R&D and characterization of wavelength-shifting reflectors for the LAr instrumentation of LEGEND-200 and for future LAr-based detectors

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Motivation ①: In LEGEND-200[*], a shroud of **Wavelength-Shifting Reflectors (WLSR)** surrounds the wavelength shifting fibers of the LAr veto:

The germanium crystals of LEGEND-200[*] are immersed in LAr, which is instrumented with fibers coupled to SiPMs to act as an anti-coincidence veto. WLSR increase the efficiency of the system.

[*]See S. Schönert’s slides presented on Wednesday: https://indico.physics.ucsd.edu/event/1/contributions/67/
These Wavelength-Shifting Reflectors (WLSR) both shift the VUV light to the visible and reflect the shifted light towards the fibers:
In LEGEND-200, 13 m² of WLSR had to be prepared to surround 6 tons of LAr.
But in future experiments much larger volumes of LAr will/might have to be instrumented with WLSR:

Motivation: Investigate a PEN-based easily scalable WLSR for large detectors that use LAr.

LEGEND-1000
LEGEND-200
ARGO (?)
Dark-Side 20K

PEN: polyethylene naphthalate
Objectives

① Develop and characterize wavelength-shifting reflectors (WLSR) for the LAr instrumentation of LEGEND-200

② (...) and for even larger LAr-based experiments

Important: high VUV-shifting efficiency, high vis-reflectivity (low vis-absorption)

- Estimate the QE of TPB and PEN in LAr
- Measure the vis-reflectivity & absorption of WLSR materials
Reflectivity and absorption of UV-Vis light: For these measurements, we use a spectrophotometer with a calibrated integrating sphere (IS)

Several materials were measured: here we focus on Tetratex (TTX), TTX+TPB\(^+\), TTX+PEN (sanded\([\text{ref}]\))

Advantages of TTX\(*,1,2,3,\):
- Light-weight
- Radio-pure\(^1\)
- Low-outgassing\(^2\)


\([+]\) TPB (tetraphenyl butadiene) was vacuum evaporated on TTX, PEN was only pressed against it (there may have been an air gap between the films). \([\text{sanded}\]) PEN was sanded with grade P240 sandpaper in random directions.
The absolute Reflectance of a thin film (254 μm) of Tetratex (TTX) is over 94.5% in the blue region.

Advantages of TTX*:1,2,3:
★ Light-weight
★ Radio-pure
★ Low-outgassing
★ Highly-reflective
A layer of evaporated TPB or sanded PEN coupled[^1] to TTX reduces the observed UV-Vis reflectivity.

[^1]: direct absorption, or by photon trapping and subsequent absorption.
The absorption lengths of the investigated TPB and PEN films were quantified* in the UV-vis region.

* For this, a second spectrophotometer was used, see the back-up slides.

Even if PEN’s QE = TPB’s, the light yield from the PEN+TTX WLSR is lower because light is lost due to scattering/absorption.
For LEGEND-200, 600 nm of TPB were evaporated on the surface of TTX inside LEGEND’s cryostat.

The 600 nm thickness performed best in response to VUV light while absorbing little of vis light.
An evaporator was designed for the in-situ coating and a witness sample is used for characterizing the resulting WLSR.

Witness sample: Optimum efficiency in response to VUV. Further characterization is done so that the QE of TPB can be measured and then input in the simulations of LEGEND-200.
Objectives

1. Develop and characterize wavelength-shifting reflectors (WLSR) for the LAr veto of LEGEND-200

2. (...) and for even larger LAr-based experiments

- Important: high VUV-shifting efficiency, high vis-reflectivity (low vis-absorption)

- Estimate the QE of TPB and PEN in LAr

- Measure the Reflectivity & absorption of WLSR materials

- Measure the samples in LAr and extract parameters

- Characterization of the surface of the samples with microscopy

\[
\text{QE} = \frac{\text{emitted photons}}{\text{absorbed photons}}
\]
The SEM\[*\] shows that evaporated TPB fills well the pores of TTX.

\[\text{SEM}=\text{Scanning electron microscopy}\]

\[*\]SEM = Scanning electron microscopy
We used fluorescence microscopy\[^{[*]}\] to check the uniformity of the TPB coating at larger scales

\[^{[*]}\]:

A TPB dip-coated TTX sample is shown for comparison: gaps where less/no light is emitted are observed.

