A New ^{82}Se detector for Neutrinoless Double Beta Decay Searches

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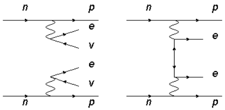
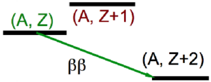
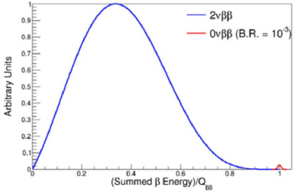
Neutrinoless Double Beta Decay

- Neutrinos are the only particles in the SM that can have Majorana mass term
- For certain atoms, single β decay is not energetically favored, but double β decay is
- "Smoking gun": neutrinoless double beta decay (bump at the end-point of double beta decay), lepton-violating process
- Extremely low background and excellent energy resolution needed

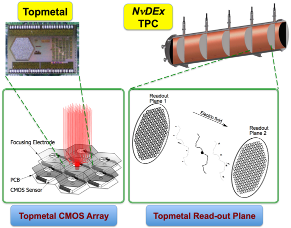


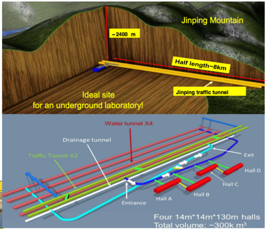




NνDEx: No ν Double beta decay Experiment, HP$^{82}SeF_6$ TPC

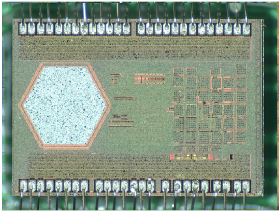
- Q-value=2.998 MeV ⇒ above most natural background
- Signal-background discrimination via event topology
- Placed at China JinPing Laboratory (CJPL), 2,400 m rock overburden ⇒ background strongly suppressed
- SeF_6 is toxic (<0.05 ppm in environment) and electronegative: negative ions will drift
- Topmetal-S sensor designed to detect negative ions, give us good energy resolution without e^- avalanche amplification $\sim$1% FWHM ⇒ ROI: 30 keV

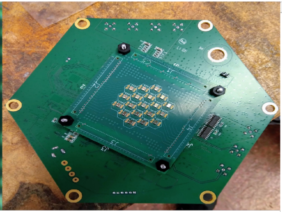


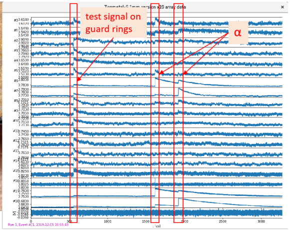


Topmetal-S Sensor

- Two tapeouts already conducted, third one under production
- First tapeout was tested with α, issues with the signal collected (5% of the expected value)
- Chips were redesigned, according to preliminary tests, this problem was solved in the second tapeout
- Input noise <130 e$^-$ achieved so far, NνDEx goal: 45 e$^-$

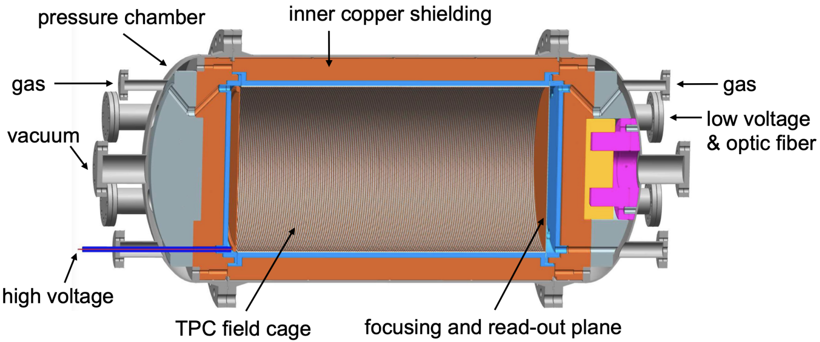






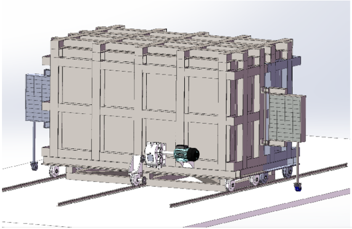
See also **C. Gao et al., PoS TWEPP2018(2019)**; **B. You et al., Nucl. Instrum. Meth. A 988 (2021), 164871**

