Status of R&D on double phase Argon detector: the ANKOK project

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Abstract. Liquid argon is known to be an excellent target material for WIMP dark matter direct search experiment. Since PY2012, we are working on a new dark matter search project (ANKOK) at Waseda university using the double phase argon detector technique. As a first stage of the project, we are currently concentrating our effort on improvement of the scintillation light detection efficiency so that the experiment has better sensitivity for low mass down to 10 GeV/$c^2$ WIMP. In this report, we describe R&D status of the ANKOK experiment.

1. Introduction

Liquid argon is known to be an excellent target material for WIMP (weakly interacting massive particle) dark matter direct search experiment. Use of its ionization and scintillation signals, and scintillation pulse shape provides strong discrimination ($>10^8$) between the electron and nuclear recoil events. Since liquid argon is inexpensive, it has a large advantage for the future large (ton scale) experiments. Relatively small atomic mass ($A=40$) gives higher nuclear recoil energy for WIMP-Ar nuclear scattering. Thus argon has potential advantage for low mass WIMP ($\sim$10 GeV/$c^2$) search. On the other hand, the 128 nm VUV scintillation light of argon is relatively hard to detect with nominal photo sensors, and use of wavelength shifter reduces the light detection efficiency, $\sim$5 pes/keVee for argon [1, 2] compared to $\sim$15 pes/keVee xenon [3].

Since PY2012, we are working on a new dark matter search project (ANKOK) at Waseda university using double phase argon detector technique. We are currently concentrating our effort on further improvement of the scintillation light detection efficiency so that the experiment has better sensitivity for low mass ($\sim$10 GeV/$c^2$) WIMP. In the next few years, we are targeting to construct a detector with fiducial mass of several tens of kg, and to collect the underground physics data.

In January 2013, we have built a double phase argon detector with fiducial mass of 10 kg. Target of this study is to establish basic techniques, such as safety handling of the cryogenic liquid, purification of liquid argon, and stable operation of the double phase detector. Selected results on this study are described in section 3.

In August 2013, we have built a simple single phase liquid argon detector with fiducial mass of 0.2 kg. Target of this study is to maximize the light collection efficiency of the argon scintillation light, and to quantitatively understand the background discrimination ability of pulse shape discrimination, which are described in section 4.
2. Waseda Liquid Argon Test Stand

Figure 1. Schematic view of Waseda liquid argon test setup (left), and monitoring plots for 10 days of detector operation, inner vessel pressure (right-top), liquid surface level (right-middle), liquid argon purity (right-bottom).

Waseda liquid argon test stand is located at Nishi-Waseda campus of Waseda university. Figure 1 shows the schematic view of the cryogenic and argon purification system. The cryostat has its size of about 30 cm diameter and 100 cm length (75L vessel). A Gifford-MacMahon(GM) cryocooler (Sumitomo CH-110) with available cooling power of 200W (@90K) is mounted on top of the vessel. A molecular turbo pump (Pfeiffer Hipace-300) is also mounted on top of the vessel and the vessel is evacuated to $\sim 10^{-4}$ Pa for 2 weeks to remove impurities inside the vessel. Purification of liquid argon is firstly performed during filling the vessel. Commercial liquid argon which typically contains impurity about 1 ppm is passed through a hand-made purification cartridge [4]. Additionally a gas recirculation and purification system (SAES Microtorr) has been implemented to maintain and improve the liquid argon purity. We note that both the purification cartridges have ability to remove electronegativities (oxygen, water, etc) but not for nitrogen impurities which can be affected to scintillation light yield.

Figure 1 shows monitoring summary plots for $\sim$10 days of data taking run. During this period, we have successfully operated the detector: Inner vessel pressure has kept 1.35±0.1 atm; liquid surface level has kept within 1mm; attenuation time of drift electron has been stable at $\sim 200\ \mu s$, which corresponds to $\sim 1.5$ ppb O$_2$ equivalent impurity.

3. Results from 10 kg Double Phase Detector

The 10 kg double phase detector has radius of 25 cm and drift length of 20 cm. Maximum -20 kV (1 kV/cm) of high voltage is generated by using 20-stage Cockcroft-Walton (CW) generator located inside the liquid argon, and each stage of CW generator is connected to field shaping ring made by 1/8” stainless-steel tube. Figure 2 shows picture of the 10 kg double phase detector from the backview of CW location. Argon scintillation light is detected by using 5 PMTs located bottom of the detector, 4 of 2” PMT (HAMAMATSU R6041-506) and 1 of 3” PMT (HAMAMATSU R11065). These PMTs do not have quantum efficiency for 128 nm argon scintillation light, so surface of PMT window is coated by TPB wavelength shifter (128 nm to 430 nm). Quantum efficiencies for 2” PMT and 3” PMT are $\sim 25\%$ and $\sim 30\%$, respectively at 430 nm. For simplicity, in this detector we do not locate reflectors at the side of the detector, thus the geometric acceptance for scintillation light collection is small (<3%). Top of the detector is 1 mm-thick copper anode plate, and a stainless-steel grid plate with 100 um thickness and 4 mm
pitch is inserted 1 cm bellow the anode plate. Liquid surface is kept in the middle of the anode plate and the grid plate, and $\sim 3$ kV/cm of electric field is supplied for drift electron extraction. The PMT signal is read out through 100MS/s 14bit FADC (CAEN V1724). We have collected electron recoil event using cosmic muon triggered by external hodoscope. Figure 2 shows typical electron recoil event. This event has significant slow component with time constant of $\sim 1.5$ $\mu$s (top plot) in S1 signal, and large S2 peak (bottom plot) which is due to proportional light for extracted electrons from liquid to gas.

