Towards Simultaneous Measurement of Arrival Time and Wavelength for Single Optical Photons in Large Neutrino Detectors

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Optical event reconstruction in large neutrino detectors is ultimately limited by chromatic dispersion[1]. At present no photodetectors can provide sufficient information to correct for chromatic dispersion on a photon-by-photon basis over continuous wavelength spectra of Cherenkov and scintillation light.

Recent advances in the development of Large-Area Picosecond Photo-Detectors (LAPPDs) allow for single photon measurements with time resolution of better than 100 ps [2-3]. However, in a typical liquid scintillator there is a 2 ns time-of-flight difference between photons with wavelengths of 370 nm and 600 nm over the 6.5-meter travel distance. In future very large detectors like Theia[4], the effect of chromatic dispersion will be significant over an even smaller wavelength range. Therefore, without knowing photon wavelengths, event reconstruction algorithms cannot use the full potential of the available timing information. Resolving the wavelength of all individual photons simultaneously with precision measurement of the arrival time (and position) at the detection surface would allow to appropriately choose the velocity for every photon when back-tracing them to the point of origin during an event reconstruction procedure.

In addition, there has been great recent interest in large hybrid detectors that are using scintillation and Cherenkov light to perform a broad range of measurements to deepen our understanding of neutrino physics including physics associated with neutrino mass[4]. Cherenkov/scintillation light separation has been explored separately either by using timing[5-12] or spectral threshold sorting[13]. Thus, an additional advantage of time-wavelength resolving photodetectors would be their ability to separate Cherenkov and scintillation light in large liquid scintillator detectors by simultaneous spectral and temporal photon sorting (see Fig.1 and discussion about red-sensitive PMTs in Ref.[5]).

In both examples it is necessary to not only resolve the photon wavelength but also to simultaneously achieve high detection efficiency for single photons and low jitter. While existing detectors have been separately optimized for each individual metric, a fundamental question is whether it is possible to simultaneously optimize each metric in the same detector[14].

We suggest to increase communication (and collaboration) between particle physics community and experts in other fields to explore possibility of simultaneous detection of photon arrival time and wavelength within the limits of the uncertainty principle.

Recent developments in quantum science are now opening up a new approach where photodetectors can be designed from the ground up based on fundamental physics principles[14]. For example, a general modeling framework[15] based on quantum master equations can establish the fundamental limits of single photon detection and identify the broad design principles. Applicability of this modeling framework to designing a time-wavelength resolving photon detection architecture has been already presented[16] at the CPAD2019 workshop.

Utilizing the full potential of time-wavelength resolving capabilities will require development of dedicated reconstruction algorithms that take into account spectral information. Before time-wavelength measurements become possible for single photons over large areas, such algorithms can be tested experimentally using a small number of fast photodetectors (e.g. LAPPDs) coupled with a grid of filters so that position of the photon hit would correspond to a narrow range in spectral sensitivity. For example, in experiments such as ANNIE[17] and NuDot[18], for certain type of events the total number of photons per detector surface area could be sufficiently high. Therefore, even after reduction in photon detection efficiency due to filters, it could still be possible to demonstrate experimentally how accounting for chromatic dispersion improves event reconstruction. Fermilab Test Beam Facility is also a valuable resource where even smaller-scale optical tracking tests can be performed[19].

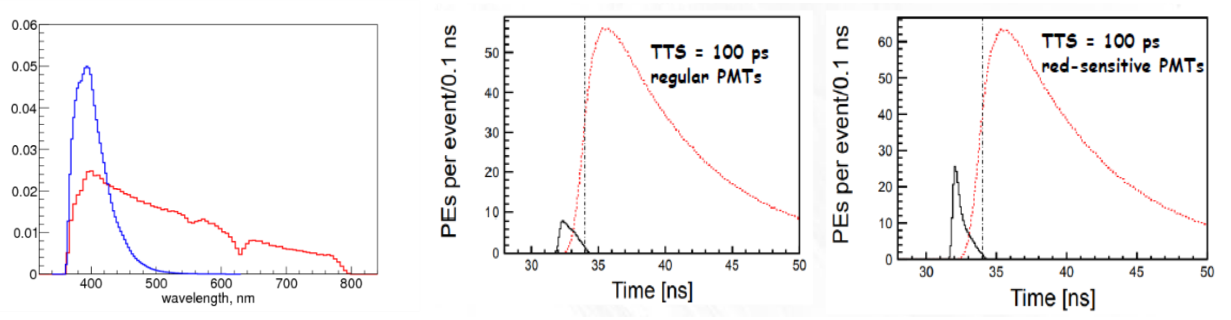

Figure 1: Left panel: normalized spectra of Cherenkov (red line) and scintillation (blue line) light from a charged particle in a simulation of liquid scintillator detector similar to KamLAND. Middle and right panels: separation of Cherenkov (black solid lines) and scintillation (red dotted lines) light by using photon arrival time at the photo-detector surface. Regular PMT spectral detection efficiency (middle panel) is compared with red-sensitive PMTs (right panel). Charged tracks are generated at the center of a 6.5 m liquid scintillator detector similar to KamLAND. See Ref. [5] for simulation details.