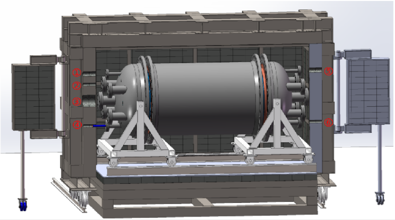
NνDEx-100



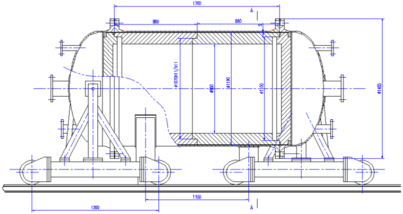
- 100 Kg of SeF_6 (10 atm).
- Start with SF_6 (non poisonous) to check for gas the system, then switch to SeF_6
- First run (2025): nat. Se, applying for funding for enrich. Se
- CDR posted on arxiv, sent for publication, currently under review: **X. Cao et al, arXiv:2304.08362 [physics.ins-det]**.

Detector

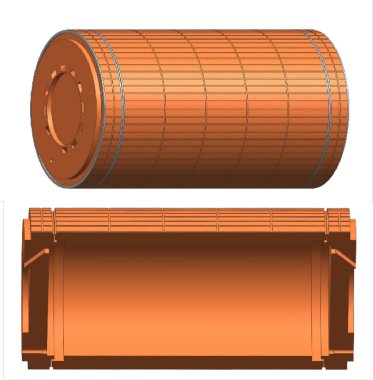




A 20 cm thick lead shield is placed around the detector to stop the γ rays

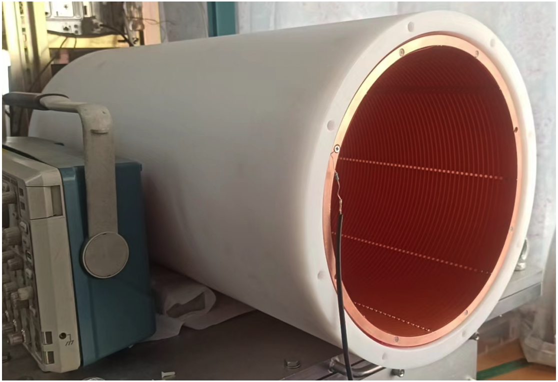


Inner Copper Shield



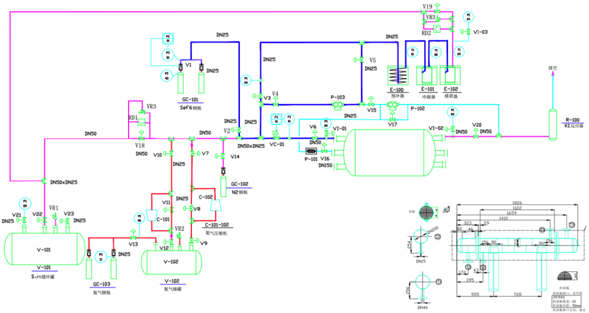
- Low-radiation oxygen-free copper
- 12 cm thick

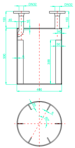
Field Cage



- POM insulator layer + POM supporting structure + FPCB
- Finished with an initial design, a 30cm-diameter prototype is made and being tested

Gas System





condenser

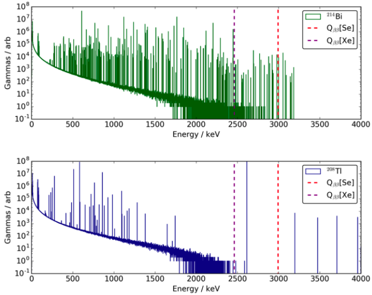
pre-cooler

chiller

- A cold trap for SeF_6 storing
- A tank for SeF_6 storage, in case of emergency
- Negative pressure room with gas monitor & SeF6 reactor
- Test with SF_6 gas before filling SeF_6 each time

γ Background

- γ from natural radioactivity (mostly ^{238}U).
- Using a 20 cm lead shield can be reduced down to $\sim$0.4 events/year ($\sim 1.4\times10^{-4}$evts/kg·keV·yr)
- Additional shielding would not decrease it further, since it comes mostly from radioactive contamination in the detector
- No topological cuts considered so far!



