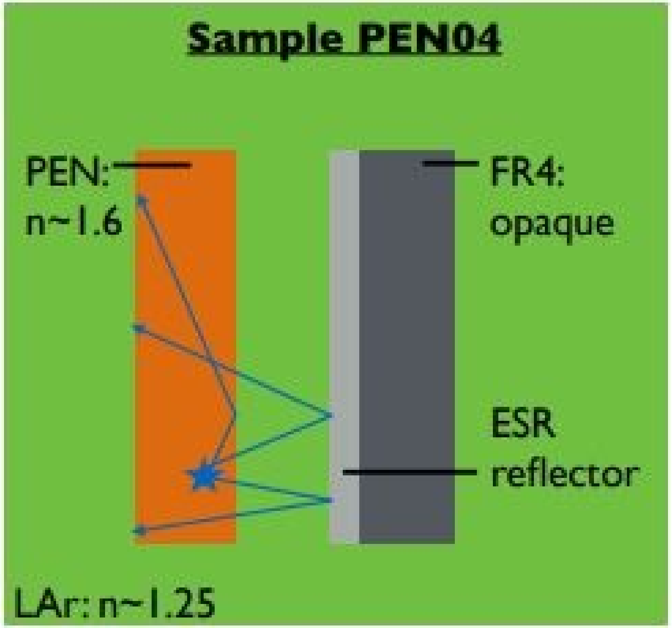




- Comparison’s of “clear” PEN01 (pink) and “hazy” PEN03 (blue) with an Ocean Optics STS-VIS UV-Vis spectrometer. Note the higher transmittance of PEN01, but lower diffuse reflectance
  - Absorbtion, transmission alone don’t explain performance discrepencies between different PEN samples
  - PEN02 was also the thickest sample, and has ~ 1cm attenuation length
  - Not enough to explain performance difference, however

Variation in optical coupling

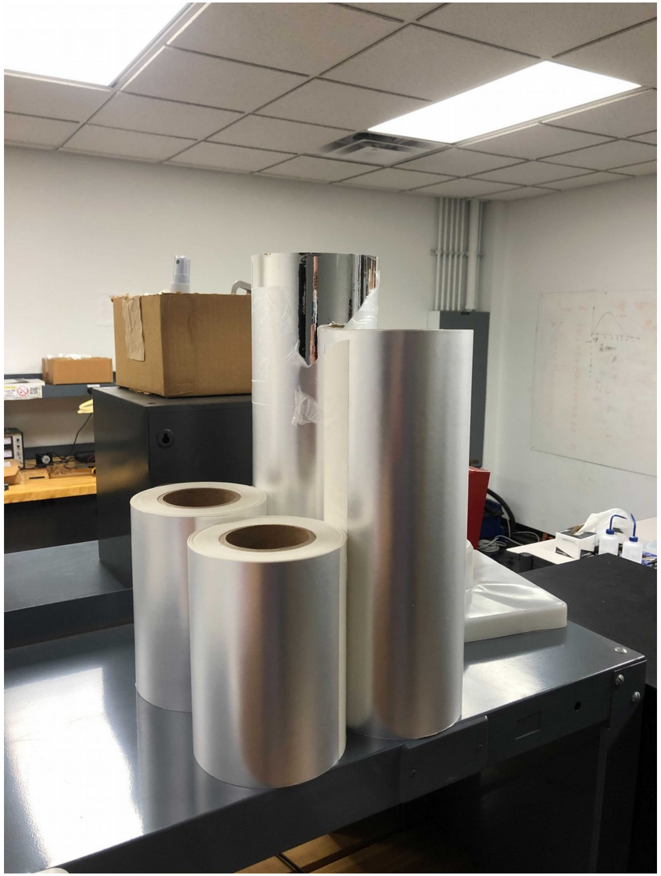




- PEN03 was adhered to the ESR reflector via acrylic-based adhesive (n~1.5)
- PEN04 was mechanically coupled to ESR, allowing lower-index (n=1.25) LAr to separate the materials, resulting in total internal reflection of light above the PEN-LAr interface's critial angle of roughly 50°
- This hypothesis was tested by remeasuring PEN03, mechanically coupled instead of adhered
  - Result: (96.4±3.0)% the performance of PEN04

