Low Radioactive Material Screening and Background Estimation for the PandaX-4T Experiment

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Introduction

The Particle AND Astrophysics experiment with Xenon (PandaX-4T), located in the China Jinping Underground Lab (CJPL), utilizes the dual-phase xenon time projection chamber (TPC) to search for dark matters. The most promising candidate is Weakly Interacting Massive Particles (WIMPs).

PandaX-4T has developed and utilized various detection technologies to precisely measure the bulk radioactivity of materials, radon emanation, krypton concentration in the xenon target, and the radon daughters contamination on the surface.

The PandaX-4T experiment and Radioactive Origins

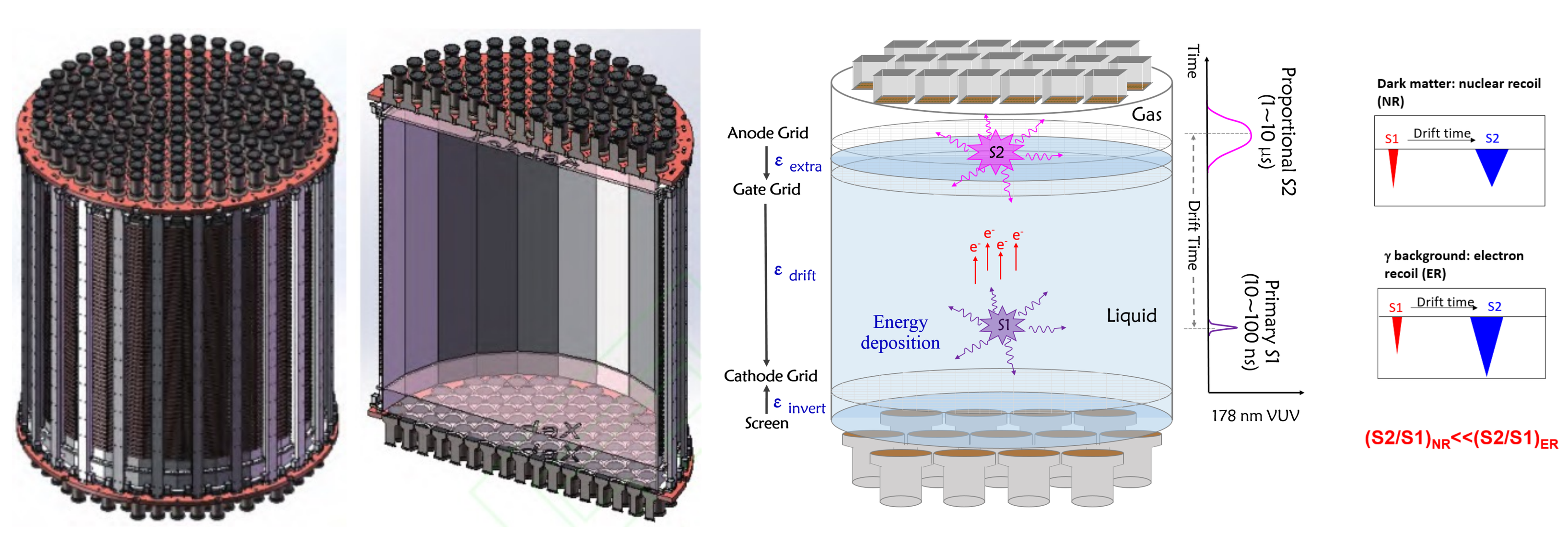

Fig 1: The diagram of the PandaX-4T TPC

TPC is a type of particle detector that uses an electric field together with a sensitive volume of gas or liquid to perform a three-dimensional reconstruction of a particle trajectory or interaction position. The incident particles will deposit energy to produce scintillation lights for the so-called S1 signal. Electrons driven by the drift field from the liquid xenon into gas xenon undergo electroluminescence in the gas phase. It is called the S2 signal. Combining the S1 and S2 signals, the event positions in three dimensions can be reconstructed.

The background signals can be divided into two categories. Signals caused by interactions with atomic electrons are called electron recoil (ER) events, while signals resulting from interactions with the nuclei of the xenon target are nuclear recoil (NR) events. The background of PandaX-4T originates from three main sources: radioactive isotopes in materials (bulk and surface), xenon target impurities, and neutrino-related background.

