Status and prospect of the ANKOK project: Low mass WIMP dark matter search using double phase argon detector

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Abstract. The ANKOK project is a direct dark matter search experiment using an argon detector specialized for the low mass (\( \sim 10 \text{ GeV}/c^2 \)) WIMP detection. We are currently proceeding with R&D efforts to understand the background sources, develop and apply new photo sensor that is directly sensitive to 128 nm argon scintillation light and improve electron recoil type background rejection. In the next few years, we are planning to construct such an argon detector in an underground laboratory with enough sensitivity to detect low mass WIMP.

1. The ANKOK Project

Dark matter appears to exist through astronomical and cosmological observations, and many groups have been trying to detect it directly using a variety of techniques and target materials. The Weakly Interactive Massive Particle (WIMP) is a leading dark matter candidate. Using NaI crystal detector, the DAMA experiment [1] has measured an annual modulation signature that is similar to the predictions for a WIMP with a mass of approximately 10 GeV/c^2 (called the “low mass region”). Other experiments using liquid xenon detectors, such as XENON [2] and LUX [3], have excluded this region. In contrast, no argon detectors have so far been developed with sensitivity in the low mass region [4, 5, 6, 7].

The ANKOK project is a direct dark matter search experiment using argon and targets the low mass region. Figure 1 shows the nuclear recoil energy distribution produced in argon by a WIMP of mass \( M_x = 10 \text{ GeV}/c^2 \) and WIMP-Nucleon cross section \( \sigma_{x-N} = 1.0 \times 10^{-42} \text{ cm}^2 \). The end point of the recoil energy for a 10 GeV/c^2 WIMP is about 20 keV, which requires the detector to reach lower energy threshold after sufficient event selection to achieve the necessary background reduction. Figure 2 shows the 90% confidence level (C.L.) upper limits for several cases assuming zero background contamination. If we can push the energy threshold below 10 keV, an exposure of 100 kg \( \times \) days would allow us to explore the low mass region. To attain such an energy threshold, background rejection at low energy is of key importance, rather than scaling up detector size and/or exposure time.

The primary target of ANKOK project is to design and construct an argon detector with enough sensitivity to explore the low mass region. At present, we are considering two ways to sufficiently suppress the background contamination; one is to apply a high electric field in the double phase detector. The use of ionization and scintillation signals, together with the scintillation pulse shape, provides strong discrimination between the electron recoil (ER)
background and nuclear recoil (NR) events. The second way is to construct a detector with a high efficiency for light detection using silicon photomultiplier (SiPM), we will use a Multi-Pixel Photon Counter (MPPC) produced by Hamamatsu Photonics K.K., and thus providing greater scintillation pulse shape discrimination (PSD). Two possible MPPC detector setups are being studied. One uses an MPPC that is sensitive to visible photons, and has a high photon detection efficiency of approximately 50%; in contrast, conventional photomultiplier tubes (PMTs) have quantum efficiencies of about 30%. The other option is to use a new MPPC that is directly sensitive to vacuum ultra-violet (VUV) light ($\lambda < 150$ nm). Such an MPPC has recently been developed by Hamamatsu Photonics K.K., and the performance of this new photo-device, which is capable of detecting argon scintillation light, is described in Ref. [8].

Over the next few years, we will construct such a detector and use it to collect data at the Kamioka Underground Observatory in Japan. In the following sections, we focus on the R&D status of the double phase detector; we describe the prototype detector configuration, and discuss the R&D efforts to improve the background rejection.

2. Status of R&D

The Waseda liquid argon test stand is located at the Nishi-Waseda campus of Waseda University in Tokyo, Japan. The details of the test stand, which provides high purity liquid argon with respect to O$_2$, H$_2$O, and N$_2$, are described in Ref. [9].

We developed a double phase prototype detector, shown in Fig. 3, which consists mainly of polytetrafluoroethylene (PTFE). The 1 cm thick quartz light guides, with transparent indium tin oxide (ITO) electrodes, are mounted on the top and bottom of the detector, and a wire grid plane (4 mm pitch, 100 $\mu$m diameter stainless steel wire) is inserted 1 cm below the surface of the top light guide. The liquid argon surface is kept centered in the space between the top light guide and the wire grid. Two PMTs (HAMAMATSU R11065, quantum efficiency $\sim 30\%$ at 420 nm) are located on the top and bottom of the detector, where they are placed in contact with the light guides. Since these PMTs are insensitive to the 128 nm argon scintillation light, we deposited a tetraphenyl butadiene (TPB) wavelength shifter (128 nm to 430 nm) using vacuum evaporation onto the surface of the light guide and the 3M ESR reflector that covers the inside wall of the detector.

An incident particle interacting with the liquid argon generates a primary scintillation light signal $S_1$, and ionization electrons drifting in the applied field to the liquid surface, where
A stronger field is applied to extract the electrons into the gas phase so that the electrons emit the electroluminescence light signal S2.

![Figure 3. Schematic view of the double phase prototype detector.](image)

Figure 3. Schematic view of the double phase prototype detector.

Normal (atmospheric) liquid argon contains about 1 Bq/kg of the $^{39}$Ar $\beta$-decay radioisotope; this is usually the dominant source of the ER background in an argon detector. The flux of environmental gamma rays is expected to be similar in the underground laboratory, where the flux of cosmic-ray muons and environmental neutrons is significantly reduced relative to a surface laboratory. To achieve a detailed understanding, and consequent reduction of the internal and external background components, we have installed about a 10 cm thick passive lead shield around the detector. The energy spectrum of the background measured by the prototype argon detector is shown in Fig. 4, where it is overlain with a simulated spectrum based on GEANT4 [10]. The flux of environmental gamma rays used in the simulation was obtained by measurements using a $3''$ NaI(Tl) detector. The details of the simulation and flux measurements are described in Refs. [11, 12]. The event rate of the environmental gamma component and the $^{39}$Ar component are comparable below a few hundred keV$_{ee}$.

