Cherenkov/scintillation separation via spectral photon sorting with dichroicons for next-generation neutrino detectors

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Spectral photon sorting with dichroic filters is realized with the dichroicon device, which diverts long and short wavelength photons to separate PMTs with minimal photon loss. This technique allows a detector to identify a pure population of long-wavelength Cherenkov photons outside of the scintillator spectrum. Identification of Cherenkov photons in a bright liquid scintillator is a powerful tool for background rejection, as Cherenkov photons carry directional information, and the ratio of Cherenkov to scintillation light can be used for particle identification. Here we describe a simulation of a next-generation 50 kt liquid scintillator neutrino detector utilizing dichroicons for photon detection. Included is preliminary work on direction reconstruction, and an exploration of alpha tagging, both of which would be beneficial in reducing backgrounds for a wide range of neutrino physics topics.

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Next-generation neutrino detectors such as THEIA [1] plan to detect neutrino interactions via photons produced in a scintillating target medium. To ensure high energy resolution, scintillators with high light yields are preferred, as the energy resolution is typically limited by photon statistics. Consequently, the number Cherenkov photons produced in these target media is typically several orders of magnitude fewer than the scintillation. This disparity in intensity makes Cherenkov photons difficult to identify, however they carry information not found in the scintillation signal, including the direction and type of charged particle that produced the light.

Direction is encoded in the angular distribution of the Cherenkov photons, which are emitted at a constant angle with respect to the momentum of the producing particle. Reconstructing direction would allow for directional rejection of solar neutrinos or other directional sources in future neutrino programs, as well as an enhanced ability to study the directional solar neutrinos. Particle type can be inferred with the relative amount of Cherenkov and scintillation light, as alpha particles, for instance, typically produce no Cherenkov photons while still producing a bright scintillation signal. Tagging these alphas with their lack of Cherenkov photons would be beneficial in reducing radioactive backgrounds, particularly in the energy region of interest for neutrinoless double beta decay searches.

Identifying the Cherenkov photons present in a bright scintillation signal can be approached in several ways. The Cherenkov photons are typically emitted very promptly compared to scintillation photons, so the signal can be identified by looking early in the event with very fast PMTs [2]. The scintillating cocktail can be adjusted chemically such that the scintillation light comes much later [3, 4], lessening the requirement for fast PMTs. The scintillator light yield can also be decreased by combining it with a non-scintillator like water [5, 6], which reduces the suppression of Cherenkov light at the expense of energy resolution. Finally, the Cherenkov and scintillation light can be discriminated by wavelength, as scintillation is typically within a narrow emission band, while Cherenkov is broad spectrum light. The dichroicon [7] is a device which performs such spectral sorting, by separating the photons into long wavelength PMTs (mostly Cherenkov) and short wavelength PMTs (mostly scintillation) using dichroic filters.

A simulation model of the dichroicon has been developed in *Chroma* [8, 9] and calibrated against the measurements of a benchtop prototype [7]. This model was simplified and scaled up to use a 20" diameter large area PMT to collect photons passed by the short-pass dichroic filters, and a cylindrical 5" PMT to collect the long wavelength photons reflected by the dichroic filters shown at the top of Fig. 1. This dichroicon unit was then tiled around a cylindrical volume to simulate a large-scale neutrino detector, seen from the inside at the bottom of Fig. 1. In this model a 50 kt volume of the scintillator LAB with 2g/L of PPO [10] is surrounded by 90% coverage of simplified dichroicons, which gives effectively 90% coverage of both long and short wavelength photons, as the dichroic filters allow the long and short PMTs share the same solid angle. Using this model, we have begun to evaluate the impact of spectral photon sorting on future neutrino experiments.

