Cherenkov Light in Liquid Scintillator at the NOvA Experiment: A Cautionary Tale

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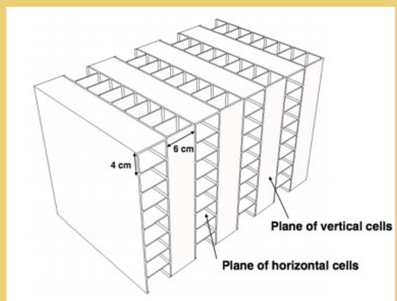
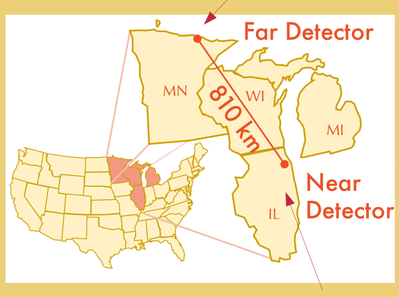
1) NOvA

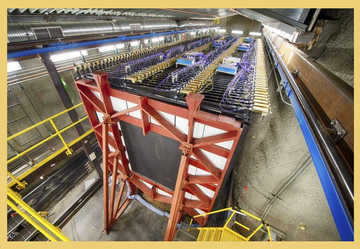
- NOvA is a two-detector, long-baseline neutrino oscillation experiment
- Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells
- Wavelength shifting fibers carry scintillation light to avalanche photodiodes



Far Detector has a 14 kton mass and is located 810 km from the, in Ash River, MN.



Near Detector has a 0.3 kton mass and is located 1 km from the target, on the FNAL campus.

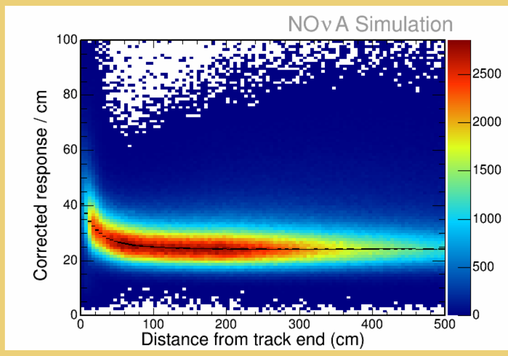


2) Measuring Energy

- NOvA's liquid scintillator consists of a mineral oil solvent, pseudocumene as its primary scintillant, and PPO and bis-MSB as secondary fluors
- Formulation is designed for high light output in the 400 – 500 nm absorption band of k-27 dye used in wavelength shifting fibers

NOvA's liquid scintillator composition[1]

Scintillator component	Percent by mass
Mineral oil	94.6%
Pseudocumene	5.23%
PPO	0.14%
bis-MSB	0.0016%

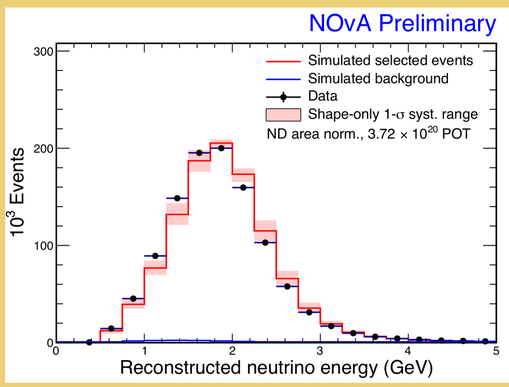


Detector response to simulated cosmic muons

- Light output is calibrated using cosmic muon tracks near their minimum ionizing point
- If the scintillation efficiency were perfectly linear, this calibration point would sufficient to determine the energy lost by a particle in a cell for any observed light signal

3) Birks-Chou Suppression

- Quenching and recombination effects cause some energy absorbed by scintillator to be emitted non-radiatively
  - Degrades scintillator efficiency
- Effects increase as a function of energy lost per unit length
- Non-radiative losses are modeled as linear (Birks suppression[2]) or quadratic (Birks-Chou suppression[3])
- Best data/MC agreement for energy deposited along muon tracks required:
  - k_B 4x larger than found in experiments using similar scintillators[4,5]
  - k_C negative, leading to unphysical enhancements for highly ionizing particles