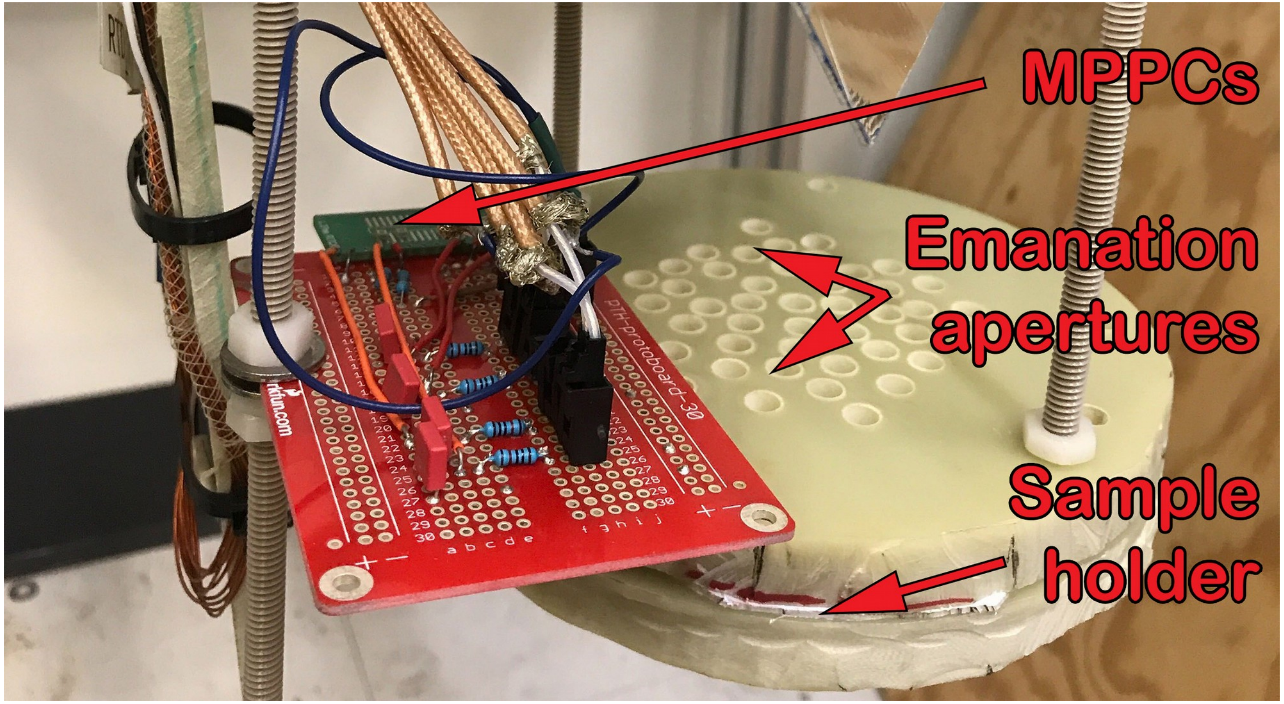
Other PEN Sample Differences

- Some documentation that Teonex Q65FA (PEN01) may have proprietary surface coatings
- Molecular orientation may impact scintillation yield
  - PEN03, PEN04 (Teonex Q53) were biaxially oriented
  - Not known if PEN01 was biaxially oriented
  - PEN02 has low crystallinity, and amorphous molecular structure
  - *For more info, see: Wavelength shifters for applications in liquid argon detectors, Kuzniak, Szelc arXiv:2012.15626*
- Storage, aging, and exposure also effect performance
  - However, no reason to believe these samples were exposed for prolonged periods of time



