Searching for 0νββ of $^{136}$Xe with PandaX-III

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Detection channels

\[
(T^{\nu}_{1/2})^{-1} = F_N \left| \langle m_{\beta\beta} \rangle \right|^2 \frac{m^2}{m_e^2}
\]
Detection channels

\[(T_{1/2}^{0ν})^{-1} = F_N \frac{|\langle m_{\beta\beta} \rangle|^2}{m_e^2}\]

Electrons/holes

- GERDA
- Majorana
- COBRA
- PandaX-III
- CDEX-300v
- NvDEX

Photons

- AMoRE
- CUPID
- CUPID-CJPL
- KamLAND-Zen
- SNO+
- CANDLES
- NEXT
- SuperNEMO
- JUNO- 0νββ
Detection of double beta decay

- Examples:

\[ ^{136}_{54}Xe \rightarrow ^{136}_{56}Ba + 2e^- + (2\bar{\nu}) \]
\[ ^{130}_{52}Te \rightarrow ^{130}_{54}Xe + 2e^- + (2\bar{\nu}) \]

- Measure energies of emitted electrons
- Electron tracks are a huge plus
- Daughter nuclei identification

Simulated track of 0v\beta\beta in high pressure Xe

Sum of two electrons energy
PandaX Detectors

PandaX-I: 120kg LXe (2009 – 2014)

PandaX-II: 500kg LXe (2014 – 2018)

PandaX-xT LXe (future)

WIMP searches (0νββ as well)

PandaX-III: 100kg - 1 ton HPXe for 0νββ (future)

PRL 117, 121303 (2016)
Outline

• Characteristics of high pressure gaseous TPC for $0\nu\beta\beta$

• Hardware development
  • Micromegas detector modules
  • Prototype TPC and test setups
  • Electronics and DAQ
  • Infrastructure

• Simulation and analysis efforts
PandaX-III: high pressure gaseous TPC for $0\nu\beta\beta$ of $^{136}\text{Xe}$

- TPC: 100 kg scale high pressure TPC at 10 bar operating pressure
- Charge only readout with millimeter level spatial resolution
- Good energy resolution and tracking capability for signal-background discrimination
0νββ of $^{136}\text{Xe}$ in gasesous TPC

- Electrons from $^{136}\text{Xe}$ travel around 10 cm in 10 bar xenon
- Mostly one single track
- Two Bragg blobs at the ends (two electrons)
Gas medium: Xe + TMA (三甲胺)

- Better energy resolution: 3% FWHM (@Q_{0\nu\beta\beta}) (expected)
  - TMA suppress light; more ionization
  - TMA as a quencher, increase the stable working voltage
- Better tracks
  - TMA suppress diffusion


Charge readout plane

- 52 Micromegas modules mounted on a backplate
- Mosaic layout to cover readout planes
  - Minimal dead zone
  - Strip and mesh signal readout
  - Second iteration with custom-designed face-to-face connectors

Prototype backplate
Charge-only readout plane with MicroMegas (MM)

- MicroMegas amplifies drift electron signal via avalanche
  - >1000 gain expected in 10 bar xenon (100 um gap)
- 3mm pitch
- Strip readout to have reasonable number of readout channels
Microbulk --> Thermal bonding Micromegas from USTC

• Original choice was Microbulk Micromegas from CERN
• Switched to thermal bonding Micromegas from USTC since early 2020
Recent progress on USTC thermal bonding MM

- Now 5th version of thermal bonding Micromegas under testing.
- Tested in 1/8/10 bar argon mixture gases.
- Best energy resolution at 6 keV ($^{55}$Fe) is 15% in 1 bar argon/CO$_2$.
- No dead channels!
Development of thermal bonding Micromegas

Readout PCB

Thermal bonding MM

Low background, Energy resolution, uniformity

V1 V2 V3 V4 V5

3mm edge, long term stability
Test setups, prototype, and full vessel at SJTU

MiniTPC:
1 MM, 16 bar

Prototype TPC:
7 MM, 10 bar

Full vessel: low background
SS, 4 m³ inner volume

1 MM, flow gas
Prototype TPC at Shanghai

- About 600 L inner volume
- Field cage: 66 cm diameter, 78 cm drift length
- 16 kg of xenon at 10 bar
- SS pressure vessel
- 7 MM
Field cage

- Tiled Kapton Flexible PCB + SMD resistors
- Tested in small and medium scale
  - HV performance comparable with copper bar options
- Fabricated by TangChen (JUNO vendor) for low background control
Front end electronics

Frontend electronics based on AGET ASIC chips

- 64 channel per AGET
- 512 sampling point per channel
- Dynamic range up to 10 pC
- Sampling rate: 1 MHz to 100 MHz

V6 for mass production, in progress
Quest for low background

Sample: 976mHz
Background: 20mHz

Sample: 26mHz
Background: 20mHz

Sample: 193 mHz
Background: 17 mHz

Low background connector found by USTC
Backend

Backend: The Trigger and Data Concentrator Module – TDCM

- Designed by Saclay for PandaX-III and T2K-II
- A custom-made 6U form factor carrier board with two physical layer mezzanine cards for 32 FECs
- Backup option: DCM from USTC
DAQ chain

- DAQ chain joint test is ongoing with promising results
- DAQ software based on MIDAS reaches stable state
Gas circulation and purification system
Detector installation fixture
Clean room at CJPL-II
Traditional “cut” based analysis

- Reconstructing tracks in XZ, YZ planes
- Number of tracks optimization by tuning “track distance”
- Energy of end blobs cut optimization

[Graphs and diagrams related to the text]
Convolutional Neural network (CNN) for track classification

- XZ, YZ 2D snapshots of an event as input of CNN to spill out an index of signal/background
- Prepare image collections for CNN training, validation, and classification.
- No track reconstruction needed.
- More effective than traditional cut based approach.

Test Samples

Kalman filter based track reconstruction

• Iterative process with Kalman filter in Bayesian formalism to better reconstruct the tracks and calculate $dE/dx$

• Improve $0νββ$ search sensitivity by 3 times to $2.7 \times 10^{26}$ year

• Tao Li (SYSU), Shaobo Wang, et al arXiv:2102.08221
Double beta decay to excited states

- Double beta decay to excited states of $^{136}\text{Ba}$
- Dual-electron + Gamma emission: clearer signature
- Position sensitivity and dual-beta/gamma discrimination to enhance search sensitivity: NLDBD-ES by 4.8 times, and DBD-ES by 1.8 times.

\[ E_{\text{max}} = 879 \text{ keV} \]

\[ 760 \text{ keV} \quad 818 \text{ keV} \]
Summary

- **PandaX-III** 100-kg scale high pressure gas TPC module
  - Sub-systems move forward
  - Assembly starts soon
- Half-life sensitivity with 3 years of data: $9 \times 10^{25}$ yr (90% CL)
  - Will fully exploit tracking feature to further improve the sensitivity