Our sample: Light is always observed from the coating in a range from tens of $\mu$m to cm.
We used fluorescence microscopy\[*\] to check the uniformity of the TPB coating at larger scales and their degradation when exposed to ambient light.

\[*\] Excitation light: 390 nm, [\[\] 2-week-long exposure
For sanded* PEN, we observed that photons seem to undergo total internal reflection in the film - The diffuse surface of the scratches allows them to exit.

[*] sanded with grade P240 sandpaper in random directions
TTX, PEN+TTX and TPB+TTX were measured in a LAr Setup (LArS)[1].

In the sample cell, all structural parts of the sample holder were covered with a low outgassing EUV-FIR absorber[^1].

[^1]: Metal velvet absorber from acktar with reflectivity below 1% from the extreme UV (EUV) to the far infra-red (FIR)
An Am-241 alpha source induced LAr scintillation photons which could be directly detected by a VUV-vis sensitive PMT.
By using the absorber as a “sample” and measuring the number of photons detected ($N_{\text{PMT}}$), we can characterize the effective light yield ($LY_{\text{eff}}$) in the setup.

Measurement of $LY_{\text{eff}}$:
- Well-localized source
- VUV-vis sensitive PMT
- Absorber as a reference

Value from absorber measurement later input in the simulations

\[
N_{\text{PMT}}^{\text{det}} = \left( \frac{LY_{\text{eff}}}{Q_{\text{PMT}}} \right) E_{\text{VUV}} \cdot \Omega_{\text{PMT}}
\]
When measuring a WLSR sample, more light is detected due to the enhancement caused by the shifting and reflection of light by the sample.

\[
N^\text{det}_{\text{PMT}} = \left( \frac{L_{\text{eff}}}{V_{\text{PMT}}} \right) \cdot QE_{\text{PMT}} \cdot \Omega_{\text{PMT}}
\]

Value from absorber measurement later input in the simulations.
To ensure the increase in light detected is due to shifted light, we re-did the measurements in a *Vis-only mode*: an acrylic window blocked the VUV light from reaching the PMT.
The light yield in the **Vis-only** mode corresponds to the *additional light* detected in comparison to that of the **VUV-only** (absorber) mode.

\[
\text{Absorber} \quad \sim 550 \text{ PE} \\
\text{TPB+TTX} \quad \sim 1250 \text{ PE} \\
\sim 700 \text{ PE more light}
\]

Their sum was proved to agree with that of the **VUV+vis** mode.
Then we match the simulation to the number of photoelectrons (PE) detected in the measurements: **First for the absorber**

From the absorber measurement, we find $L_Y^{\text{eff}}$. The number of photoelectrons detected ($N_{\text{PMT}}^{\text{det}}$) is given by:

$$N_{\text{PMT}}^{\text{det}} = L_Y^{\text{eff}} \cdot Q E_{\text{PMT}}^{\text{UV}} \cdot \Omega_{\text{PMT}}$$
Then we match the simulation to the number of photoelectrons (PE) detected in the measurements of the WLSR samples.