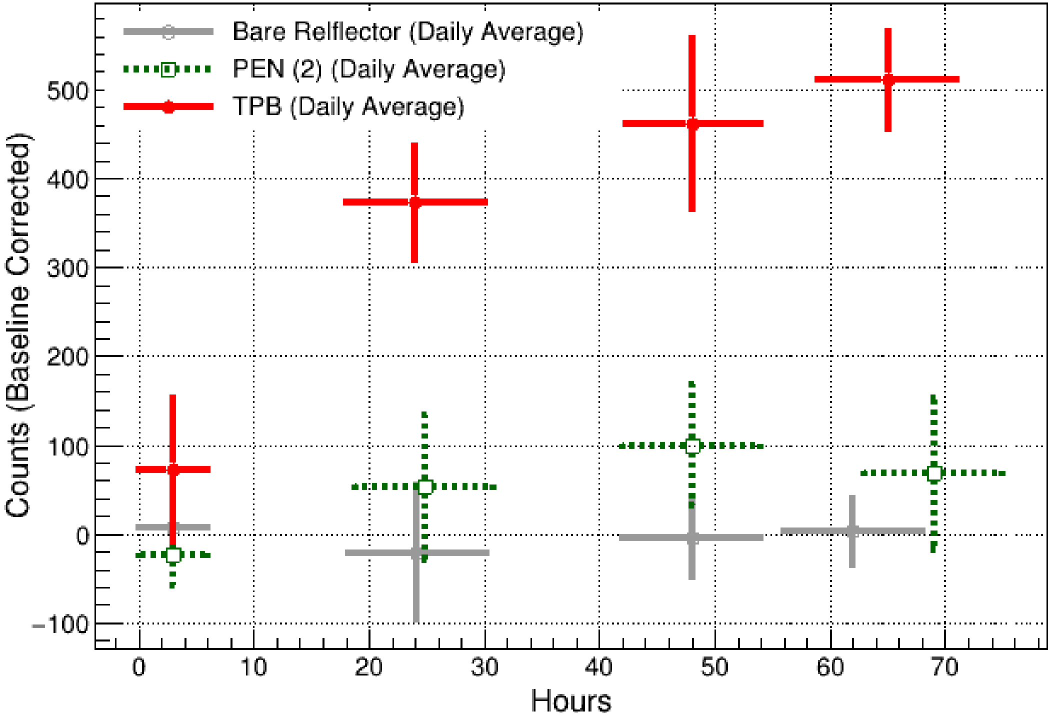
Emanation Studies

- Similar setup to WLS efficiency measurements
- PEN, TPB samples sandwiched between g10 plates
  - Apertures exposed to LAr
  - MPPC’s did not directly face the sample or apertures
  - Alpha source again attached above samples
  - Data-taking procedure repeated, but over 72 hours



Emanation Results

- TPB once again seen to increase light collection counts over ~24-36 hours
  - Trend is comparable to 2016 results
- PEN04 counts remained relatively low: below 100 during the 69 hour run
  - A linear best fit gives 2.6 ± 0.2 counts/hr
  - 1.2 standard deviations of zero, after considering 2 count/hr electronics drift
- Data taken concurrently with a pulsed UV LED similarly showed negligible change in single-hit count rates for the bare reflector and PEN