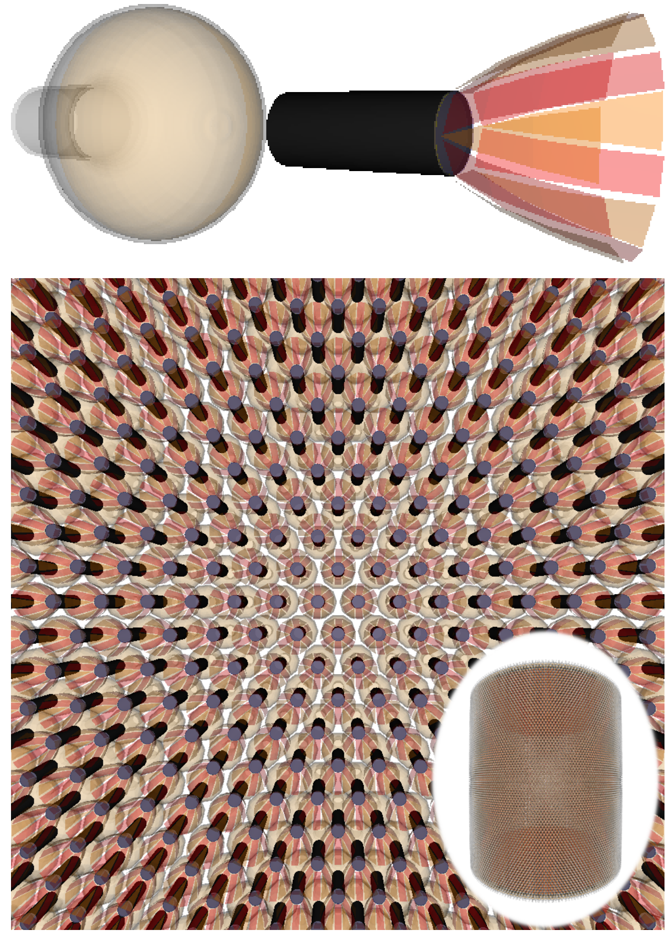

FIG. 1. A rendering of the *Chroma* geometry for (top) a dichroicon unit with (left to right) 20" large area PMT, cylindrical 5" long-wavelength PMT, and dirchroic filter concentrator, and (bottom) the dichroicon units tiled to create a 50 kt neutrino detector, viewed from inside the detector, with the full cylindrical geometry shown in the inset.

A reconstruction algorithm developed in [11] has been modified such that it uses hit time information from all (short and long wavelength) PMTs to perform a position and time fit, and then uses the angular distribution of photons detected on long wavelength PMTs to perform a direction fit. An angular distribution of long-wavelength PMTs that detected photons from 2.6 MeV electrons generated at the center is shown in Fig. 2, which clearly shows the Cherenkov topology. The angular resolution achieved when applying this algorithm to electrons generated at the center of this simulation is shown in Fig. 3, and indicates an angular resolution of 35 deg at 5 MeV, which can be compared to the 27 deg resolution achieved

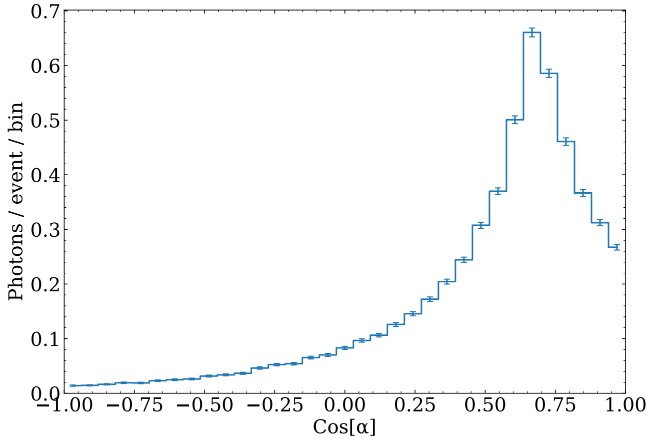

FIG. 2. The distribution of the cosine of the angle between photons detected by long-wavelength PMTs and the initial direction of a 5 MeV electron simulated at the center of the detector geometry. The Cherenkov topology is clearly visible.

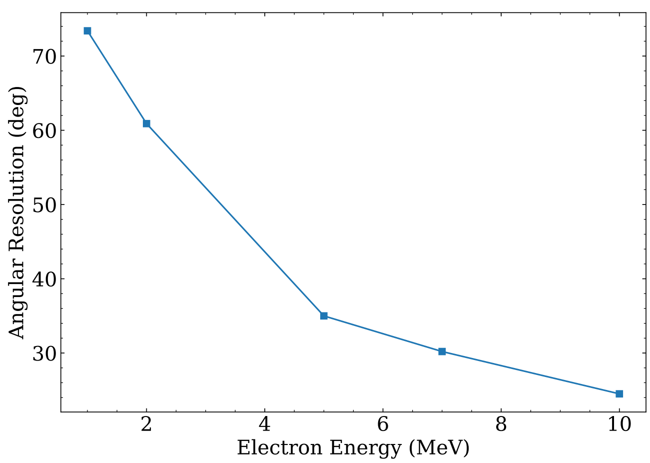

FIG. 3. The angular resolution across a range of energies for electrons simulated at the center of the 50 kt liquid scintillator detector.

by the water-Cherenkov detector SNO [12] at the same energy.