From the absorber measurement, we find \( L_{\text{eff}} \).

\[
N_{\text{PMT}}^{\text{det}} = (L_{\text{eff}}) \cdot Q_{\text{PMT}}^{\text{UV}} \cdot \Omega_{\text{PMT}}
\]
We match the simulation to the number of photoelectrons (PE) detected in the measurements of the WLSR samples for given optical parameters of the samples[^*]

\[
N_{\text{det}}^{\text{PMT}} \sim L Y_{\text{eff}} \cdot (Q E_{\text{PMT}}^{\text{VUV}} \cdot \Omega_{\text{PMT}} + E_s \cdot Q E_{\text{PMT}}^{\text{vis}})
\]

- **Vis. reflectivity of TTX:** ~95% (this work, in air)
- **VUV reflectivity of TTX:** <17% (this work, in LAr)
- **Vis. absorption lengths of TPB and PEN** (this work)
- **VUV absorption of PEN:** 100%
- **VUV absorption length of TPB:** 250 - 450 nm

[^*] Other optical parameters used in the simulation are listed in the back-up slides

Sample enhancement \((E_s)\) depends on the geometry and optical properties of the sample.

We match the simulation to the number of photoelectrons (PE) detected, **taking the uncertainties of optical parameters of the samples**[*] **into account**

Some optical parameters of the sample have large uncertainties: we simulate the setup and fit the QE of TPB and PEN for the entire range of uncertainties.

- Vis. reflectivity of TTX: ~95% or lower
- VUV reflectivity of TTX: from 0 to 17%
- Vis. absorption lengths of TPB and PEN: measured value ± 60%

[*] Other optical parameters used in the simulation are listed in the back-up slides
We then obtain an *expected* value and a lower limit for the QE of TPB and PEN.

Some optical parameters of the sample have large uncertainties: we simulate the setup and fit the QE of TPB and PEN for the entire range of uncertainties.

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<td>$87 \pm 4,(\text{stat}) \pm 6,(\text{syst})%$</td>
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<td>PEN</td>
<td>$72 \pm 4,(\text{stat}) \pm 5,(\text{syst})%$</td>
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The lower limit takes all the optical uncertainties into account.
We thus obtain an expected value and a lower limit for the QE of TPB and PEN.

First measurement of the QE of TPB @ LAr.

Values from TPB agree with that measured by Benson et al at RT (Eur. Phys. J. C, 2018) and adjusted to the increase observed at 87K by Francini et al (JINST 2013)

First measurement of PEN's efficiency independent of TPB


Preliminary!
Manuscript in progress.

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Summary and Outlook

➔ For the LAr veto of LEGEND-200, ~13 m² of Tetratex were coated in-situ with TPB.
➔ We measured the specific WLSR from LEGEND-200 and PEN+TTX with spectrophotometers, microscopes and in a LAr setup.
➔ The quantum efficiency of TPB and PEN in LAr (at 87K) were estimated for the first time.
➔ The results from TPB can now be input in the simulations of the LAr veto of LEGEND-200
Back up slides
References

Two spectrophotometers are used to quantify the absorption lengths of the investigated TPB and PEN films in the UV-vis region.

A wavelength-resolved spectrophotometer is used to decouple the reflected and re-emitted light.
Optical parameters used in the simulation

- $n_{\text{index}}$ and $\lambda_{\text{Rayleigh}}$ from [M. Babicz, S. Bordoni, JINST 15(09):P09009, 2020]
- Light yield (LY) in LAr: ~25 ph/keV [from absorber measurement]
- VUV reflectivity of TTX: ~95% (this work)
- VUV reflectivity of TTX: <17% (this work)
- VUV absorption of PEN: 100%

VUV-only absorber measurement

\[ N_{PMT}^{\text{det}} = \left[ \frac{LY_{\text{eff}}}{Q_{\text{PMT}}^{\text{VUV}}} \right] \cdot \Omega_{\text{PMT}} \]

VUV+vis WLSR measurement

\[ N_{PMT}^{\text{det}} \sim \left[ \frac{LY_{\text{eff}}}{Q_{\text{PMT}}^{\text{VUV}}} \right] \cdot \left[ Q_{\text{PMT}}^{\text{VUV}} \cdot \Omega_{\text{PMT}} + E_s \cdot Q_{\text{PMT}}^{\text{vis}} \right] \]