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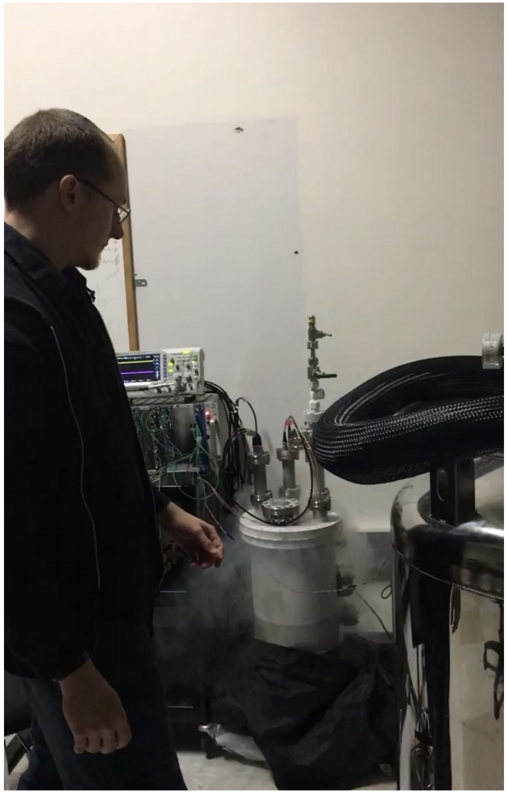
Conclusions

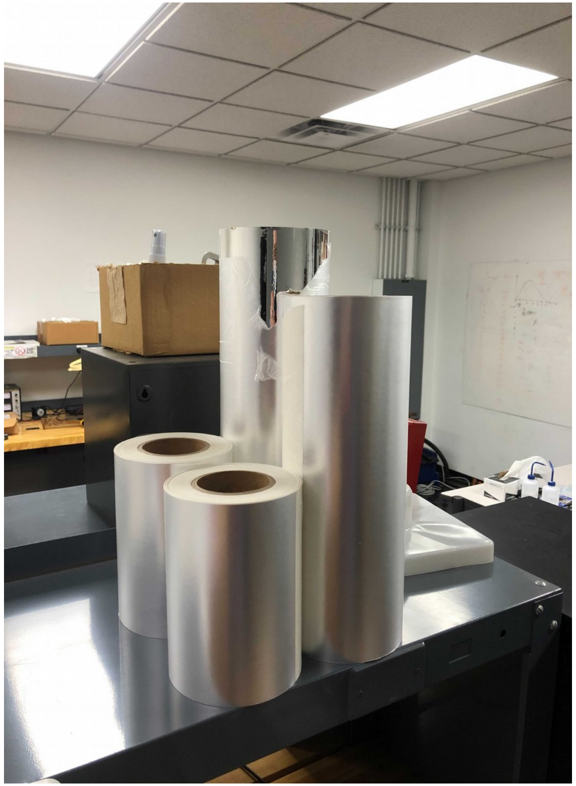
- As neutrino and dark matter LArTPC experiments scale in size, PEN remains a feasible alternative to TPB for WLS coatings
- PEN is cheap and easy to use – readily available in bulk as films or sheets and easily applicable to detector elements
- In these studies PEN performed up to **34% as well** as TPB, depending on the PEN grade and optical coupling
  - Substantial variability between samples was observed and studied
- PEN also shows relative stability compared to TPB in a LAr environment
  - However, such measurements could be expanded, carried out over longer periods of time
  - Further tests could also be carried out with the molecular sieve and filter, to conclusively determine if PEN is found within the argon

Above: PEN sheets, below: ProtoDUNE

Thanks for your attention!

Questions?





Backups

Citations

1) *Data-driven light response calibration in MicroBooNE, Patrick Green, Lidine 2019*

2) *Environmental Effects on TPB Wavelength-Shifting Coatings, C. Chiu et. al., arXiv:1204.5762*

3) *Emanation and Bulk Fluorescence in Liquid Argon fromTetraphenyl Butadiene Wavelength Shifting Coatings, J. Asaadi et. al., JINST 2019, arxiv.org/abs/1804.00011*