Alpha particle identification has been explored by simulating alpha and beta particles with the same quenched energy (number of scintillation photons) and inspecting the signal on the long-wavelength PMTs, which are primarily sensitive to Cherenkov photons. A quenched energy comparable to neutrinoless double beta decay in ^{130}Te is chosen to highlight potential background rejection capabilities. The mean number of long-wavelength hits is indeed higher for betas than alphas as shown in Fig. 4 due to Cherenkov production with betas. The detected long wavelength photons from alphas are all scintillation, and indicate that the filters could be optimized for better rejection of scintillation. Fig. 5 shows a clear Cherenkov signal in the hit time residuals of betas at early times, which would allow for discrimination of alphas in a neutrinoless double beta decay region of interest. A similar method provides some discrimination between single and double beta events, as can be seen in the ^{130}Te $0\nu\beta\beta$ plots in Figs. 4 and 5, which could further constrain backgrounds.

The developed simulation already indicates that dichroicons and spectral sorting will offer powerful background rejection in future large-scale neutrino detectors, and there are still many potential improvements to these techniques to explore. *Chroma* offers a flexible path forward for testing different configurations of the dichroicon concept, including other readout methods and geometries. These paths are being explored and incorporated into a robust simulation that can be used to evaluate the sensitivity of such a detector to future neutrino programs.

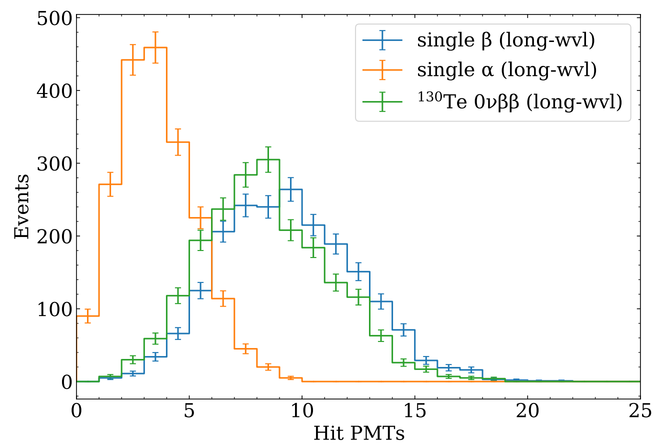

FIG. 4. The number of long-wavelength PMTs that detected photons for alpha and beta events with the same quenched energy as ^{130}Te neutrinoless double beta decay, showing alpha/beta discrimination based on Cherenkov photon identification in a 50 kt liquid scintillator detector.

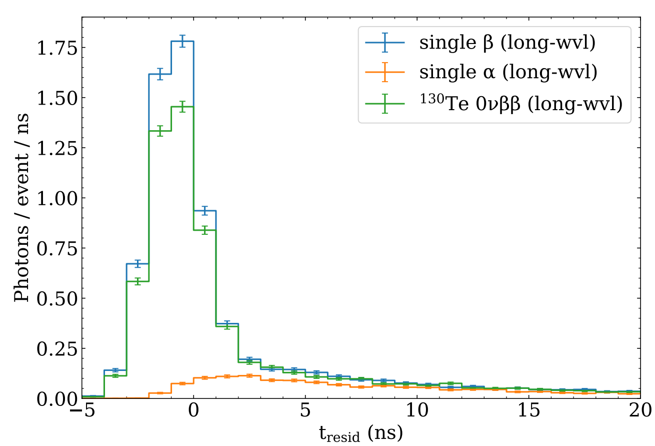

FIG. 5. The hit time residuals of long-wavelength PMTs for the events shown in Fig. 4. The Cherenkov is clearly visible at early times for the beta events.

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