

Low background control of the PandaX-4T dark matter experiment

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Abstract. The PandaX-4T is a dark matter direct search experiment with a dual-phase xenon detector. It is located at Jinping underground laboratory in Sichuan, China. In 2.8-ton fiducial mass and energy region of interest (range from 1 to 10 keV), the total electron recoil and nuclear recoil backgrounds are estimated to be $(4.9 \pm 0.5) \times 10^{-2}$ mDRU and $(2.8 \pm 0.5) \times 10^{-4}$ mDRU. With an exposure of 5.6 ton-years, the expected sensitivity of PandaX-4T could reach a spin-independent dark matter-nucleon cross section of 6×10^{-48} cm² at a dark matter mass of 40 GeV/c². An overview of detector design, background control and current status will be presented in this paper.

1. Introduction

Dark matter (DM) has become one of most interesting topics in particle physics and cosmology. There are lots of evidences supporting the existence of DM, such as the galaxy rotation curves (Figure 1). A significant difference exists between the observed curves and the curve derived by applying gravity theory due to ordinary matter. A possible solution is to hypothesize the existence of DM to compensate mass difference. There are many DM models. Weakly interacting massive particles (WIMP) is one of the most competitive DM candidate. WIMP detection focuses on the DM mass range from MeV to TeV. Figure 2 shows detection methods of primary DM experiments in the world according to the three types: ionization signal, light signal and heat signal. Particle and astrophysical xenon experiments (PandaX) utilize a dual-phase xenon time projection chamber (TPC) to observe both light and ionization signals.

Figure 3 shows the detection principle of TPC. Inside TPC, nuclear recoils from WIMPs will produce two signals. One is a prompt scintillation signal (S1) due to scintillation photons in liquid xenon (LXe). The other is a delayed signal (S2) from ionization electrons, which drift to liquid surface under electric field and then produce electroluminescence photons in the xenon gas. Both signals are collected by photomultiplier tubes (PMTs). The TPC technique has a lot of advantages. First, LXe provides good shielding ability. Second, LXe has no long-life isotopes and can be easily purified, to control intrinsic radioactive background. Third, one can reconstruct 3-D positions of scattering vertex based on the S1-S2 drift time difference and PMT patterns. Last but not least, one can identify the electron recoil (ER) events, that an incident particle interacts with shell electron of a xenon atom, and nuclear recoil (NR) events, that the incident particle interacts with nucleon, by ratio of S2/S1. The majority of ER background can be rejected using this method.



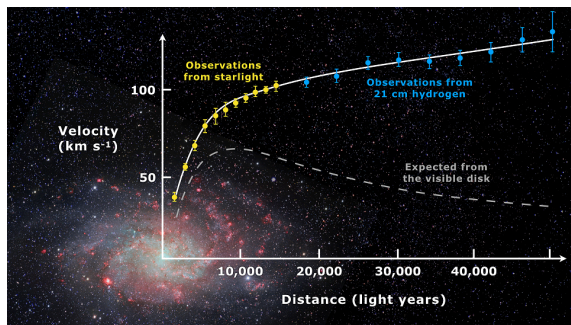


Figure 1. Rotation curve of spiral galaxy Messier 33

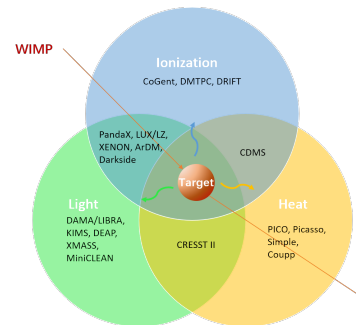


Figure 2. Detection methods of DM experiments

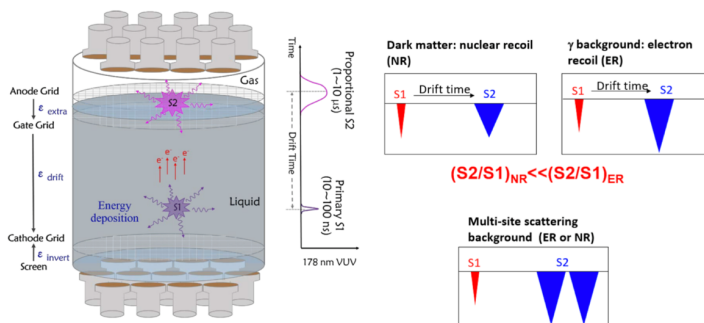


Figure 3. Detection principle of the dual-phase xenon TPC

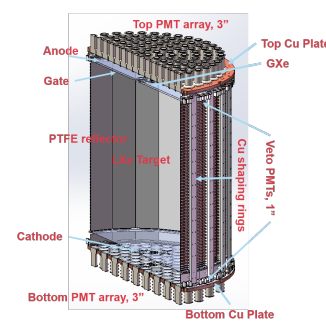


Figure 4. TPC construction

2. PandaX-4T dark matter experiment

Up to now, Three generations of PandaX project searching for WIMPs are performed. The first-phase mission of the experiment (PandaX-I) has been completed with 120 kg liquid xenon target mass. The second phase mission (PandaX-II) with 580 kg target mass has published a latest result that the lowest 90% confidence level exclusion on the spin-independent cross section is $2.2 \times 10^{-46} \text{ cm}^2$ at a WIMP mass of 30 GeV/c² [1]. PandaX-4T, the ton-scale DM experiment, commissioning is now ongoing.

