nEXO studies on optical properties of SiPM

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nEXO photon detection system

- nEXO is proposed 5 tons liquid xenon (90% enriched in ^{136}Xe) time projection chamber for studying 0νββ decay of ^{136}Xe.
- nEXO target energy resolution is <1% at Q-value of 0νββ (2458.07 ± 0.31 keV).
- nEXO choose SiPM as photon detectors and covers the TPC barrels.

- 24 SiPM ladder staves totaling to 4.5 m^2 of VUV SiPMs area.
- The energy resolution requirement imposes challenges on nEXO light detection system.

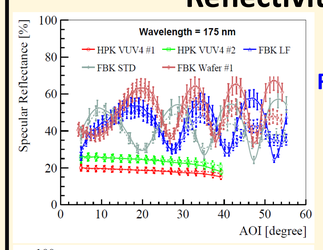
✓ Overall light detection efficiency : > 3%
✓SiPM PDE : > 15 % at 170-180 nm
✓Dark noise : < 50 Hz/mm^2 at -104 C

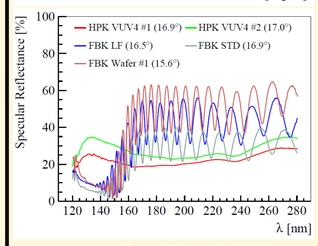
- Light detection efficiency = SiPM PDE + Photon transport Efficiency
- SiPM PDE depends on Filling factor, transmittance, quantum efficiency and trigger efficiency
- Photon Transport Efficiency (PTE): depends on detector geometry, reflective electrodes, SiPM reflectivity.

- Further, PDE and reflectivity are angular dependent and needs to be measured towards optimization of light in nEXO.
- The collaboration has developed experimental facilities to measure the angular resolved reflectivity of SiPM and material used in the detector construction. The facility may also allow PDE measurement of SiPMs. The studies are performed in vacuum and LXe towards developing possible model to evaluate parameters in LXe from vacuum measurement.

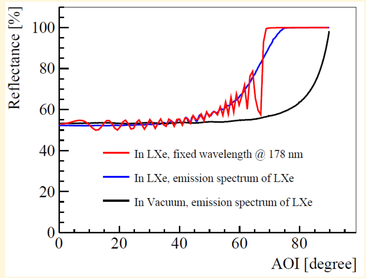
- arXiv:1805.11142
- Phys. Rev. C 97(2018) 065503
- For more details, please see Neutrino 2020 poster ID: 548
- For more details, please see Neutrino 2020 poster ID: 60
- For more details, please see Neutrino 2020 poster ID: 84

Reflectivity measurement in vacuum





Optical properties of SiO_2 layer (thickness, t) (Refractive index, η) and (extinction coefficient, κ)
Reflectance data + Snell's law + Fresnel's equation

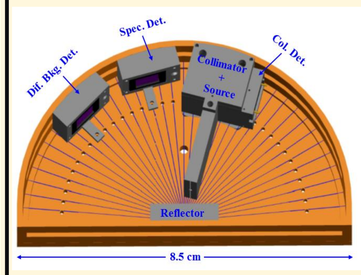


- Reflectance of FBK-Si-Wafer in LXe at 15° of incident angle is further calculated 52.2 ± 1.6 %
- Thus, Establish relationship between reflectivity measurements in vacuum and LXe

arXiv: 1912.01841V1

LIquid Xenon Optical Characterization (LIXO)

JINST 15 (2020) P01019



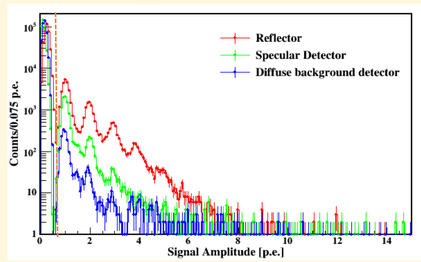
✓Apparatus immersed in LXe
✓^{252}Cf source excites Lxe (~175nm light)
✓Collimator + quartz window assembly prevents radiation damage and helps in light collimation.
✓Collimator SiPM provides trigger and light stability measurement.
✓Sample positioned at "Reflector"

Measurement approach

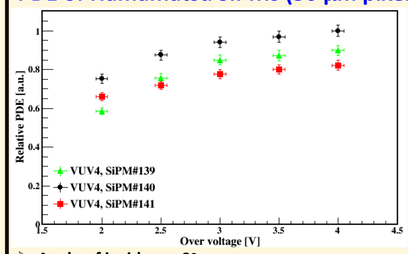
- Low photon counting
- Probability of observing no photon
- $P(0) = \frac{number\ of\ zero\ p.e.\ events}{total\ number\ of\ selected\ events}$
- Poisson distribution, average number of p.e's seen by sample is $\mu^R = -\log[P(0)]$
- Similarly for specular detector determine (μ^S)
- In presence of isotropic diffuse source (μ^D)

$Rel.\ PDE = \mu^R - \mu^D$ $\quad R = \frac{\mu^s - \mu^D}{\mu^R - \mu^D}$

Typical spectrum

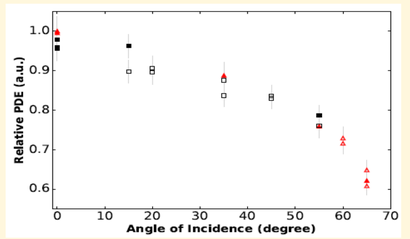


PDE of Hamamatsu SiPMs (50 µm pixel)