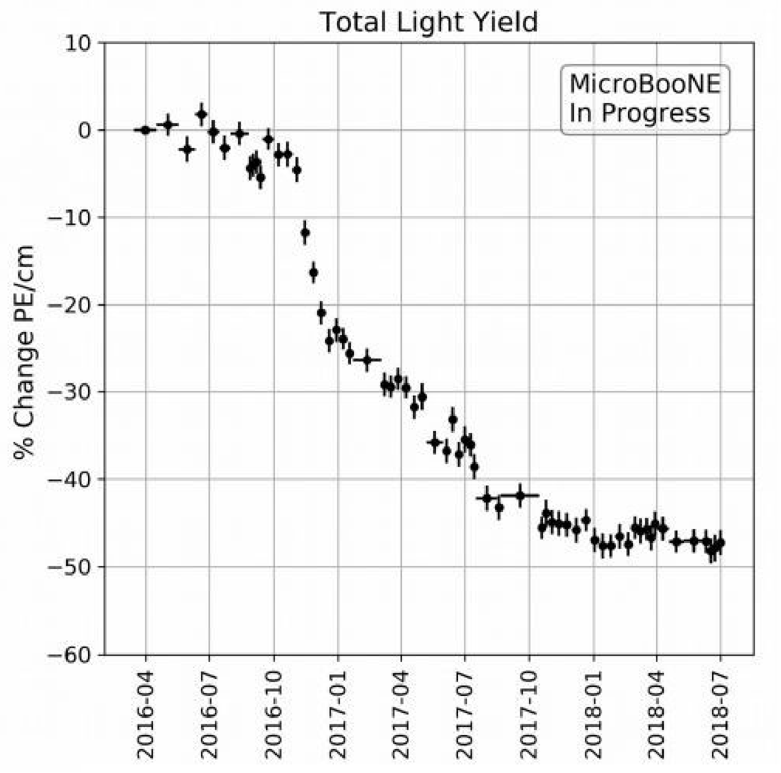
4) *Measurements of the intrinsic quantum efficiency and absorption length of tetraphenyl butadiene thin films in the vacuum ultraviolet regime, Benson et. al., Apr. 2018, European Physical Journal C*

5) *Polyethylene naphthalate film as a wavelength shifter in liquid argon detectors, M. Kuźniak, B. Broerman, T. Pollmann, G. R. Araujo, Eur. Phys. J. C (2019) 79:291, arXiv:1806.04020*

6) *Wavelength shifters for applications in liquid argon detectors,M. Kuzniak, A. Szelc, arXiv:2012.15626*

Motivation: Stability of Wavelength Shifting Coatings

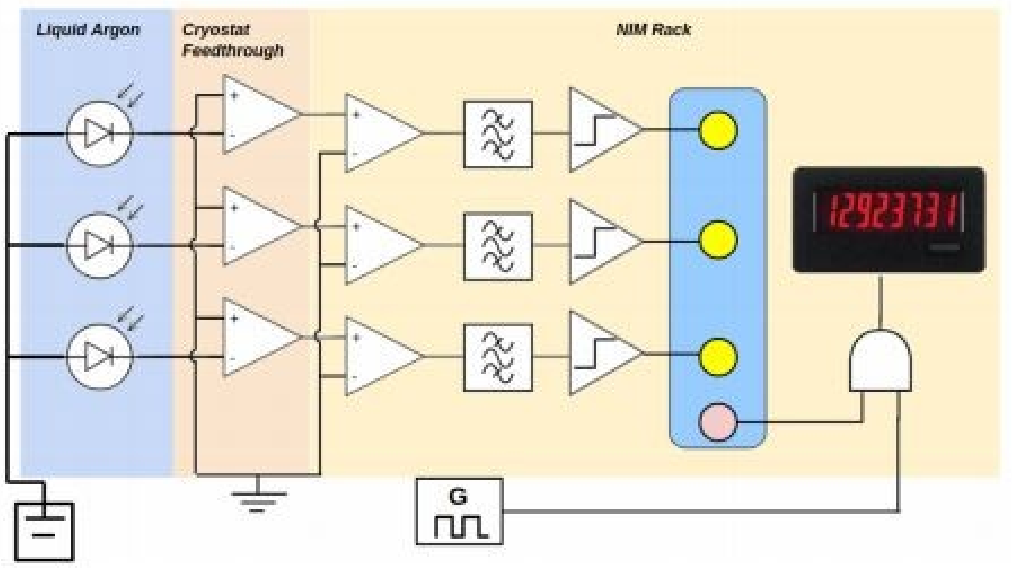
- Some LAr experiments have seen higher than expected single photo-electron background rates
  - Rates scales with drift voltage, indicating ionization
  - Seems to happen whether argon is purified
- Light yields from PMT+TPB assemblies in LAr have also decreased over time →
  - TPB has been known to degrade after exposure to UV light
  - Recent studies indicate TPB dissolves into liquid argon, where is can create light