D.R. Nygren et al., JINST 13 (2018) 03, P03015

Source	Evts/yr	10^5Evts/(keV kg yr)
Walls	0.004	0.12
Lead	0.003	0.09
HDPE	0.005	0.16
SSV	0.026	0.86
ICS	0.050	1.67
POM	0.330	10.99
Total	0.42	13.9

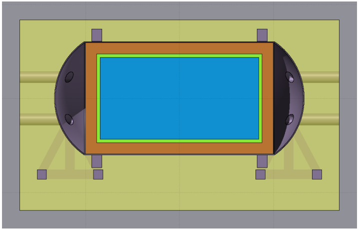
X. Cao et al, arXiv:2304.08362 [physics.ins-det]

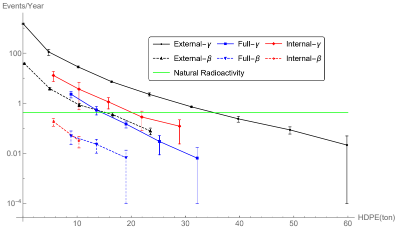
Neutron Background

Two possible ways neutrons can provide background

- Create unstable isotopes in the fiducial volume, β decay $\Rightarrow$ background
- Be absorbed inside the detector, γ's will be emitted
  This will be the dominant contribution to the neutron background, however sub-dominant with respect to γ. HDPE needed to stop neutrons: filling the space between lead and SSV + 30 cm external shield $\Rightarrow$ 0.03 events/year

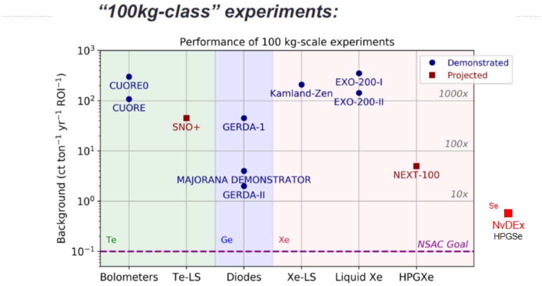
Q. Wang, Z. Huang, P, Hu and EC, arXiv:2307.12785 [physics.ins-det]





Other Sources of Background & Sensitivity

- Due to slow drift velocity of ions, pile-up backgrounds could be an issue $\Rightarrow$ Considering adding scintillation light read-out with silicon PM at the HV end
- Cosmic-generated ^{56}Co, ROI background $\sim$3400/yr, half-life 77 d, need $\sim$3 years to cool down underground



Plot from B. Jones, "Review of Neutrinoless Double Beta Decay Searches", talk given at NDM22

0.5 background evts/yr w/o topological cuts $\Rightarrow$ Assuming same efficacy as in NEXT for topological cuts $\sim$ 0.05 evts/yr$\Rightarrow$ Effectively, 0-background experiment $\Rightarrow$ $3 \times 10^{25}(3 \times 10^{26})$ yr sensitivity with nat (enriched) Se (5 years run)

Summary & Future Plan

- NνDEx concept combines advantages from the high Q-value of ^{82}Se and TPC's ability to see event topology, using novel topmetal sensor technology.
- NνDEx-100 is being built.
- $3 \times 10^{25}(3 \times 10^{26})$ yr sensitivity with nat (enriched) Se (5 years run)
- Very low background index, very good prospects for scalability

Plan:

- 2023: Completed CDR,study of topmetal sensors using radioactive sources (in progress)
- 2024: Move to CJPL, noise reduced to 45 e^-
- 2025: assembling the whole system, begin data-taking
- 2026: First Results

More than 30 people from 8 institutes in China; colleagues from all around the world are welcome to join!

Backup Slides

γ Background: Radioactive Contamination

Values of radioactivity assumed in the simulations for different part of the geometry (for the materials of the detector, NEXT values were used)

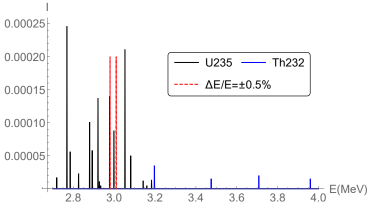
Material	Subsystem	^{238}U Activity (mBq/kg)
Concrete	Experimental hall	6.8×10^3[1]
Lead	External shielding	0.37 [2]
HDPE	External shielding	0.23 [2]
Steel	Pressure vessel	1.9 [2]
Copper	Inner copper shielding	0.012[2]
POM	Field cage	0.23[2]