![Figure 4. Energy spectrum measured by the prototype detector.](image)

The new VUV sensitive MPPC is expected to improve the spatial resolution of the double phase detector [8], as well as improving light detection efficiency. Four VUV sensitive MPPCs were mounted on the side wall of the detector around the liquid surface to provide better resolution near the detector wall, as shown in Fig. 5a. The single top PMT was replaced with three PMTs of the other type (HAMAMATSU R6041-506), and the single bottom PMT was replaced with three PMTs of the same type (R11065). The geometrical arrangement of the three PMTs and four MPPCs is also shown in the top view in Fig. 5b. Figure 6 shows the correlation between the fraction of the S2 light yield measured by “MPPC1” and that measured by “PMT1”. The fraction is approximately 1/3 for PMT1 and 1/4 for MPPC1 at the center of the detector, as expected (black oval). In contrast, the fraction measured by MPPC1 increases rapidly at the edge of the detector (red oval). This feature demonstrates potential to improve the fiducialization near the detector wall.

We expect that the electric field $E$ in the fiducial region will play a crucial role in the
Figure 5. (a) Schematic view of the detector built to demonstrate the fiducialization. (b) The geometrical arrangement of the PMTs and MPPCs in a view from the top.

discrimination between ER and NR events. Although liquid argon is an excellent material for particle detection, its low energy response is still not well-determined, in particular above 1 kV/cm. Figure 7 shows the field dependence of the S1 and S2 light yields for ER events obtained using a $^{22}\text{Na}$ gamma ray source. With an increase in the electric field, the S1 light yield decreases, and the S2 light yield increases. We confirm that reasonable NR/ER reduction is possible using PSD and S2/S1 light yield ratio under high electric fields ($E \approx 2.0$ kV/cm) for an energy deposition of approximately 40 keV$_{\text{nr}}$, as shown in Fig. 8. We obtained the NR events and ER events using a $^{252}\text{Cf}$ neutron source and a $^{22}\text{Na}$ gamma ray source, respectively. Note that these are preliminary results, and detailed and quantitative studies are ongoing.

Figure 6. Correlation between the fractions of the S2 light yield measured by PMT1 and by MPPC1.

Figure 7. Electric field dependence of S1 and S2 light yields for ER event.

Figure 8. Particle identification performance of the prototype detector under high electric fields ($E = 2$ kV/cm) with energy deposition of approximately 40 keV$_{\text{nr}}$. 
As a part of our effort to achieve a detailed understanding of the detector response, we have constructed a liquid argon response model to explain the scintillation and ionization yields under electric fields, referring to the NEST package [13] developed for a liquid xenon experiment. Some of the detailed and ongoing efforts on this work through Monte Carlo simulations are described elsewhere [11].

### 3. Summary and Prospect

The ANKOK project is a direct dark matter search experiment using argon, which targets WIMP with mass of approximately $10 \text{ GeV}/c^2$. The primary goal of the ANKOK project is to design and construct a detector with enough sensitivity to search for low mass WIMP.

We are currently proceeding with R&D efforts using the prototype detector. The observations of the $^{39}$Ar signal have been obtained in a surface laboratory by constructing a passive lead shield to reduce the environmental gamma ray background. The application of VUV sensitive MPPC to the double phase detector has demonstrated potential to improve fiducialization near the detector wall. We expect that the electric field in the fiducial region and an understanding of the liquid argon response will play a crucial role in this search.

Since environmental gamma rays have been successfully reduced, we next plan to start observing ER backgrounds from other sources such as radiation from the materials inside the detector. It is important to identify any highly radioactive materials and to establish procedures for reducing the background by physically replacing such materials and/or analytically rejecting such events. The design and studies of the high efficiency light detector have started, although they are not mentioned in this report. In the next few years, we plan first to test the low energy threshold detector at the Waseda surface test stand, and then to collect underground physics data at the Kamioka Underground Observatory.

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### References

[1] Bernabei R et al. 2013 *Eur. Phys. J. C* **73** 2648
[2] Aprile E et al. [XENON Collaboration] 2017 *preprint* arXiv:1705.06655
[3] Akerib D S et al. [LUX Collaboration] 2017 *Phys. Rev. Lett.* **118** 021303
[4] Benetti P et al. [WARP Collaboration] 2008 *Astropart. Phys.* **28** 495
[5] Agnes P et al. [DarkSide Collaboration] 2015 *Phys. Lett. B* **743** 456
[6] Agnes P et al. [DarkSide Collaboration] 2016 *Phys. Rev. D* **93** 081101
[7] Amaudruz P.-A. et al. [DEAP-3600 Collaboration] 2017 *preprint* arXiv:1707.08042
[8] Igarashi T, Tanaka M, Washimi T and Yorita K 2016 *Nucl. Instrum. Meth. A* **833** 239
[9] Tanaka M 2013 *J. Phys. Conf. Ser.* **469** 012012
[10] Agostinelli S et al. [GEANT4 Collaboration] 2003 *Nucl. Instrum. Meth. A* **506** 250
[11] Kimura M, Tanaka M and Yorita K 2016 *JPS Conf. Proc.* **11** 040003
[12] Tanaka M, Yorita K and Washimi T 2016 *PoS(ICHEP2016)* 274
[13] Szydagis M et al. 2011 *J. Instrum.* **6** 10002