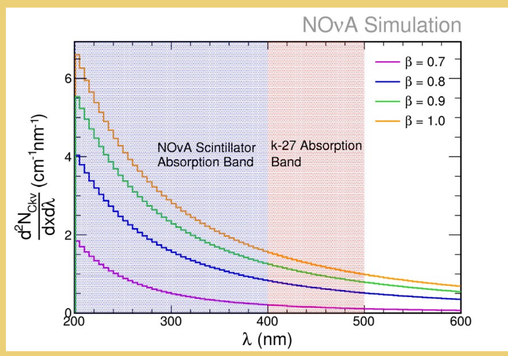
Comparison of reconstructed muon neutrino energy in Near Detector in data and Monte Carlo using 2016 Birk-Chou light model

$$\frac{dL}{dx} = \frac{L_0 \frac{dE}{dx}}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2}$$

4) Cherenkov Light

- Birks-Chou model described energy deposited by muons well, but energy deposited by protons was predicted to be ~5% higher than observed
- Since protons are heavy and generally much slower than muons, Cherenkov light could explain the disagreement since it is only produced by particles traveling faster than the speed of light in the scintillator,

$$\frac{d^2 N_\gamma}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

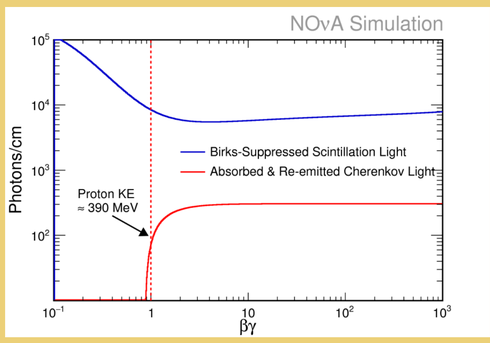


- Cherenkov light is primarily produced at much shorter wavelengths than our wavelength shifting fiber can absorb
- Cherenkov light absorbed by scintillator and re-emitted in k-27 absorption band can be experimentally important

5) 2017 Light Model

- 2017 light model includes:
  - Y_S : Scintillation yield per MeV
  - k_B: Birks' constant (cm/MeV)
  - k_C : Chou's constant (cm²/MeV²)
  - ε_C : Cherekov absorption and re-emission efficiency
  - C_γ : Number of Cherenkov photons produced with wavelengths between 200 – 400 nm

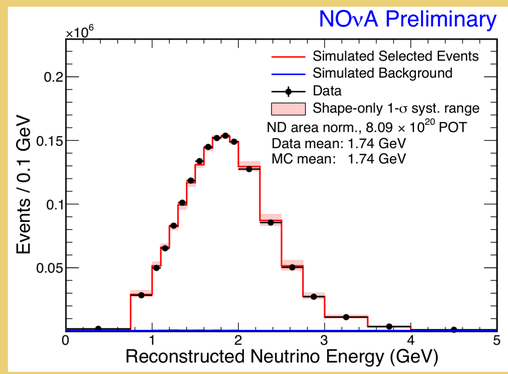
$$N_\gamma^{tot} = Y_S \frac{E_{dep}}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2} + \epsilon_C C_\gamma$$



- Model was tuned using cosmic muons at Near and Far Detectors and selected quasi-elastic ν_μ interactions at Near Detector
- k_B consistent with experiments using similar scintillator and k_C consistent with zero

6) Conclusions and Next Steps

- 2017 Birks-Chou + Cherenkov light model significantly improved data/Monte Carlo agreement
- Systematic uncertainty on 2017 light model was assessed by determining alternate Y_S and ε_C parameters to cover residual proton data/Monte Carlo disagreement
- Light model is no longer a dominant source of systematic uncertainty
- Bench measurements are planned to directly measure
  - Birks' constant
  - Scintillator index of refraction
  - Cherenkov absorption and re-emission efficiency



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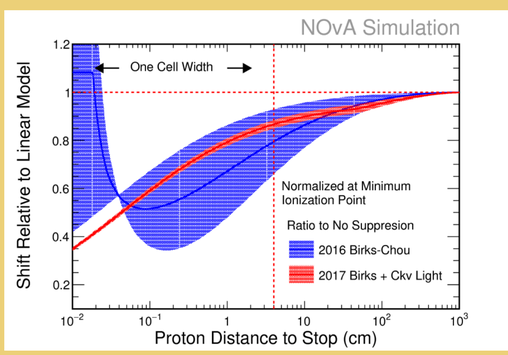

Comparison of 2016 and 2017 light models as a function of distance until a proton stops

References

[1]S. Mufson et al., Nucl. Instrum. Methods A799, 1 (2015)
[2]J. Birks, Proc. Phys. Soc. A64, 874 (1951)
[3]C. Chou, Phys. Rev. 87, 904 (1952)
[4]L. Winslow, PhD thesis, Univ. California Berkeley (2008)
[5]M. Agostino et al., Astropart. Phys. 97, 136 (2018)

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http://novaexperiment.fnal.gov