- Angle of incidence 0°
- The three SiPM's PDE varies ~ 8% (RMS)

PDE of Hamamatsu SiPMs 141 vs θ



- PDE reduces with increase of angle of incidence
- At 65° PDE is ~60% of the normal incidence

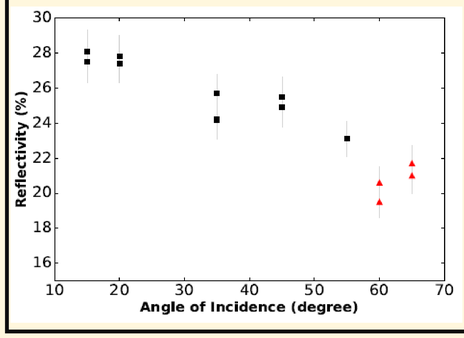
Validation of approach

- Silicon wafer with a 1.5 µm SiO_2 layer
- The reflectivity of wafer at 15 degrees is 50.8 ± 2.3 % (consistent with evaluated from vacuum mesurement).
- The reflectivity of Si wafer with detector SiPM biased to 4.0 OV, is consistent within 1.5σ.

Reflectivity of Hamamatsu SiPM at 15° of incidence angle

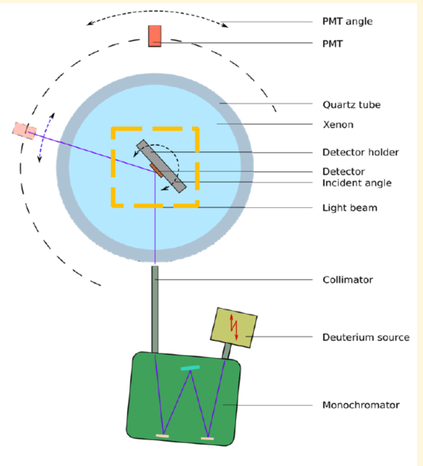
Quantity	SiPM 139	SiPM 140	SiPM 141
μ^S (p.e)	0.0273 (3)	0.0259 (2)	0.0274 (3)
μ^R (p.e)	0.0943 (9)	0.0943 (9)	0.1022 (4)
μ^D (p.e)	0.0036 (5)		
Sys. Corr., rel %	16.2 ± 2.5		
Light Stability error, rel %	3		
Reflectivity, %	30.4±1.4	28.6±1.3	28.0±1.3

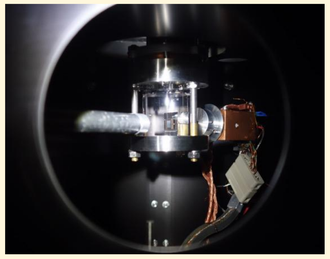
Reflectivity of Hamamatsu SiPM 141 vs θ

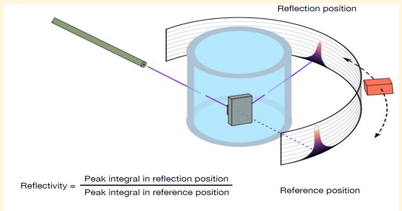


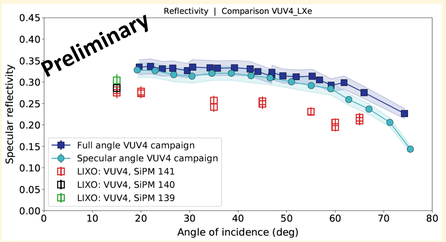
- The reflectivity of Hamamatsu SiPM reduces with increase in angle of incidence and is contrary to Fresnel's calculations.
- The fall in PDE and reflectivity with incidence angle further needs to be understood (imperfect transparency layer on the top of silicon, impurity profile etc.)

Independent and complimentary LXe setup









- The Hamamatsu SiPM reflectivity was observed to reduce with increasing incident angle.
- The independent and complimentary angular scan measurements are consistent.

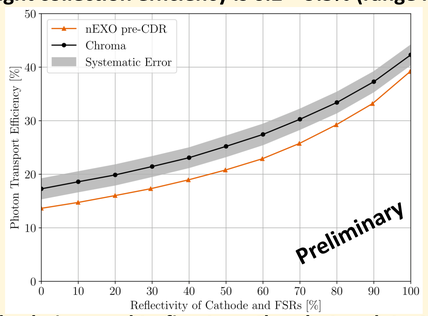
Conclusion

✓SiPMs have met the R & D requirements of nEXO photon detection system.

✓LIXO laboratory is established and characterized SiPMs in LXe at VUV wavelength.

- PDE of three Hamamatsu SiPMs is consistent within ±8% (RMS).
- SiPM PDE reduces with incident angle and at 65°,PDE decreases to ~60% of PDE at normal incidence.
- Specular reflectivity of Silicon wafer in LXe is 50.8 ± 2.3 % at 15° of incidence and is consistent with predicted reflectivity in LXe evaluated by measurements in vacuum
- Reflectivity of the three measured SiPMs is consistent within error bars.
- The reflectivity of Hamamatsu SiPMs also reduces wrto angle of incidence and is confirmed from complimentary and independent setup.

➢ pre-CDR and earlier nEXO sensitivity did not include angular resolved PDE and Reflectivity. The new study (Neutrino 2020 poster ID: 548) incorporates the above measurements. At 80% reflectivity of field shaping rings and cathode, the predicted average light collection efficiency is 6.2 – 9.5% (range is due to choice of SiPMs)



✓Simulations are also being used to fine tune the photon detection system along with establishing quality control parameters of the system.