Measurement of the scintillation efficiency for low energy nuclear- and electronic-recoils in liquid argon detector for WIMP search

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Abstract. A liquid argon (LAr) scintillation detector is known to offer several attractive features to search for WIMP dark matter. A key quantity in this search is the conversion efficiencies of nuclear- and electronic-recoils (NR and ER) energy deposition into the scintillation signal. Two measurements are performed to study these properties: (1) scintillation efficiency for a few tens of keV NR under electric fields up to 3 kV/cm; (2) efficiency for ER ranging from a few keV to 1 MeV at null field. We present the results of these measurements and discuss the LAr response based on traditional models.

1. Introduction
Liquid argon (LAr) scintillation detectors are attractive relative to searching for dark matter in the form of the weakly interacting massive particle (WIMP) with mass in the GeV to TeV range [1, 2]. The main features of the detector are efficient conversion of energy deposition into observables (scintillation and ionization signals); powerful discrimination of the nuclear recoil (NR) signal from the electronic recoil (ER) background using the scintillation pulse shape; and relatively high recoil energy for WIMP-Ar nuclear scattering.

The conversion efficiencies of NR and ER energy depositions into the observables are key quantities of the detector, and these efficiencies depend on both the recoil energies and an electric field applied in the detector. Although several groups have measured these efficiencies, systematic understanding and indepth discussions that include low energy and high electric fields have not been conducted. We present the results of two measurements related to LAr properties: measurement of the scintillation efficiency for a few tens of keV of NR under electric fields of 0–3 kV/cm (section 2), and measurement of a few keV to 1 MeV ER at null field (section 3).

2. Measurement for NR under electric fields up to 3 kV/cm
We measured the scintillation efficiency for NR using a double-phase time projection chamber (TPC). The observables of this detector are the primary scintillation signal (S1) and the secondary electroluminescence signal (S2) caused by ionization electrons extracted to the gas phase. The TPC has a sensitive region of diameter of 6.4 cm and height of 10 cm with two 3 in. photomultiplier tubes (PMTs). A Cockcroft-Walton circuit is mounted in the LAr surrounding the TPC to form an electric field inside the TPC. A $^{252}$Cf neutron source is placed at a distance of 1 m from the TPC. A NaI(Tl) scintillator located beside the source provides timing information.
Figure 1. S1 spectrum of the NR data sample taken under 3 kV/cm and MC-derived spectrum simultaneously fitted to the data for the entire TOF range of interest (43–111 ns). The MC spectra (colored lines) representing the contribution of each TOF bin, from 43–47 ns (red) to 107–111 ns (violet), are also shown.

Figure 2. Scintillation efficiencies for NR referenced to 511 keV γ-ray line ($\mathcal{L}_{\text{eff}}$) as a function of NR energy. The colored solid lines represent the results from this work, and the corresponding dashed lines are extrapolations.

by detecting the associated γ-ray. The incident neutron energy from the source is reconstructed based on time of flight (TOF), i.e., the time difference between the NaI(Tl) and TPC signals.

Energy deposits by the neutrons are simulated in a Geant4-based Monte Carlo (MC) simulation. Observed S1 and S2 spectra of each TOF bin (4 ns interval) are fit with spectra derived from the MC and an NR model. The fit is performed simultaneously with both S1 and S2 spectra of each TOF bin (total 17 bins) taken under different fields (total 6 points) to obtain several parameters in the model. Figure 1 shows an example of the S1 spectra and the fitted MC spectra taken under 3 kV/cm. Figure 2 shows the scintillation efficiency $\mathcal{L}_{\text{eff}}$ under electric fields referenced to the 511 keV γ-ray line at null field. The uncertainty of the result is evaluated as approximately 10% through the energy and field range. More details can be found in [3].

3. Measurement for ER from a few keV to 1 MeV

The scintillation efficiency for ER at null field is measured with a single-phase detector. The detector consists primarily of polytetrafluoroethylene (PTFE) with a sensitive volume of a diameter of 6.4 cm and length of 5 cm, viewed by the two 3 in. PMTs. The LAr region surrounding the detector has four 2 in. PMTs and serves as an active veto for ambient radiation. The vessel for LAr containment is surrounded by a passive shield consisting of 2 cm thick oxygen free copper and 10 cm thick lead.

Data are taken using a variety of calibration sources (figure 3). Relatively high energy γ-ray sources, such as $^{22}\text{Na}$, $^{137}\text{Cs}$, and $^{133}\text{Ba}$, are placed outside the vessel. A $^{241}\text{Am}$ γ-ray source is placed in the active veto region. An event from the $^{241}\text{Am}$ is proved by detecting the associated α-ray with the veto region’s PMTs. The $^{252}\text{Cf}$ neutron source is also used to induce 110 and 197 keV quasimonoenergetic lines from $(n,n’\gamma)$ reaction with $^{19}\text{F}$. As a few keV ER calibration source, we use $^{37}\text{Ar}$ in atmospheric argon [4]. It produces X-rays and Auger electrons with a total energy release of 2.8 keV. Figure 4 shows the measured scintillation efficiency with respect to that of 511 keV as a function of ER energy. Decreased efficiency below 100 keV can be attributed to the Thomas-Imel box model [5]. This trend is similar to that observed in liquid xenon scintillation detectors [6]. More details, including the absolute light detection efficiency of the detector and uncertainties of this measurement, will be reported in [7].
Figure 3. (Left) Scintillation spectrum measured at null field, with the Gaussian plus background model fitting around the 2.8 keV peak from $^{37}$Ar. (Right) Spectra measured by the calibration sources with the fit of corresponding full absorption peaks.

Figure 4. Measured scintillation efficiency with respect to that of 511 keV (black point) fit with the Thomas-Imel box model (red line). Since a higher energy $\gamma$-ray produces multiple interaction sites, the fit range is constrained to below 200 keV. Comparison with the ARIS dataset [8] is also shown (blue and cyan points).

4. Conclusion
We perform two measurements related to the systematic understanding of LAr response. These results make use of the detector design and interpretation between experimental data and physics processes in the field of WIMP dark matter search. These understandings are expected to be useful to other physics experiments using a LAr detector.

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