Plot credit: Patrick Green and MicroBooNE, LIDINE, U Manchester 2019

Triggering

- Output signals from each MPPC were carried TI-OPA656 pre-amplifiers. These signals were then fed into three channels of a Lecroy Model NIM-based amplifier for further signal enhancement.
- To help remove spurious electronics-based noise, signals were then routed to a band-pass filter designed to filter signals below 1 kHz and above 1 MHz, leaving the signal largely unaffected.
- Filtered pulses were passed to a NIM discriminator which triggered on signals above ~ 30mV for at least 1 ns. The discriminator threshold was chosen such that one single photoelectron (SPE) pulse would fire the discriminator while remaining above the residual noise floor
- After a threshold-crossing, the discriminator transmitted out a 1signal to a NI-coincidence logic unit. The coincidence logic board took all three discriminator output signals as input and generated an output pulse based on a logic configuration requiring either one, two, or three-fold coincidence.



- When the logic condition was satisfied, a 50 ns output pulse was sent to a NIM-based 10 digit counter

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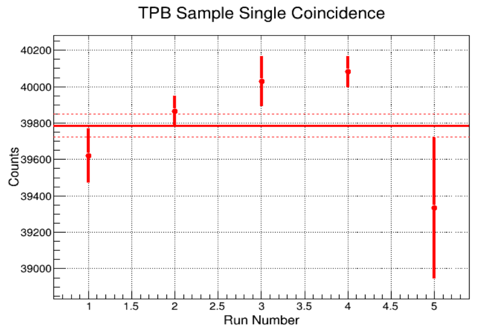
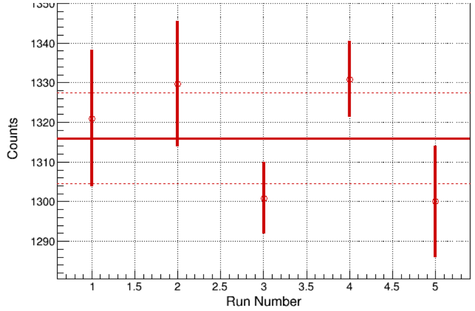
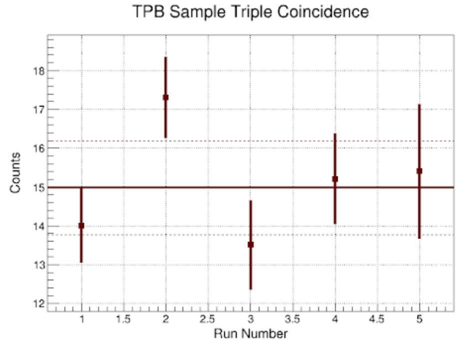
Backgrounds and systematics

- Argon purity: designated by supplier as 99.9999% pure, with specifications of <1.0 ppm for O_2 and H_2O and <5 ppm for N_2
- Purity re-checked using a 10 cm length purity monitor
  - Showed no change in measured electron lifetime before and after active re-circulation and purification, within the monitor's O(1 ms) precision
- Dark counts observed as described above
  - Counts in double, triple coincidence mode with samples present, MPPC's on consistently showed 0
- Right: Single-hit (top), double-coincidence (middle) and triple-coincidence (top) count rates for the TPB-coated reflector sample. Solid horizontal lines indicate the mean count rate, while dotted lines indicate per-trial uncertainties expected from Poisson statistical fluctuations. All modes generally exhibit stable behavior across trials
  - The statistical spread between data points appears to be larger than any systematic time-dependent drift upward or downward in count rates, indicating that, for shorter measurement periods, coherently time-varying systematics, such as decreasing LAr purity, supply HV drifts, or readout electronics drifts, have only a minor impact on measured light collection

