Nuclear Inst. and Methods in Physics Research, A 910 (2018) 22–25

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Scintillation and ionization ratio of liquid argon for electronic and nuclear recoils at drift-fields up to 3 kV/cm

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ARTICLE INFO

Keywords:
Argon
Two-phase detectors
Time projection camber
Particle identification
Dark matter

ABSTRACT

A two-phase argon detector has high discrimination power between electron recoil and nuclear recoil events based on the pulse shape discrimination and the ionization/scintillation ratio (S2/S1). This character is very suitable for the dark matter search to establish the low background experiment. However, the basic properties of S2/S1 of argon are not well known, as compared with xenon. We report the evaluation of S2/S1 properties with a two-phase detector at drift-fields of 0.2–3.0 kV/cm. Finally, the discrimination power against electron recoil background of S2/S1 is discussed.

1. Introduction

Two-phase noble gas detector technology has been used widely for weakly interacting massive particle (WIMP) dark matter detection experiments (e.g. DarkSide-50 [1,2], LUX [3], PandaX-II [4], and XENON-1T [5]). Its technology aims for electron recoil (ER) background rejection from nuclear recoil (NR) signal using ionization(S2)/scintillation(S1) ratio. However, DarkSide-50 does not make use of the S2/S1 ratio for background rejection. It is well known that the S1 and S2 light yields depend on the strength of electric field, imposed in drift interaction region, mainly due to recombination effect of ionizing electrons. Such properties are well measured by previous experiments, such as SCENE [6] (0–0.97 kV/cm, 10.3–57.3 $\mathrm{keV_{nr}}$, nr : nuclear recoil) and ARIS [7] (0–0.5 kV/cm, 7.1–117.8 $\mathrm{keV_{nr}}$) where drift-fields are lower than 1 kV/cm and the ER/NR discrimination power of S2/S1 is not explicitly described. In this paper, we focus on the drift-field dependence of S2/S1 properties up to 3.0 kV/cm. Although liquid argon (LAr) scintillation has strong pulse shape discrimination (PSD) power [8], to simplify, S2/S1 discrimination power is separately discussed from PSD property in this paper.

2. Experimental setup and basic performance

This experiment was conducted in the Waseda liquid argon test stand [9,10]. Fig. 1 shows the schematic view of a two-phase detector we developed for this study. It mainly consists of a polytetrafluoroethylene (PTFE) cylinder with an active LAr volume of $\phi 6.4\ \mathrm{cm} \times \mathrm{H}10\ \mathrm{cm}$ (≈ 0.5 kg). Two photomultiplier tubes (PMTs, HAMAMATSU R11065) are located on the top and bottom sides of the fiducial volume, where they are placed in contact with the transparent indium-tin-oxide (ITO) coated quartz light guides. A stainless steel wire grid plane is inserted 1 cm below the top light guide. Tetraphenyl-butadiene (TPB) wavelength shifter (from ultra vacuum violet scintillation light to visible light) is deposited on the inner surfaces of the detector by vacuum evaporation method. The liquid argon surface is kept centered in height between the top light guide and the wire grid, and the operation inner gas pressure is kept at 1.5 atm stably. To form a high electric field time projection chamber (TPC), a Cockcroft–Walton circuit (CW) generates high voltage (max: 30 kV) in the liquid argon and makes the drift-field (max: 3.0 kV/cm) in the detector. The potential difference of 4.5 kV is applied between the anode and the wire grid plane. By using the relative dielectric constant ε and the position of liquid surface, the fields for electron extraction (in liquid, $\varepsilon = 1.53$) and S2 emission (in gas, $\varepsilon = 1.00$) are calculated to be 3.6 kV/cm and 5.4 kV/cm, respectively.