HPGe Counting Stations

- **Principle**

When an external incident particle generates energy deposition in the depletion region of the germanium crystal, the electron holes generated by ionization are rapidly dragged in two directions by the high-intensity electric field in the region, and the total amount of electrical signals captured by the electrodes at both ends quantitatively represents the amount of deposition energy.

- **System**

At CJPL, two gamma counting stations (JP-I and JP-II in the following) are assembled with high-purity germanium crystals, a shielding structure with 10-cm-thick copper and 20-cm-thick lead.

Fig 2: The HPGe counting station

- **Sensitivity**

Fig 3 shows the sensitivity of JP-I and JP-II over duration for a typical measurement of PTFE sample with a mass of 173 g. The main reason for the sensitivity difference between the two detectors is the size of the crystal.

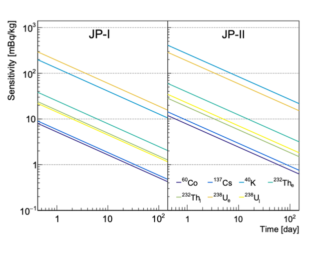

Fig 3: sensitivity of JP-1 and JP-II HPGe detectors for a PTFE sample

Conclusion

Various screening technologies have been established and are able to meet the requirements of different radioactivity measurements in the PandaX-4T experiment. The total material background of PandaX-4T is calculated to be (9.9 ± 1.9) × 10^{-3} mDRU for ER and (2.8 ± 0.6) × 10^{-4} mDRU for NR. In addition, ^{nat}Kr in the detector is estimated to be < 8 ppt. Meanwhile, surface cleaning procedures were investigated to further reduce the material surface background.

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Radon Emanation systems

The PandaX-4T collaboration has designed three radon emanation measurement systems.

Fig 4: The radon emanation system (cold trap)

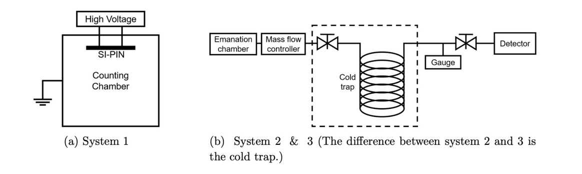

Fig 5: Schematics of radon emanation systems

An electrostatic method was used to collect the positively charged ions of radon daughter nuclei under an electric field and use SI-PIN diodes to measure energy deposition. A cold trap at liquid nitrogen temperature can be added to the system to achieve ^{222}Rn enrichment by a factor of 500. Performance of radon systems and partial measurement results are shown in the table.

Table 1: Performance of radon emanation measurement systems

No.	Chamber	Cold trap	Volume [L]	Blank [mBq]	Efficiency [%]
1	Cylinder	no	7.4	1.07 ± 0.01	24.6 ± 0.2
2	T-type	no	0.7	0.08 ± 0.01	12.7 ± 1.0
3	T-type	yes	0.7	<0.10	7.9 ± 0.1

Table 2: Radon emanation measurement result (90% C.L.)

Name	Detector	Rate [mBq]
PMT R11410 [pc]	1	<0.03
SAES Getter	2	<0.4
Inner vessel	3	<17.9

Krypton Assay Station

- **Design**

Fig 6: The krypton assay station

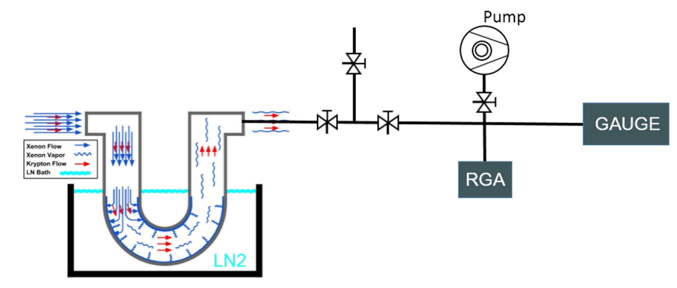

Fig 7: Schematic of the krypton assay station

The cold trap is installed between a mass flow controller (MFC) and a residual gas analyzer (RGA). It is immersed in liquid nitrogen (-196 ℃).