### 4. Results from Single Phase Detector

Since target of the 0.2 kg single phase detector is to optimize the light collection efficiency, we have build a simple and small detector. It is consists of 2 of 2” PMT located face to face with 6 cm distance, and TPB coated reflector (3M ESR) surrounding these PMTs (Fig. 3). We have collected electron recoil events using $\gamma$-rays from several radioactive sources, $^{57}$Co, $^{60}$Co, $^{22}$Na, $^{137}$Cs, and $^{252}$Cf. Also collected nuclear recoil events using neutrons from $^{252}$Cf source.

Figure 3 shows scintillation light signal waveform for nuclear recoil (top) and electron recoil (bottom) events found in $^{252}$Cf data sample. While nuclear recoil event has small fraction of slow component, electron recoil event has large slow component as expected.

#### 4.1. Light Yield

We have determined light yield of the 0.2 kg detector in the unit of the energy deposition of $\gamma$ rays (pes/keVee). Figure 4 shows observed light yield distribution for $^{137}$Cs $\gamma$ ray ($=662$ keV). Points and histogram in the figure correspond to the data and simulation, respectively. The nominal light yield is determined by scaling the horizontal axis of the simulated distribution so that the simulation and data distribution are the best $\chi^2$ match. $^{137}$Cs $\gamma$ ray sample indicates 1.90$\pm$0.12 pes at the best $\chi^2$ value. The same procedure is performed for other $\gamma$ sources and the result summarized is in Fig. 4. All data points are consistent with $\sim$1.8 pes/keVee within a standard deviation.

Following studies for increasing the light yield are ongoing. (1) 2” PMT (HAMAMATSU R60401-506) we have used for the 0.2 kg detector has relatively small quantum efficiency (25% at 430 nm) while we have PMT (HAMAMATSU R11065-20) with higher quantum efficiency (38% at 430 nm) in hand. (2) Further optimization of the TPB coated reflector (3) Improvement in liquid argon purity especially removing the nitrogen impurities. (4) Use of infrared argon
Figure 3. Picture of the 0.2 kg single phase detector (left), and typical nuclear recoil (right-top) and electron (right-bottom) recoil events in $^{252}\text{Cf}$ data sample.

Figure 4. Observed number of photoelectron $^{137}\text{Cs}$ data sample in the 0.2 kg detector (left), and summary of light yield measured by using several $\gamma$ sources (right).

4.2. Background Reduction
To estimate background reduction ability of the 0.2 kg detector, we have define a simple parameter, Slow/Total, which is fraction of the light yield observed as a slow component to total light yield. Total and Slow light yields are defined as collected light yields in the time range of [-50 ns, 8 $\mu$s] and [100 ns, 8 $\mu$s], respectively while t=0 corresponds to the trigger timing. Figure 5 shows the Slow/Total distribution for $^{252}\text{Cf}$ data sample. One can find clear two peaks which can be well distinguished, the larger peak around Slow/Total = 0.7 is the electron recoil events and the other peak around Slow/Total = 0.2 corresponds to nuclear recoil events. Note that the distribution is made after selecting the event with Npe > 100 pes, the separation power between two peaks is rather vague for the events with lower light yield.

The shape of the Slow/Total distribution can be predicted by simple binomial distribution $P[X = k] = \binom{n}{k} p^k (1 - p)^{n-k}$ while $n$ is the number of observed photoelectron, and $p$ is the average
number of Slow/Total. Figure 5 shows the Slow/Total distribution in $^{22}$Na data (points) and binomial model (histogram) for the case on $n$ is around 500 pes. Data and binomial model are in good agreement, but the data shows small excess in both the lower and higher tail. Studies to understand features of such tail events are in progress.

5. Summary
In PY2012, we have started a new dark matter search project (ANKOK) at Waseda university using double phase argon detector technique. We have established basic techniques for the double phase argon detector operation by using the 10 kg double phase detector. To maximize the argon scintillation light collection efficiency, we have build the 0.2 kg single phase detector, and so far, we have achieved $\sim$1.8 pes/keVee of light yield. We still have several handles to improve the light yield and such studies are ongoing. Electron and nuclear recoil type events are collected using several radioactive sources, and we have studied background reduction ability by defining simple parameter, Slow/Total. We found the Slow/Total distribution was well modeled by simple binomial model. More detailed and quantitative studies to understand the background reduction ability are ongoing.

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