Preliminary Test Results of LAr Prototype Detector (Postprint)

Authors: Li Pei-Xian, Guan Meng-Yun, Yang Chang-Gen, Zhang Peng, Liu Jin-Chang, Yong-Peng Zhang, Guo Cong, Wang Yi

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Abstract

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Full Text

Preamble

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Li Pei-Xian[12], Guan Meng-Yun[1], Yang Chang-Gen[1], Zhang Peng[1], Zhang Yong-Peng[12], Guo Cong[12], Wang Yi[12], Liu Jin-Chang[1]

[1]Institute of High Energy Physics, CAS, Beijing 100049, China
[2]Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: WIMPs are a well-motivated galactic dark matter candidate. Liquid argon (LAr) is an attractive target for the direct detection of WIMPs. The LAr prototype detector is designed to study the technology and properties of LAr detectors. The prototype detector has an active volume containing 0.65 kg of liquid argon. The liquid nitrogen (LN) cooling system allows the temperature of liquid argon to be maintained at the boiling point (87.8 K) with fluctuations less than 0.1 K. The prototype was calibrated with a Na^{22} source, yielding a light output of 1.591±0.019 p.e./keV for 511 keV gamma rays using the domestically-made argon purification system.

Key words: LAr technology, scintillation light, light yield, Dark Matter

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Introduction

The Planck data provide compelling evidence for a significant cold dark matter component in the composition of the Universe. Weakly interacting massive particles (WIMPs) are a well-motivated galactic dark matter candidate. Numerous direct detection experiments are being developed to detect WIMPs. Liquid argon (LAr) detectors are particularly attractive for the direct detection of WIMPs. Liquid argon is an excellent scintillation material, with a high light yield of approximately 40 photons per keV.

Liquid argon provides outstanding pulse-shape discrimination (PSD) based on scintillation timing. The excitation and ionization of the medium from particles interacting with argon atoms lead to two excited states. These two excited states have different lifetimes: about 6 ns for the singlet state and 1.6 µs for the triplet state. With sufficient photon statistics, PSD allows discrimination of nuclear recoil events from electron-induced background events at better than 10 , providing a way to detect rare nuclear recoil events.

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2 The LAr Prototype Detector Design and Structure

The liquid argon prototype detector, shown in Fig. 1 [Figure 1: see original paper], consists of a double-wall vacuum stainless steel cryostat and an inner vessel that contains 0.65 kg of active liquid argon. This inner vessel is completely immersed in a liquid argon bath contained within the cryostat. The inner vessel consists of a PTFE cylinder and two fused silica windows. The cylinder has a height of 9.2 cm, an inner diameter of 8.0 cm, and a wall thickness of 1.0 cm. The PMTs are positioned in the outer LAr bath, viewing the active volume through the top and bottom fused silica windows which serve as the top and bottom lids of the inner vessel.

The wavelength-shifted light is collected by two arrays of PMTs viewing the active volume through these fused silica windows. Three HAMAMATSU R8520-06mod PMTs (1-inch) are installed in the top array, and one HAMAMATSU R11065 PMT (3-inch) is installed in the bottom array. To reduce escape of the wavelength-shifted light from the inner vessel, the spaces between the PMTs are filled with PTFE reflectors. A layer of LAr about 1 mm thick optically couples the PMTs to the windows. The room-temperature quantum efficiency of the R11065 is 25% at 420 nm. The PMTs are operated at a typical gain of 4.2×10 .

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3 Cooling, Purification and Recirculation System

The liquid nitrogen (LN) cooling system, shown in Fig. 2 [Figure 2: see original paper], consists of a 100 L liquid nitrogen dewar and a cold-head. The boiling point of liquid nitrogen is about 10 K lower than that of liquid argon at the same pressure, allowing us to use liquid nitrogen to liquefy gaseous argon. The cold-head is located inside the cryostat but outside the inner vessel. The 100 L liquid nitrogen dewar is connected to the cold-head through a lengthy bellows. The liquid nitrogen flows into the cold-head, leaving its latent heat to provide cooling capacity.

