Mitigation of Cosmogenically Induced Background from ^{42}Ar / ^{42}K using Encapsulation with Ultra-Pure Plastic for the LEGEND Experiment

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LOW RADIOACTIVITY TECHNIQUES 2022 WORKSHOP VIII

Are neutrinos their own antiparticles?

Dirac : $\nu \neq \bar{\nu}$, $\Delta L = 0$, Standard Model

Majorana : $\nu = \bar{\nu}$, $\Delta L \neq 0$, Beyond Standard Model

Motivation for $0\nu\beta\beta$ decay : Neutrino oscillation ($m_\nu \neq 0$)
Observation of $2\nu\beta\beta$ decay

Search for $0\nu\beta\beta$ decay ⇒ Neutrinos are Majorana in nature

$\mathbf{0\nu\beta\beta}$: (A,Z) → (A,Z+2) + e^- + e^-

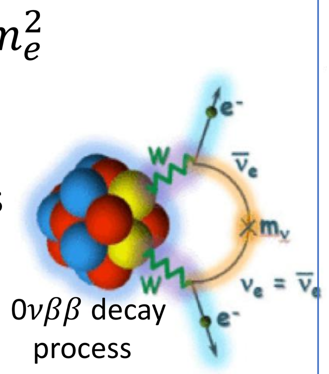
Theory: $(T_{1/2}^{0\nu})^{-1} = G^{0\nu}\, g_A^4\, |M^{0\nu}|^2\, m_{\beta\beta}^2/m_e^2$

Experiment: $T_{1/2}^{0\nu} \propto a\, \epsilon\, \sqrt{\mathcal{E}/(B.\Delta E)}$

Measurement of half-life leads to neutrino mass

Experiment	Isotope	Half-life $T_{1/2}^{0\nu}$ (10^{26} yr) [90% C.L.]	Neutrino mass $m_{\beta\beta}$ (meV)
KamLAND-Zen	^{136}Xe	> 2.3	< 36 - 156
GERDA	^{76}Ge	> 1.8	< 80 - 180
EXO - 200	^{136}Xe	> 0.35	< 90 - 290
MAJORANA	^{76}Ge	> 0.27	< 200 - 430
CUORE	^{130}Te	> 0.22	< 90 - 310

Current limits on $0\nu\beta\beta$ decay half-life and effective Majorana neutrino mass [1-5]



$0\nu\beta\beta$ decay process

LEGEND Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

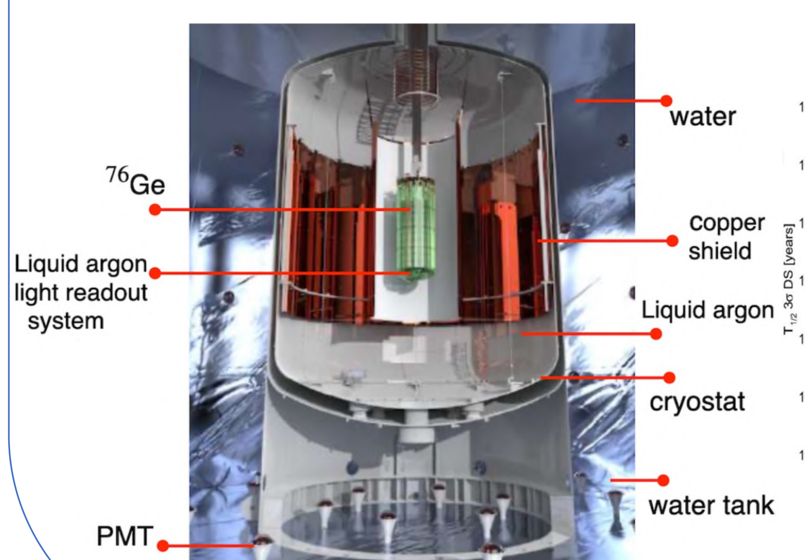
Goal: ^{76}Ge → ^{76}Se + e^- + e^-

Merger of GERDA and MAJORANA

Major Improvements in LEGEND-200:

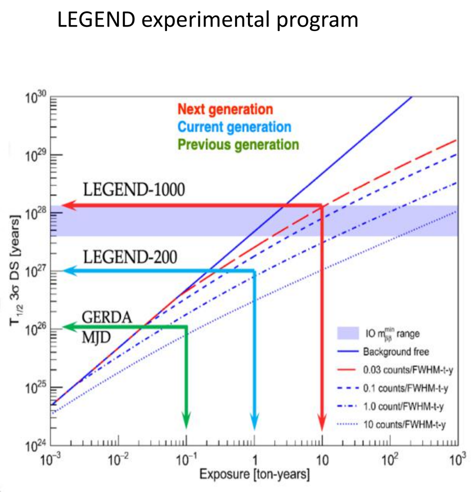
(I) Larger germanium mass
(II) Components with lower radioactivity
(III) High purity liquid argon (coolant, shielding and active veto)
(IV) PEN is structural element instead of copper and silicon

Experiment	LEGEND-200	LEGEND-1000
Status	Prepare for data taking	Planned
Location	LNGS	LNGS/SNOLAB
Isotope	^{76}Ge	^{76}Ge
Active mass	200 kg	1000 kg
Discovery sensitivity	10^{27} yr	10^{28} yr
Run time	5 yr	10 yr



LEGEND-200 Detector at LNGS [6]

LEGEND experimental program



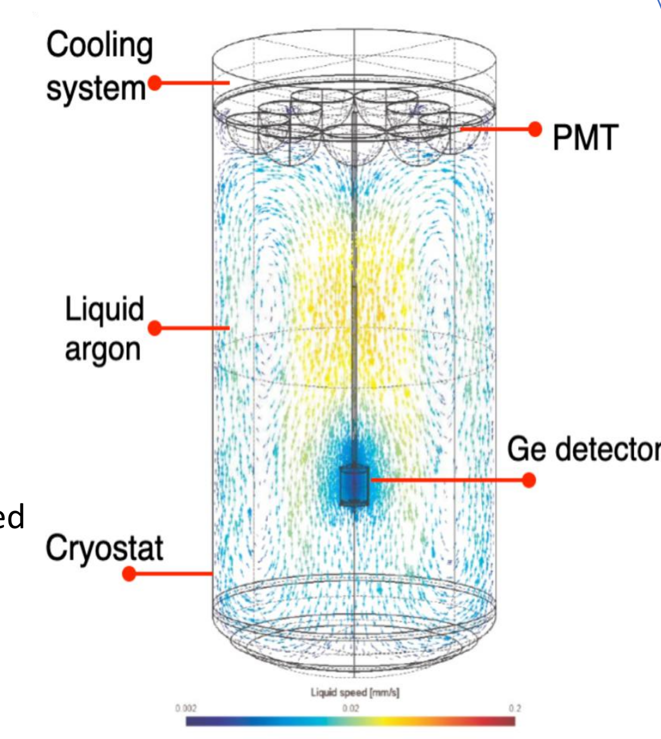
Dependence of discovery sensitivity on exposure and background [6]

Presence of ^{42}Ar/^{42}K in liquid argon in GERDA

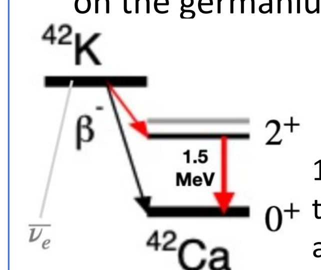
Thermally driven convection of neutral and charged particles in cryogenic fluid.

The flow is driven by heat exchange between the walls of the cryostat and active cooling system at the top.