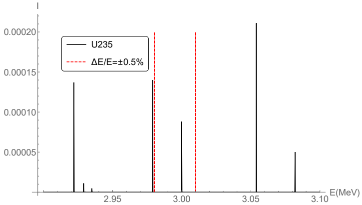
[1] H. Ma *et al.*, "In-situ gamma-ray background measurements for next generation CDEX experiment in the China Jinping Underground Laboratory.", Astropart. Phys., 128:102560, 2021.
[2] V. Alvarez *et al.*,"NEXT-100 Technical Design Report (TDR): Executive Summary" NEXT-TDR, JINST,6237:T06001, 2012.

γ lines

- Main contribution to γ flux from ^{238}U and ^{232}Th decays
- Due to the high Q-value, we are above the 2.614 MeV line from ^{232}Th decay chain (^{208}Tl)$\Rightarrow$ γ background considerably reduced
- Main contribution from ^{238}U decay chain (^{214}Bi)

Instead of simulating the full decay chain, we took the γ lines information from the ENDF/B-VIII.0 database and wrote a code that create γ's according to that distribution

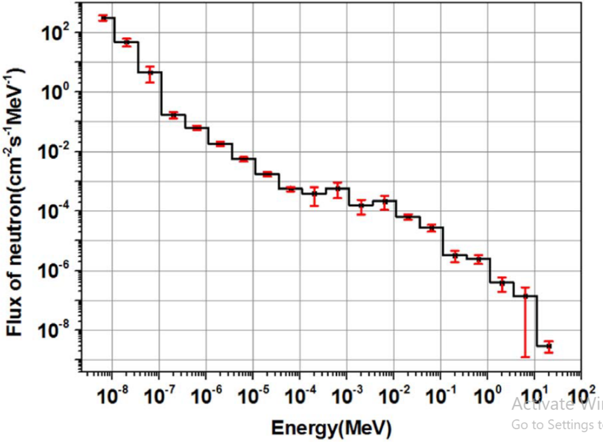




γ lines for ^{238}U and ^{232}Th from ENDF/B-VIII.0 database

Neutron Spectrum

We used the neutron spectrum reported in **Q.D. Hu** *et al.*, **Nucl.Instrum.Meth.A 859 (2017) 37-40**

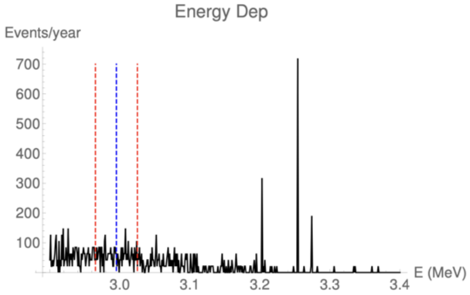


Total neutron flux: $(2.69 \pm 1.02) \times 10^{-5} cm^{-2} s^{-1}$

Cosmogenic Activation

- Cosmogenic muons can activate nuclei in the material of the detector on surface
- ^{56}Co is the most dangerous isotopes, after exposure in Lanzhou, estimated background $\sim$ 3400 events/year.
- $\sim$ 3 years of cooling down underground required for the background to be less than γ's
- Other isotopes with long enough lifetime have Q-value<3 MeV

isotope	Q (MeV)	$T_{1/2}$
^{54}Mn	1.4	312d
^{56}Co	4.6	77d
^{57}Co	0.8	272d
^{58}Co	2.3	71d
^{60}Co	2.8	5.3yr



Energy Resolution

- Q-value for ^{82}Se=2.998 MeV, Ionization energy $W_{SeF6} \simeq 32$ eV, $\Rightarrow N_e = 2.36 \times 10^4$
- Fano Factor $\Rightarrow$ lower bound to the energy resolution (cannot get better than this). For SeF_6, at 3 MeV:

$$\sigma/\mathrm{E} = 0.142\% \qquad \mathrm{FWHM/E} = 2\sigma\sqrt{\mathrm{Log}[4]} = 0.34\%$$

- Energy resolution is worsened by the presence of noise, etc...
- Other factors to be taken into account: changing focusing efficiency (need to reach ∼100%), sensor temperature variation, etc...