We adjust the cooling power by controlling the vaporized nitrogen flow using the pressure of the LAr cryostat as the process variable. A proportional-integral-derivative (PID) controller regulates the temperature of the LAr. Test results show the LAr temperature fluctuation is less than 0.1 K.

To obtain maximum light yield, dissolved electronegative impurities such as nitrogen, oxygen, and water must be reduced to levels below 0.1 ppm. A special domestically-made purification system, developed by Beijing Beiyang United Gas Co., Ltd., combined with a gas recirculation loop fulfills this requirement. Before filling with argon, the LAr cryostat is pumped for several days until the pressure reaches about 10 Pa. Feed argon gas (95% purity) is then purified by the purification system and flows into the LAr cryostat, as shown in Fig. 3 [Figure 3: see original paper]. After filling with liquid argon, we start argon recirculation to further improve purity. Liquid argon is vaporized by a heater installed at the bottom of the LAr cryostat. A senior aerospace metal bellows pump drives the argon gas to recirculate through the purification system and flow back to the cold-head to be liquefied again. Argon gas is passed through the purification system several times until the scintillation properties no longer improve.

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4 DAQ System and Single-Photoelectron Calibration

A LeCroy WAVERUNNER 610Zi oscilloscope is used to record signal waveforms from the 3-inch and 1-inch photomultiplier tubes for offline analysis.

The trigger requires a coincidence between one 1-inch PMT and one 3-inch PMT signal within 300 ns. The threshold is 10 mV for the 3-inch PMT and 6 mV for the 1-inch PMT. When an event satisfies the trigger condition, data in a 10 µs time window (1.6 µs before the trigger, 8.4 µs after the trigger gate) is stored on a local hard disk.

We use an LED installed in the cryostat to perform single-photoelectron calibration of the 3-inch PMT. The pulse width for LED runs is 200 ns. The trigger is generated by a pulse generator. The spectrum and fit of the single-photoelectron response are shown in Fig. 4 [Figure 4: see original paper]. We obtain a calibration of approximately 1.436±0.021 pC/PE.

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5 Event Analysis and Light Yield

We determine a baseline and subtract it from the waveform for each individual channel. The average of the digitized samples in the 1.6 µs pre-trigger region (where no signal is expected) is calculated. Once the baseline has been subtracted, the waveform integral is evaluated to determine the charge of the event.

The detector is exposed to a 70 µCi ^{22}Na gamma source. The ^{22}Na source emits two 510.99 keV gamma rays in opposite directions, allowing us to use these two gammas in coincidence. The ^{22}Na source is collimated by a thick lead collimator aimed at the center of the inner vessel. On the opposite side of the ^{22}Na source, another collimator is aimed at a plastic scintillator, which serves as the coincidence detector. The plastic scintillator is coated with black tape as a reflector and uses one 3-inch PMT for readout.

Fig. 5 [Figure 5: see original paper] shows the gamma-induced scintillation spectrum of 50,000 events. Due to the small active volume (0.65 kg), the 511 keV gamma ray rarely deposits its full energy in the detector. Consequently, the spectrum is degraded, making the Compton edge much more prominent than the full-energy peak. This agrees with expectations from a GEANT4-based Monte Carlo simulation of the experimental setup, including all materials between the source and active volume. The full-energy peak is fit with the sum of a Gaussian and a falling exponential function. The energy resolution for 511 keV gamma rays is 6.75%.

Table 1 . The peak mean, width, and light yield of the gamma full-absorption peak. The error on µ is the statistical error from the fit. The error on LY is the fit error combined with the statistical error on the mean single-p.e. response.

Parameter	Value
E [keV]	813.21±3.79
Light Yield [p.e./keV]	1.591±0.019

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6 Conclusion

Using the customized LN cooling system and the domestically-made argon purification system, we have established a stable LAr prototype detector. With a collimated ^{22}Na source, the measured energy spectrum shows a light yield of approximately 1.591±0.019 p.e./keV for 0.511 MeV gamma rays.

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