

# Studies on liquid argon S1 and S2 properties for low mass WIMP search experiments

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**Abstract.** Liquid argon is known as an excellent target material for WIMP dark matter direct search experiment. Relatively small atomic mass ( $A=40$ ) gives high nuclear recoil energy for WIMP-Ar nuclear scattering, thus it potentially has high sensitivity for low mass WIMP ( $<10$   $\text{GeV}/c^2$ ) . There are two crucial R&D topics for the liquid argon detector to explore such low mass WIMP signal, namely, deep understanding the liquid argon scintillation and ionization process for low energy deposition ( $<10$  keV) , and increasing the signal light yield by improving the argon scintillation light collection efficiency. In this paper, we report recent results from Waseda university liquid argon test facility.

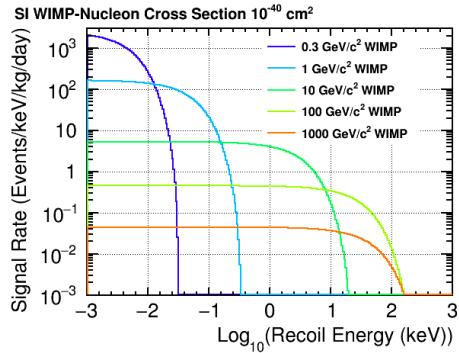
## 1. Introduction

At that moment (Summer 2019), the best limit on WIMP-nucleon cross section for WIMP mass region of 2-5  $\text{GeV}/c^2$  has been given by the DarkSide-50 experiment which uses argon as target nuclei [1]. Argon recoil energy is expected to be less than 10 keV for few  $\text{GeV}/c^2$  WIMP-argon scattering as shown in Fig. 1. The primary target of our study is detailed understanding of basic properties of the liquid argon detector for such low energy recoil signal. In this paper, we describe our liquid argon test facility at Waseda university, and report recent results from the facility.

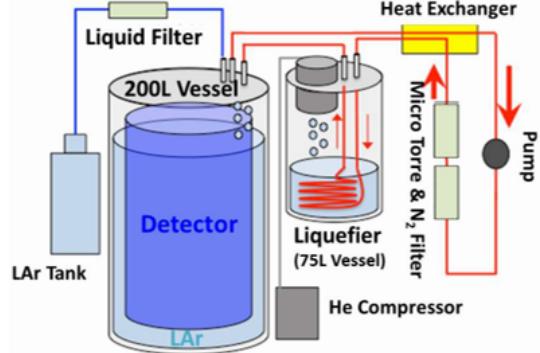
- An effort to improve the light collection efficiency which leads the world highest level of light yield (11.5 pes/keV<sub>ee</sub>).
- A new measurement of the argon scintillation and ionization efficiency for nuclear recoil under high drift field up to 3 kV/cm[2].
- An emission spectrum measurement of gas argon electroluminescence in visible light region (300 nm - 700 nm).

## 2. Waseda Liquid Argon Test Facility

Waseda liquid argon test facility is located at Nishi-Waseda campus of Waseda university in Tokyo, Japan. Figure 2 shows the schematic view of the cryogenic and argon purification system. There are two cryostats in the setup. The first cryostat is main vessel of the experiment and has its size of about 50 cm diameter and 100 cm length (200L vessel). A Gifford-MacMahon(GM) cryocooler (Sumitomo CH-110) with available cooling power of 200W (@90K) is mounted on top of the second cryostat (liquefier). The gas recirculation system through the 200L vessel and



**Figure 1.** Argon nuclear recoil energy distribution for various WIMP mass.



**Figure 2.** Schematic view of the Waseda liquid argon purification system.

the liquefier is implemented to maintain the liquid argon temperature. A molecular turbo pump (Pfeiffer Hipace-300) is mounted on top of the 200L 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 [3]. Additionally two gas purification filters (SAES Microtorr + PUREON GP) have been inserted in the recirculation system to maintain and improve the liquid argon purity.