PandaX-4T is located at China Jinping underground laboratory (CJPL). With a 2400-m marble overburden, the cosmic ray flux in CJPL can be reduced to about 1.2 events/m²/week. In addition, CJPL can be accessed horizontally.

Figure 5 shows the layout of the PandaX-4T experiment: a water shielding tank, a cryogenic and circulation system, a xenon gas storage system, a distillation tower, a cleanroom, an electronics and DAQ system and TPC.

- The water shielding containing ultra-pure water with a height of 13 m and a radius of 5 m is used in PandaX-4T to shield the radioactivity from outside and reduce the external background.
- For cryogenics and xenon handling system: the designed cooling power is 360 W at 178 K. The circulation speed can reach 100 standard liter per minute. Two cooling heads are operated for about 6 tons liquid xenon and are able to liquify about 0.7 tons liquid xenon per day.
- The distillation tower removes krypton and radon impurity from xenon with physics separation techniques based on vapor pressure. The designed krypton level of PandaX-

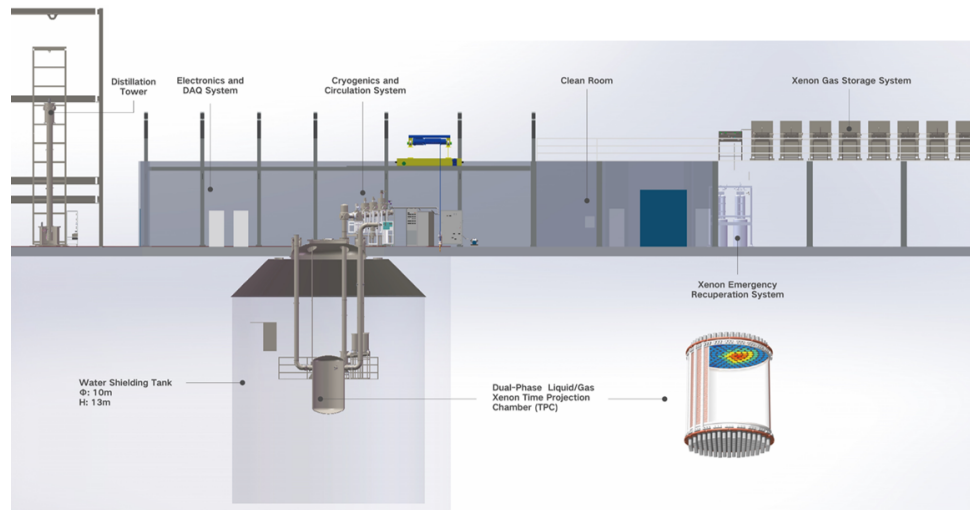


Figure 5. The layout of PandaX-4T DM experiment

4T is less than 0.1 ppt (mol/mol). And the designed radon level is less than $1 \mu\text{Bq/kg}$. In addition, we can do the operation both offline and online.

- For PMT, electronics and DAQ, the total channels are designed to be about 500, the FADC sampling rate is designed to be 250 MS/s. And we designed to use triggerless mode for DM data taking. By using parallel readout, the limit of data transmission reaches about 80 MB/s. The dark rates and gains of PMTs have been tested in room temperature and low temperature ($-60 \text{ }^\circ\text{C}$). The average rate under room temperature and low temperature are 540 Hz and 20 Hz respectively. The average gain under different temperature does not differ much, ($\sim 5.5 \times 10^6$).
- The dual-phase xenon TPC is the core of the experiment. It has a diameter of 1.2 m and a height of 1.3 m. From Figure 4, 3-inch PMT arrays (top: 169 PMTs, bottom: 199 PMTs) are arranged on the top and bottom of the TPC. Another 144 1-inch PMTs are assembled at the skin layer of xenon to veto external background. Shaping rings are placed around the chamber to perform the electric field. Between the cathode and gate, the designed drift field in liquid xenon is 400 V/cm and the designed extraction field in gas xenon is 6 kV/cm.

3. Background Estimation

The background due to radioactivity may mimic DM-standard model interaction signals. Thus, it is important to suppress, control and better understand the background in DM experiments. The background of PandaX-4T originates from three main sources: the materials radioactivity, xenon target impurity and solar neutrinos. Except neutrino background, other backgrounds can be controlled by variety of technologies.

3.1. Low background assay and control

To ensure the low radioactive background, we have the following techniques to measure the radioactivities of the materials: two high pure germanium (HPGe) counting stations, a ICP-MS, an alpha detection system, a krypton assay station and two radon emanation measurement systems.