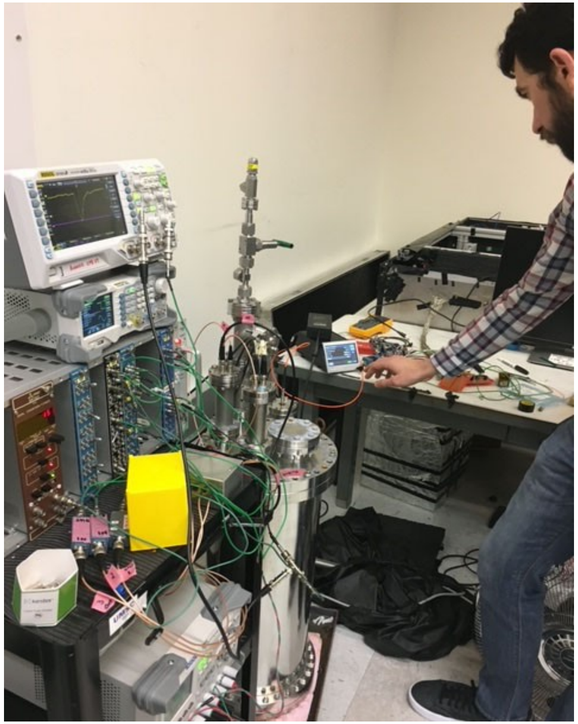






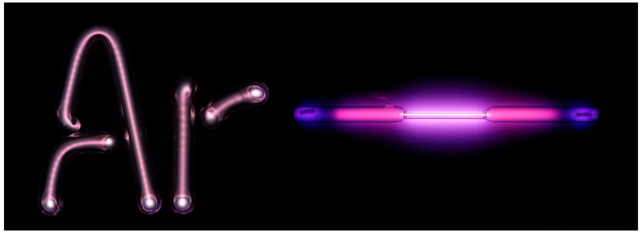
Backgrounds and systematics 2

- For Teonex Q53, the mean single-hit rates during separate runs in mid January 2021 and mid February 2021 were identical within 1.8%.
- Twin LED light measurements of a bare ESR reflector sample taken in July 2020 and February 2021 also provided mean single-hit count rates similar to within 0.8%
- As light collection results for lower-performing PEN01 and PEN02 samples were not verified with repeat measurements, we conservatively assign an additional 40% systematic uncertainty for these samples
- To summarize, we found that systematic uncertainties dominated statistical errors in measured light collection.
  - For measurements of relative light collection the dominant systematic uncertainty is attributed to the demonstrated run-to-run repeatability of the system after repeated resets (emptying, opening, closing, and re-filling).
  - For extended-run WLS emanation studies, readout electronics drift systematics are dominant



Advantages of LarTPCs

- Argon has negligible electronegativity, allowing electrons and other charge generated to ionizing radiation to reach charge collection planes/wires
- Argon produces abundant scintillation light (O ~10,000 photons/MeV)
- Argon is relatively abundant and cheap
- LAr is 1000x denser than the gas used in original TPC designs



Future Studies

Currently setting up a LAr test stand at IIT for future studies:

- Could perform longer emanation studies with PEN
  - Filter LAr with a molecular sieve to test for PEN emanation
- Further optical optimization of WLS-coated reflectors/surfaces
- Optical compatibility of advanced light collectors (like ARAPUCAs) with WLS-coated reflectors
- Design and testing of new customized WLS thermoplastic films (with ORNL)