- Attenuation time of drift electron has been stable at about 1 ms which corresponds to about 0.3 ppb O<sub>2</sub> equivalent impurity.
- No degradation of the liquid argon scintillation light is observed which corresponds to better than 0.1 ppm N<sub>2</sub> equivalent impurity.
- Liquid surface level has kept within 0.5 mm.

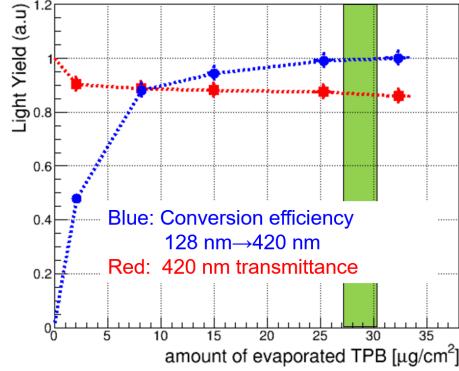
### 3. Recent Results

#### 3.1. Light Yield

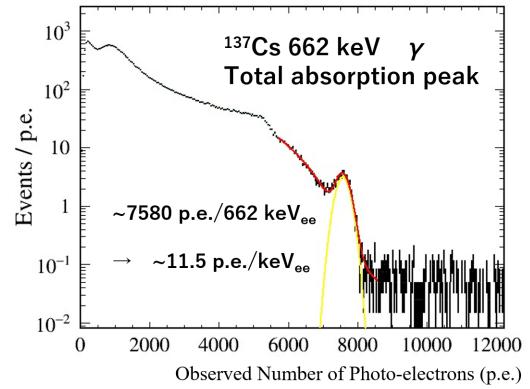
Intrinsic light yield of the liquid argon is known to be about 40 photons/keV<sub>ee</sub>. It is important to observe the light signal with high detection efficiency for better energy resolution and particle identification power. Tetraphenyl butadiene (TPB) is widely used wavelength shifter for the 128 nm argon scintillation light, and HAMAMATSU R11065 is also widely used cryogenic photomultiplier (PMT) for liquid argon detector. The detection efficiency is determined by three components, 128 nm to 420 nm conversion efficiency of TPB, collection efficiency of the 420 nm light to the PMT, and the quantum efficiency of the PMT (about 30%). The TPB vacuum evaporation procedure is carefully optimized (Fig. 3), and a small single phase liquid argon detector with fiducial mass about 0.25 kg and two R11065 PMTs is constructed. We have successfully achieved the world highest level of the light detection yield of 11.5 pes/keV<sub>ee</sub> for 662 keV <sup>137</sup>Cs  $\gamma$ -ray source (Fig. 4). This light yield can be improved even more by using photo sensors with higher detection efficiency such as SiPM. We are currently under development of an ultra-high light yield detector using HAMAMATSU MPPC which has almost twice better detection efficiency than the PMT.

#### 3.2. Scintillation and Ionization Yield for Argon Nuclear Recoil Event

Typical drift field employed by a liquid argon double phase detector is 200 V/cm [1]. The ionization yield is expected to be increased at higher drift field because of the smaller recombination probability. It is particularly important for the “S2 only” type experiment which