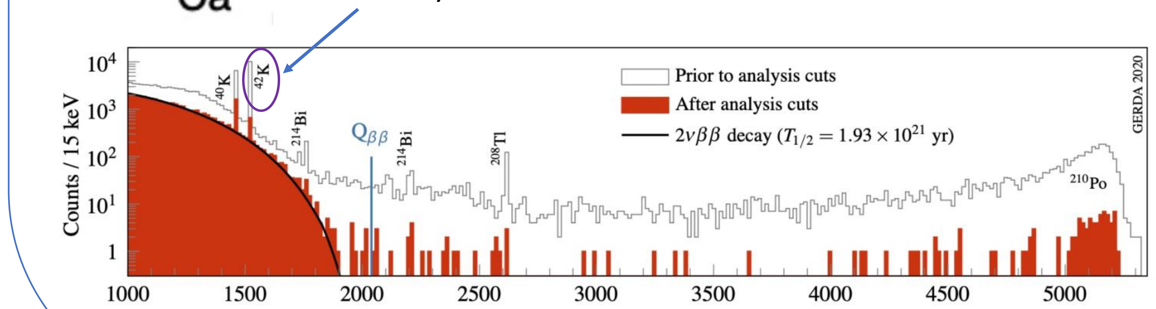
Ions can be attracted by electric field of germanium detectors as a result accumulated on the germanium surface.



Liquid argon speed distribution in cryostat (mm/s)[7]



1.5 MeV γ line is the indicator of ^{42}K as seen by GERDA



GERDA final data shows the presence of ^{42}Ar/^{42}K in liquid argon [2]

Origin of ^{42}Ar/^{42}K in natural argon

Cosmogenic alpha induced ^{42}Ar:

^{40}Ar + α → ^{42}Ar + p + p

Production of ^{42}K:

^{42}Ar → ^{42}K$^+$ + β^- + $\bar{\nu}_e$, Q_β = 599 keV, $T_{1/2}$ = 32.9 yr

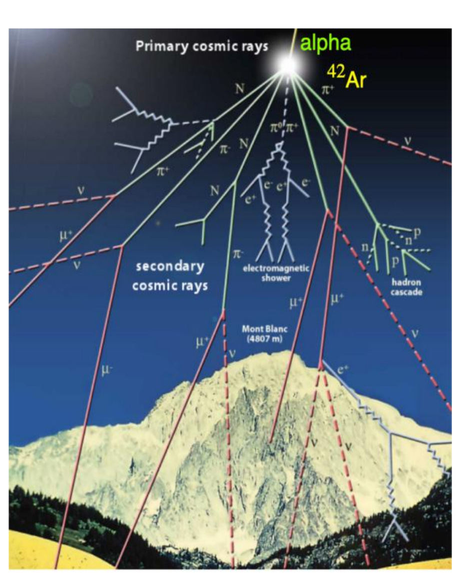
Decay of ^{42}K :

^{42}K$^+$ → ^{42}Ca^{++} + β^- + $\bar{\nu}_e$, Q_β = 3525 keV, $T_{1/2}$ = 12.3 hr

This energy continuum overlaps the $0\nu\beta\beta$ decay signal (monoenergetic peak) of ^{76}Ge at $Q_{\beta\beta}$ = 2039 keV

Underground argon is a possible mitigation of ^{42}Ar:

- Exposure of a much lower flux of cosmic particles hence the lesser production rate of ^{42}Ar.
- Extracted from CO_2 wells in Colorado.
- Expensive and requires subsystem not to vent back into atmosphere in the cause of accident.
- 18 tonne for LEGEND-1000.



Cosmogenic production of ^{42}Ar in upper atmosphere

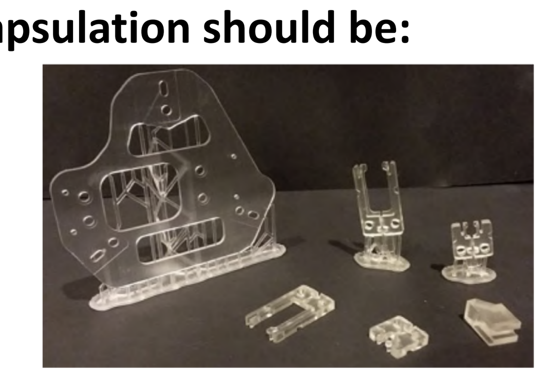
Alternative to Underground Argon is Encapsulation of Germanium Detector:

- Encapsulation of germanium detector with low background materials minimize the ^{42}K background.
- 392 germanium detectors will be used in LEGEND-1000.
- All germanium detectors have different sizes.
- Encapsulation should be custom build for every detector.
- 3D printing is a viable solution for encapsulation.