Goal:

While any spectral resolution will improve optical event reconstruction (as opposed to practically no resolution on photon wavelength at present), we believe that 10ps-10nm time-wavelength resolution is a worthwhile goal to pursue.

References:

[1] I. Anghel, “Using Fast Photosensors in Water Cherenkov Neutrino Detectors”, Proceedings of DPF 2013, arXiv:1310.2654

[2] B. Adams et al., “Timing Characteristics of Large Area Picosecond Photodetectors”, Nucl., Instr. Meth. Phys. Res. **A795**, (2015) 1

[3] B. Adams et al., “A test-facility for large-area microchannel plate detector assemblies using a pulsed sub-picosecond laser”, Rev. Sci. Instrum. **84** 061301 (2013)

[4] Theia Collaboration (M. Askins et al.), “Theia: an Advanced Optical Neutrino Detector”, Eur.Phys.J. **C80** (2020) 5, 416

[5] C. Aberle, A. Elagin, H. J. Frisch, M. Wetstein, L. Winslow, “Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors”, JINST **9** P06012 (2014)

[6] A. Elagin, H. Frisch, B. Naranjo, J. Ouellet, L. Winslow, T. Wongjirad, “Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector by Fast Timing”, Nucl. Instr. Meth. Phys. Res. **A849,** (2017) pp.102-111

[7] R. Jiang and A. Elagin, “Space-Time Discriminant to Separate Double-Beta Decay from 8B Solar Neutrinos in Liquid Scintillator”, arXiv:1902.06912, submitted to Nucl. Instr. Meth. Phys. Res. **A**

[8] J. Gruszko, B. Naranjo, B. Daniel, A. Elagin, D. Gooding, C. Grant, J. Ouellet and L. Winslow, “Detecting Cherenkov light from 1–2 MeV electrons in linear alkylbenzene ”, JINST **14** (2019) no.02, P02005

[9] A. Li, A. Elagin, S. Fraker, C. Grant, and L. Winslow, “Suppression of Cosmic Muon Spallation Backgrounds in Liquid Scintillator Detectors Using Convolutional Neural Networks”, Nucl. Instr. Meth. Phys. Res. **A947** (2019) 162604

[10] M. Li, Z. Guo, M. Yeh, Z. Wang and S. Chen, “Separation of Scintillation and Cherenkov Lights in Linear Alkyl Benzene”, Nucl. Instr. Meth. Phys. Res. **A830** (2016) 303

[11] J. Caravaca, F.B. Descamps, B.J. Land, J. Wallig, M. Yeh and G.D. Orebi Gann, “Experiment to demonstrate separation of Cherenkov and scintillation signals”, Phys.Rev. **C95** (2017) 055801

[12] J. Caravaca, F.B. Descamps, B.J. Land, J. Wallig, M. Yeh and G.D. Orebi Gann, “Cherenkov and Scintillation Light Separation in Organic Liquid Scintillators”, Eur.Phys.J. **C77** (2017) no.12, 811

[13] T. Kaptanoglu, M.~Luo, B.~Land, A.~Bacon and J.~Klein, “Spectral photon sorting for large-scale Cherenkov and scintillation detectors”, Phys.Rev. **D101** (2020) 7, 072002

[14] F. Léonard, private communication started at CPAD 2018 workshop

[15] Young, S. M., Sarovar, M. & Léonard, F. General modeling framework for quantum photodetectors. *Phys. Rev. A* **98**, 063835, doi:10.1103/PhysRevA.98.063835 (2018)

[16] F. Leonard, “Novel Designs for Few Photon Detection Based on Quantum and Nanoscale Systems”, presentation at CPAD 2019, slides 13-17, https://agenda.hep.wisc.edu/event/1391/session/9/contribution/104/material/slides/1.pptx

[17] ANNIE Collaboration (A.R. Back et al.), “Measurement of Beam-Correlated Background Neutrons from the Fermilab Booster Neutrino Beam in ANNIE Phase-I”, JINST **15** (2020) 03, P03011

[18] J. Gruszko et al., “NuDot: Double-Beta Decay with Direction Reconstruction in Liquid Scintillator”, *2nd Place Prize Winner Poster* at XXVIII International Conference on Neutrino Physics and Astrophysics, Heidelberg 2018, DOI:10.5281/zenodo.1300693

[19] E. Oberla and H. Frisch, “The Design and Performance of a Prototype Water Cherenkov Optical Time-Projection Chamber”, Nucl.Instr.Meth.Phys.Res A814 (2016) 19-32