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Improving photoelectron counting and particle identification in scintillation detectors with Bayesian techniques

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ABSTRACT

Many current and future dark matter and neutrino detectors are designed to measure scintillation light with a large array of photomultiplier tubes (PMTs). The energy resolution and particle identification capabilities of these detectors depend in part on the ability to accurately identify individual photoelectrons in PMT waveforms despite large variability in pulse amplitudes and pulse pileup. We describe a Bayesian technique that can identify the times of individual photoelectrons in a sampled PMT waveform without deconvolution, even when pileup is present. To demonstrate the technique, we apply it to the general problem of particle identification in single-phase liquid argon dark matter detectors. Using the output of the Bayesian photoelectron counting algorithm described in this paper, we construct several test statistics for rejection of backgrounds for dark matter searches in argon. Compared to simpler methods based on either observed charge or peak finding, the photoelectron counting technique improves both

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energy resolution and particle identification of low energy events in calibration data from the DEAP-1 detector and simulation of the larger MiniCLEAN dark matter detector.

1. Introduction

Scintillators are a key component of many neutrino and dark matter experiments due to their relatively low cost and high light yield. In addition, many scintillators can be used for particle identification when the time profile of the scintillation light is sensitive to the energy loss characteristics of different particles. Experiments that require low energy thresholds, high energy resolution, and/or high levels of background rejection often combine a scintillating target medium with an array of photomultiplier tubes (PMTs) and a data acquisition system with sensitivity to individual photoelectrons. In order to fully capture the scintillation time profile, the PMT pulses are typically recorded using a waveform digitizer.

Many common scintillators produce light on at least two characteristic time scales. Particle identification in such scintillation detectors employs two related features: the scintillation time scales, and the probability of populating the different time scales, which depends on the particle's energy loss characteristics. The canonical approach (examples include MicroCLEAN [1], DEAP-1 [2], XMASS [3], XENON-10 [4], GERDA [5], KamLAND [6]) to time-based particle identification with a digitized time-dependent voltage waveform $V(t)$ is to estimate the fraction of the light produced on a fast timescale relative to the total amount of light produced in the event. This particle discriminant we refer to as the prompt-fraction, or f_p, and is defined as

$$f_p = \frac{\int_{T_i}^{\epsilon} V(t)dt}{\int_{T_i}^{T_f} V(t)dt}, \tag{1}$$

where T_i is some time before the prompt peak, T_f is the time defined by the end of the event window, and ϵ depends on the timing characteristics of the scintillator. Typically the f_p parameter is used to place a cut or perform some likelihood-based analysis in order to select a certain class of interactions in the scintillator. In later sections, we refer to f_p *leakage* as the probability of events from a certain class of background leaking into the f_p signal region of interest. Although particle identification with f_p is robust in the sense that it is fairly insensitive to fluctuations in the scintillation light production or PMTs, its discrimination power breaks down at low energies beyond statistical effects because it loses information about the precise timing and charge of individual photoelectrons created by photons produced in the scintillator.

The best strategy to count photoelectron (PE) pulses in a waveform depends on the intensity and time structure of the light, as well as the characteristics of the PMT electronics. A typical single photoelectron pulse from a large area PMT, shown for cryogenic measurements of a Hamamatsu Photonics R5912-02-MOD[1] 8" PMT in Fig. 1, spans 20 ns or more [7]. Additionally, there are large pulse-to-pulse variations in the amplification of a single photoelectron, resulting in a fairly broad charge distribution, shown again for the R5912-02-MOD in Fig. 2. If the light intensity observed by a PMT is very low or the time constant for scintillation light is very long (hundreds of nanoseconds or more) compared to the duration of a single photoelectron pulse, then overlap of pulses is improbable. Photoelectrons can be counted by searching for peaks in the waveform, thus eliminating the impact of the PMT charge distribution on the counting procedure.

However, if multiple photoelectrons are likely to be detected by a PMT in a time much shorter than the single photoelectron pulse duration, such as from Cherenkov or fast scintillation light, peak finding is a poor photoelectron counting strategy. Peaks from different photoelectrons may not be clearly resolved in the waveform, resulting in a systematic bias toward under-counting. A simple and unbiased technique for photoelectron counting in this case would be to integrate the waveform and divide by the mean charge of a single photoelectron. Due to the broad charge distribution of most PMTs, this normalized integral charge procedure in a waveform with pulse pileup will have more variance than peak counting in a waveform without pileup. Fundamentally, information is lost in the pileup that is difficult to recover.

Realistic detectors typically span both of these extreme cases. Many experiments observe both Cherenkov or fast scintillation *and* slow scintillation light. Moreover, the light intensity observed by a given PMT can vary dramatically depending on the energy of the event and its location in the detector. To cover all these cases, we have designed a photoelectron counting method that combines both peak finding and normalized charge integration by using Bayes' Theorem to incorporate our external knowledge of how likely photoelectron pileup is for different events, PMTs, and times in the waveform. The method also outputs an estimated photoelectron production time for each pulse, which can be analyzed for particle identification purposes in many scintillators.

To make the discussion concrete, we focus the photoelectron identification procedure specifically on liquid argon scintillation light, primarily in the MiniCLEAN dark matter experiment, but the general approach can be easily adapted to the constraints of other experiments. In Section 3 we use a GPU-based fast Monte Carlo simulation of the MiniCLEAN detector to motivate the need for improvement in the canonical prompt-fraction particle identification technique. The Bayesian photoelectron counting method is described in Section 4, and improved particle identification test statistics are defined in Section 5. We then demonstrate the effectiveness of the Bayesian photoelectron counting method in Section 6 with gamma simulation and calibration data collected from the DEAP-1 detector underground at SNOLAB. In Section 7, we describe the MiniCLEAN dark matter experiment and motivate the need for improved particle identification specifically in large liquid argon dark matter detectors. Finally, Section 8 applies the Bayesian techniques to a complete Monte Carlo simulation of MiniCLEAN.

2. Single-phase dark matter detection with liquid argon

Laboratory searches for dark matter in the form of weakly-interacting massive particles (WIMPs) require sensitivity to nuclear recoils with tens of keV of kinetic energy. WIMP-induced recoils need to be distinguished from other sources of low energy particle tracks, such as fast neutrons and radioactive decay in detector materials. Dark matter experiments must simultaneously achieve very low levels of natural radioactivity and very high rejection factors for remaining sources of backgrounds.

Liquid argon offers a promising target for WIMP detection due to its combination of extremely low cost, moderate cryogenic requirements (similar to liquid nitrogen), straightforward

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[1] Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.