R&D for Encapsulation

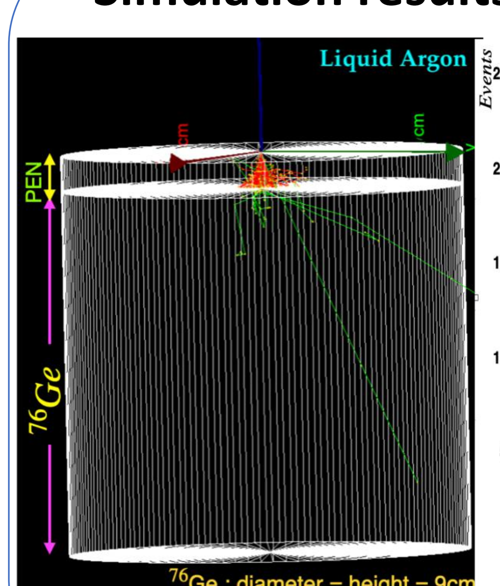
Ideal material for encapsulation should be:

- Radiopure
- 3D printable
- Transparent
- Scintillating
- Mechanically stable at cryogenic temperature
- Does not contaminate liquid argon by outgassing

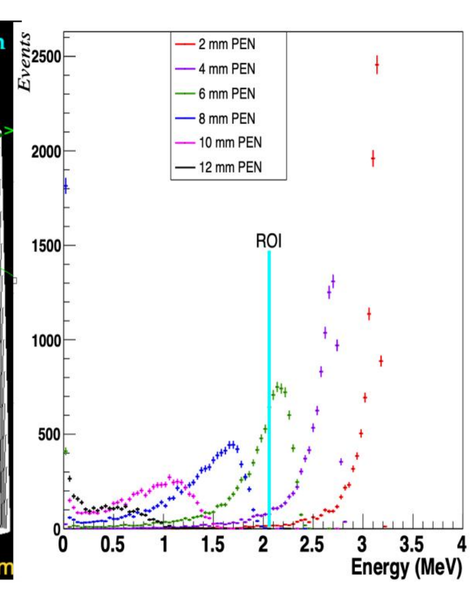


Example of 3D printed LEGEND-200 style components [8]

Simulation results of encapsulation:



GEANT4 simulation of encapsulation



Simulation results for encapsulation

Poly(ethylene 2,6-naphthalate) (PEN):

- Transparent plastic scintillator
- Shifts wavelength: UVU → 450 nm
- Same yield strength as copper at cryogenic temperature