For testing the system, ^{22}Na and ^{252}Cf radioactive sources are used for pure γ-ray (ER) events and neutron (NR) events, respectively. These sources are located 1 m apart from the center of the TPC, outside of the chamber. To detect the associated γ-ray and determine the start time of flight (TOF), an NaI(Tl) scintillation counter is placed behind the source. In this setup, TOF = 3 ns for γ-ray and TOF = 50 ns for 2 MeV neutron. The data acquisition system utilizes a 250 mega-samples per second flash ADC (SIS3316) with a three-channel coincidence trigger with the top PMT, the bottom PMT and the NaI(Tl) scintillator (coincidence width: 1 μs). With this TPC configuration, the detection efficiency of S1 light is measured to be 5.9 ± 0.3 $\mathrm{p.e./keV_{ee}}$ (ee : electron equivalent) for 511 keV γ-ray at null field, and the lifetime of the drift electron is measured to be 1.9 ± 0.1 ms. Fig. 2 shows the drift velocity determined by using the collimated ^{22}Na and ^{60}Co γ-ray data, compared with a model from ICARUS [11] and Walkowiak [12].

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https://doi.org/10.1016/j.nima.2018.09.019
Received 4 July 2018; Received in revised form 4 September 2018; Accepted 6 September 2018
Available online xxxx
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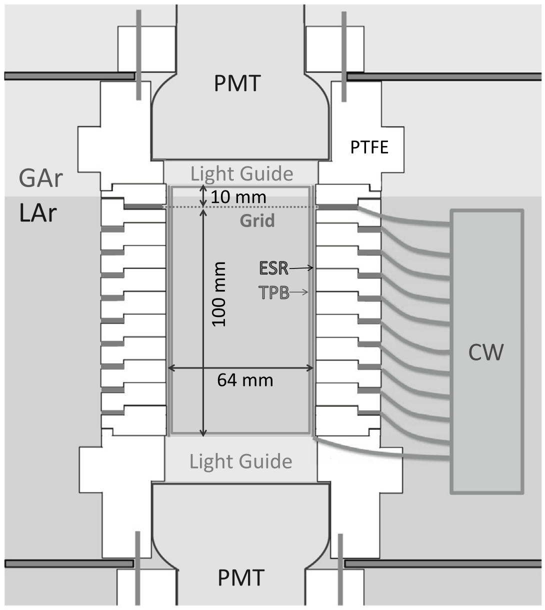

Fig. 1. Cross section of the detector.

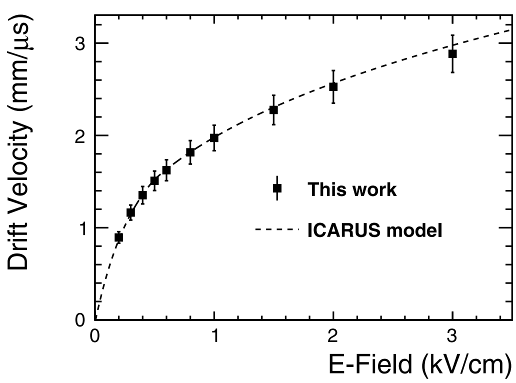

Fig. 2. Field dependence of drift velocity. The data points are our results, and the dashed line is calculated using model in the reference (ICARUS [11] and Walkowiak [12]).

3. Measurements of ionization/scintillation ratio

The upper plot in Fig. 3 shows S2/S1 ratio ($\log_{10}(\mathrm{S2/S1})$) for pure ER events from ^{22}Na source, as a function of S1 light yield at the drift-field of 1.0 kV/cm. The mean value (μ) and 1σ band are obtained by the Gaussian fit at each slice of S1 light yield.

The ^{252}Cf data at 1.0 kV/cm, where neutron events are selected by using TOF information (TOF $>$ 20 ns), is shown in the bottom plot of Fig. 3. The solid line is the mean(μ) of NR events, overlaid with a band of ER events from ^{22}Na at the drift-field of 1.0 kV/cm. Conversion calculation from S1 to recoil energy E_{nr} in the unit of $\mathrm{keV_{nr}}$ indicated by upper axis of the plot will be discussed in the next section.