- **Principle**

The krypton concentration in the outlet can be enriched by a factor of 10^6 because of different saturated vapor pressure. Then the enriched gas is measured by the mass spectrometer.

The krypton and xenon partial pressure ratio is proportional to the krypton concentration in the sample.

- **Operation**

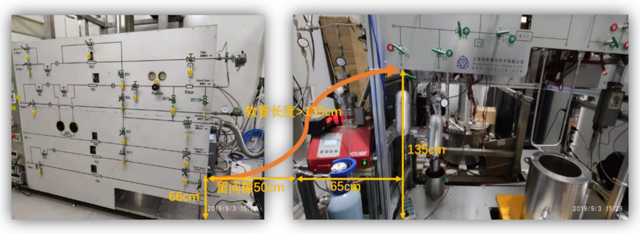

Fig 8: Layout for the DTower and the krypton assay station

The gas is transferred to the krypton assay station by the outlet of the distillation tower (DTower). 5.7 tons of xenon in PandaX-4T experiment is monitored during purification. The station can detect krypton concentration down to 7.96 ppt (parts per trillion) (@90% C.L.).

Alpha Detection System

The alpha detection system aims at measuring the surface radioactivity of the sample material. It uses an ion-implanted-silicon charged-particle radiation detector of the ULTRA-AS series from ORTEC to catch alpha radiations from the surface of sample materials, mainly ^{210}Po.

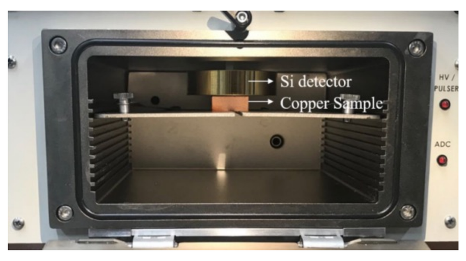

Fig 9: The alpha detection system

- Volume: 996 cm^3
- Vacuum: 10 mTorr
- Blank: 0.2 mHz

In order to remove radon daughters on copper surface, efficient surface cleaning methods have been investigated with the alpha detection system, and the average removal efficiency of ^{210}Po is shown in Table 3.

Table 3: Cleaning procedure investigation to remove radon daughters on copper surface

No.	Pickling solution	Average Removal Efficiency [%]
1	1% H_2SO_4 + 3% H_2O_2	79.4 ± 2.7
2	15% HNO_3 + 2% H_2O_2	15.2 ± 2.3
3	5% $C_6H_8O_7$ + 8% H_2O_2	99.9 ± 2.3

Background estimation

The background estimation of PandaX-4T experiment greatly depends on Geant4 simulation. A program called BambooMC is specially designed to simulate the physical processes in the PandaX-4T detector. Four cuts are developed in simulation to select DM candidates:

- energy region of interest (ROI) cut
- fiducial volume (FV) cut
- single-scatter cut
- veto cut

Combining the radioactive assay results and Monte Carlo simulation, the total material background of PandaX-4T can be estimated.

Table 4: Material background contribution in PandaX-4T detector (unit: mDRU)

Unit: mDRU	ER	NR
PMT	$(5.3 \pm 1.2) \times 10^{-3}$	$(8.9 \pm 1.5) \times 10^{-5}$
PTFE	$(2.1 \pm 0.3) \times 10^{-5}$	$(8.2 \pm 1.3) \times 10^{-6}$
Copper	$(1.7 \pm 0.2) \times 10^{-6}$	$(2.5 \pm 0.2) \times 10^{-8}$
Inner vessel	$(1.9 \pm 0.8) \times 10^{-3}$	$(4.7 \pm 3.7) \times 10^{-5}$
Outer vessel	$(2.7 \pm 1.3) \times 10^{-3}$	$(1.4 \pm 0.5) \times 10^{-4}$
Total Material	$(9.9 \pm 1.9) \times 10^{-3}$	$(2.8 \pm 0.6) \times 10^{-4}$

mDRU = 10^{-3} events kg^{-1} day^{-1} keV^{-1}