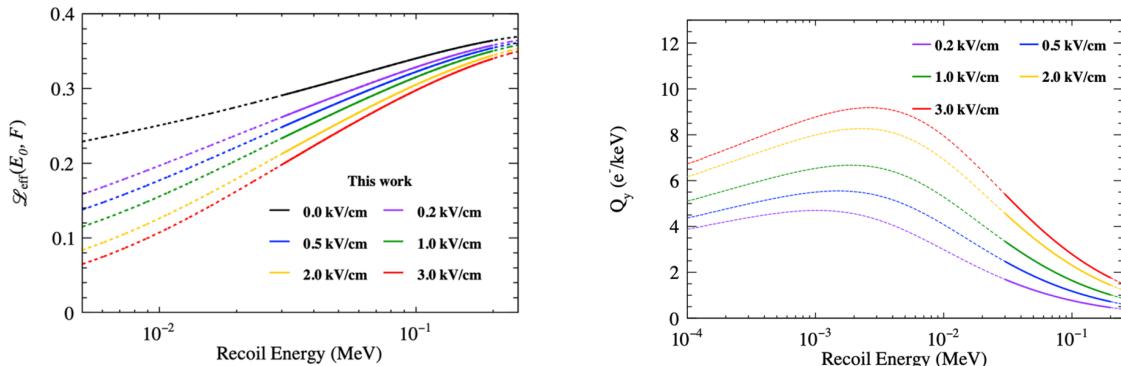


**Figure 3.** Conversion efficiency from 128 nm light to 420 nm light (blue), and transmittance for 420 nm light as a function of amount of the evaporated TPB (red). The optimal amount of the TPB is about  $30 \mu\text{g}/\text{cm}^2$  (green band).



**Figure 4.** Observed number of photo-electron distribution of the liquid argon detector for  $^{137}\text{Cs}$  662 keV  $\gamma$ -ray source.

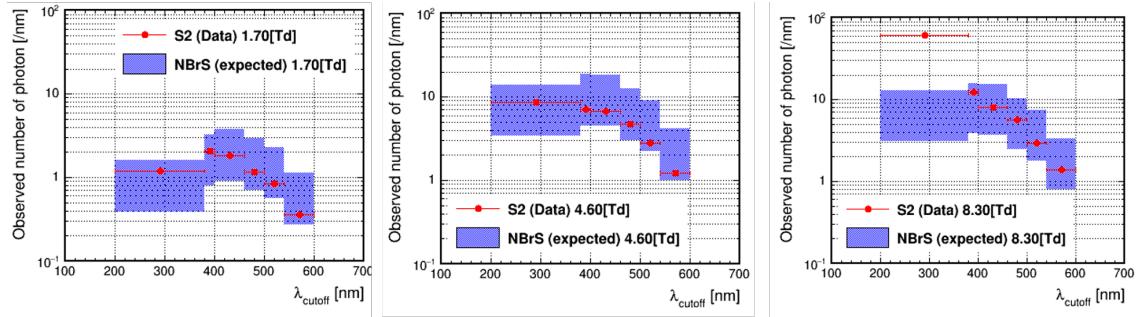
observes only the ionization signal. Figure 5 shows the first measurement of the scintillation and ionization yield for argon nuclear recoil event at very high electric field up to 3 kV/cm [2]. The calibration data are taken with  $^{252}\text{Cf}$  radioactive source. Observed scintillation and electroluminescence spectra within 30 keV to 200 keV are simultaneously fit with spectra derived from Geant4-based Monte Carlo simulation and an argon nuclear recoil response model. This result shows the ionization yield at 3 kV/cm is about 2 times greater than that at 200 V/cm.



**Figure 5.** Liquid argon scintillation (left) and ionization efficiency (right) of argon nuclear recoil events as a function of recoil energy for various electric fields from 0.2 to 3 kV/cm. The solid lines represent the results from this work, and the corresponding dashed lines are extrapolations.

### 3.3. Gas Argon Electroluminescence

It is known that the S2 signal of the argon double phase detector (electroluminescence) is the gas argon scintillation light. However recent study shows there is an additional mechanism so called neutral Bremsstrahlungs (NBrS) [4]. In fact, NBrS is dominant component in visible light region (300 nm - 700 nm). Figure 6 shows measured emission spectra of the gas argon electroluminescence at room temperature overlaid with predicted spectra from the NBrS model. The measured spectra are in good agreement with the NBrS prediction.



**Figure 6.** Emission spectrum for gas argon electroluminescence at room temperature for three different electric field, and comparison with the NBrS model [4].

#### 4. Summary

Liquid argon is an excellent target material for low mass WIMP ( $1\text{-}10 \text{ GeV}/c^2$ ) experiment. We have performed several measurements of the liquid argon basic properties at Waseda liquid argon facility. These measurements provide better understanding of the liquid argon detector for low mass WIMP search experiment.

#### Acknowledgments

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