For ER events, the S2/S1 ratio has a minimum around S1 $\sim$ 30 p.e. as shown in Fig. 3 (top). This structure has been also observed in the LXe experiments [13,14], and is explained by the difference in the recombination mechanism for events below and above the minimum. When the ER events have smaller recoil energy and hence short tracks (typically shorter than the electron diffusion length), electron-ion pairs are concentrated in a small sphere and they cause "box recombination" as described by the Thomas–Imel Box (TIB) model [15]. In this case, recombination probability becomes larger for larger energy, then the S2/S1 ratio decreases. Whereas, when the recoil electrons have larger

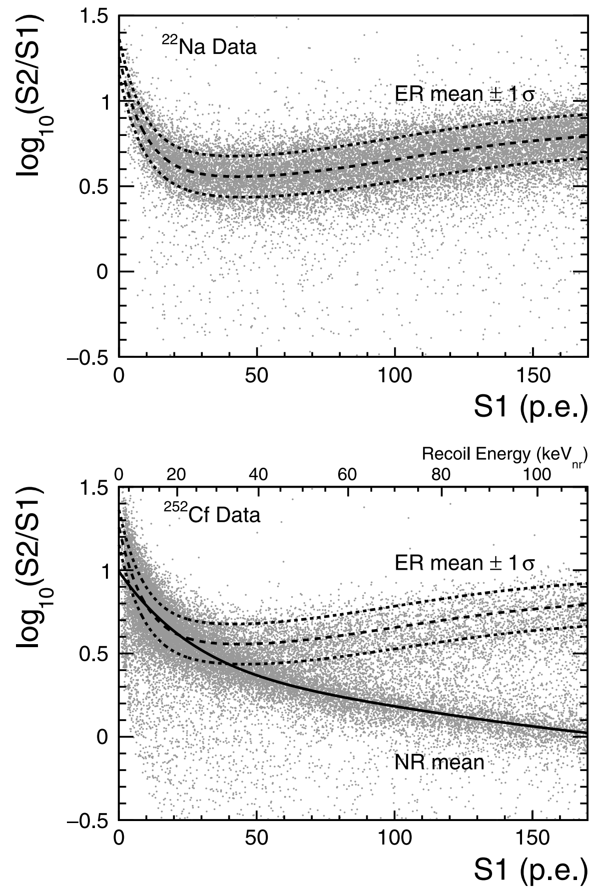

Fig. 3. $\log_{10}(\mathrm{S2/S1})$ as a function of S1 light yield at the drift-field of 1 kV/cm. Top : ^{22}Na data, Bottom : ^{252}Cf data.

energy and longer tracks, electron-ion pairs are distributed in a pillar shape and cause "columnar recombination" as described by the Doke–Birks model [16]. In this case, recombination probability becomes smaller for larger energy (with small dE/dx), then the S2/S1 ratio increases. For NR events, the tracks are short in the energy from keV to several MeV, hence they are always described by the TIB model and the S2/S1 ratio decreases monotonically as S1 increases.

The same measurements and procedures are performed for various drift-fields, 0.2, 0.5, 1.0, 2.0, 3.0 kV/cm. Energy dependence of the mean values, μ_{ER} and μ_{NR} at each electric field is shown in Fig. 4. As the electric field becomes higher, since recombination probability decreases, more S2 light yield is observed compared to S1 light yield. The standard deviations, σ_{ER}, from Gaussian fitting to ER events are summarized in Fig. 5, while the one for NR events (σ_{NR}) is flat at 0.06, not depending on S1 nor drift-field.

4. Recoil energy and recombination law

In order to evaluate the ER/NR discrimination power and its dependences of energy and electric field, we need to convert S1 light yield to nuclear recoil energy E_{nr}. In this paper, the quenching factor measured by SCENE [6] below 1 kV/cm is extrapolated up to 3 kV/cm.

Fig. 6 shows the drift-field dependence of the total quenching including nuclear- and electric-quenching for S1 light yield measured by SCENE [6] at 36.1 $\mathrm{keV_{nr}}$ where the data points are only available up to 1 kV/cm. Extrapolation for higher electric field is performed by taking into account recombination law.

The S1 light yield can be expressed as a function of recoil energy E_{nr},

$$\mathrm{S1} = LY \cdot E_{\mathrm{nr}} \cdot \mathcal{L}_{\mathrm{eff}} \cdot \frac{\alpha + R}{\alpha + 1}, \tag{1}$$