HPGe detector is a type of semi-conductor detector. The gamma rays released by the decay of radionuclides deposit energy in Ge crystal through photoelectric effect and Compton effect, producing electron-hole pairs. HPGe counting station designed and constructed at CJPL is

made up of a HPGe detector and an extra shielding system. Lead, copper and air radon control system are built in the shielding system. The sensitivity of HPGe counting station reaches \sim mBq/kg level. The radioactivity of stainless steel (SS), PMT, base, cable are measured by HPGe counting stations.

ICP-MS is able to determine elemental concentrations of samples which could be dissolved in solution. It provides multi-element analysis with high sensitivity. The sensitivity of ICP-MS is of ppt level, even sub-ppt level. ICP-MS measures the radioactivity of copper used in PandaX-4T detector [3].

The alpha detection system aims at measuring alpha decays from surface radon daughters. It uses semi-conductor silicon as a detector. The blank of the chamber is about 0.2 mBq.

The krypton assay station is established to measure the krypton concentration in xenon target. it is composed of two residual gas analyzers (RGAs), a cold trap, a mass flow controller (MFC), two cold cathode gauges, three pumps and a getter. The sensitivity of the krypton assay station reaches 10 ppt.

Radon emanation systems are established to measure the radon emanation rate of materials. Up to now, two radon emanation systems have been established. One is composed of a 7.4 L cylindrical stainless steel chamber, electronics and silicon detector. The sensitivity reaches 2 mBq. Another has a cold trap on the basis of the previous one. Its sensitivity is improved to 0.05 mBq level.

The materials used in PandaX-4T construction are selected with the techniques introduced above. Before construction, the materials were cleaned by rigorous cleaning procedures.

3.2. Background budget of PandaX-4T

Combing the measurement results of radioactivity and Monte Carlo simulation, the total background inside 2.8-ton fiducial mass is calculated to be $(4.9 \pm 0.5) \times 10^{-2}$ mDRU ($= 10^{-3}$ events $\text{day}^{-1} \text{kg}^{-1} \text{keV}^{-3}$) for ER and $(2.8 \pm 0.5) \times 10^{-4}$ mDRU for NR. For ER, the intrinsic background and neutrino background make major contributions (shown in Figure 6). Among the material background, the inner and outer vessel, that is to say, stainless steel contributes most. For NR background, PMT, neutrino and stainless steel each account for about one third (shown in Figure 7).

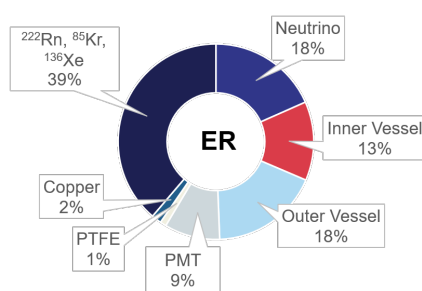


Figure 6. ER background budget

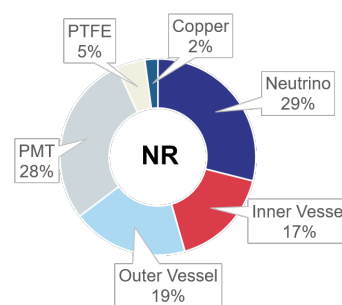


Figure 7. NR background budget

3.3. Sensitivity

Under 95% ER rejection efficiency and 40% NR acceptance [2], the expected background could be 2.5 events for ER and 2.3 events for NR with an exposure of 2 years. And the expected sensitivity of PandaX-4T could reach a spin-independent DM-nucleon cross section of $6 \times 10^{-48} \text{ cm}^2$ at a DM mass of 40 GeV/c^2 (shown in Figure 8).

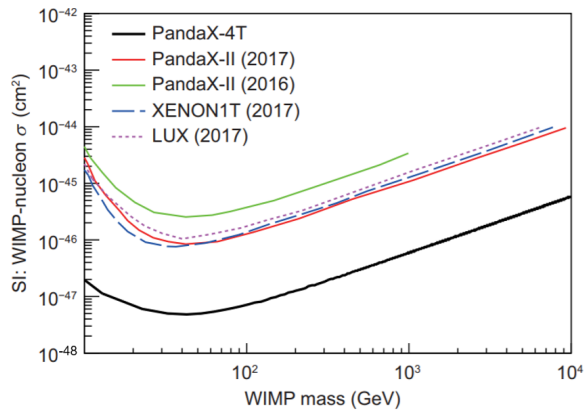


Figure 8. Expected sensitivity of PandaX-4T

4. Summary

The PandaX-4T facility is ready since August, 2019. Rigorous material assay and cleaning procedures have been established to control the background contribution. The total background is calculated to be $(4.9 \pm 0.5) \times 10^{-2}$ mDRU for ER and $(2.8 \pm 0.5) \times 10^{-4}$ mDRU for NR. Also, subsystem installation and assembly have been completed. PandaX-4T commissioning is ongoing now. The expected sensitivity is 6×10^{-48} cm² at a DM mass of 40 GeV/c².

References

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