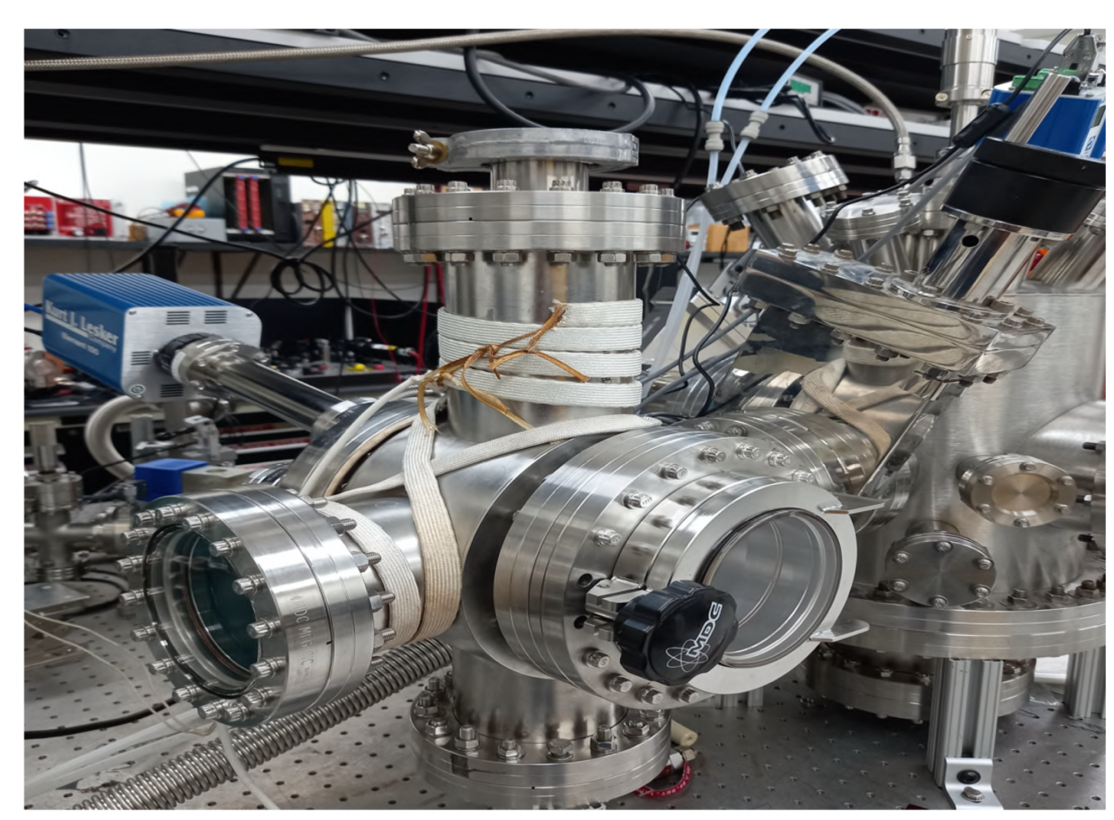
Simulation shows 6 to 8 mm PEN requires to reduce Q_β (^{42}K) below $Q_{\beta\beta}$. This is a lot of passive material next to germanium detector.

Ongoing activities :

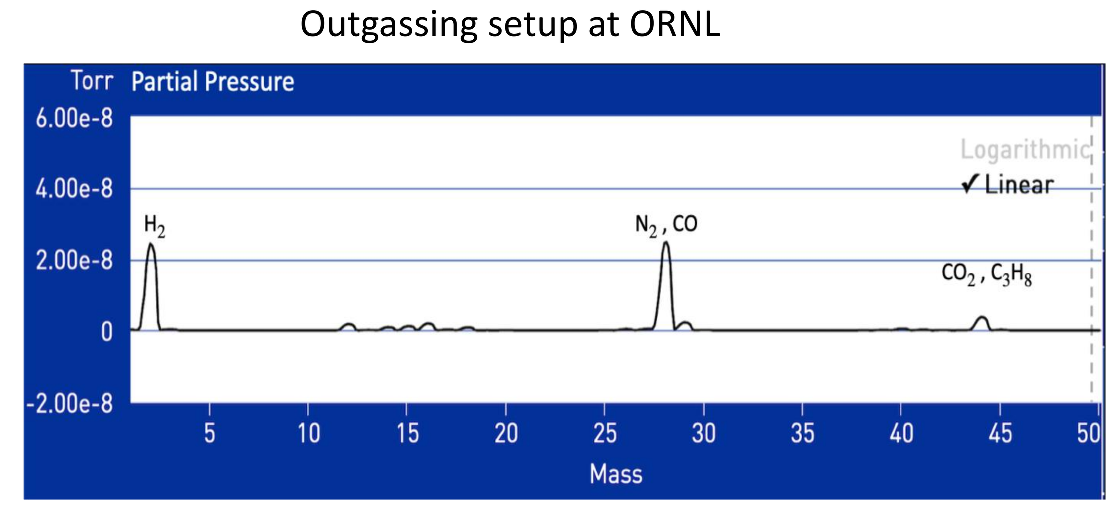
1. Outgassing measurements :

Identify emanation of molecular species from samples which could quench light in liquid argon.

Encapsulation sample is placed in sealed vacuum chamber with very low pressure, gaseous molecules are then identified by residual gas analyzer.



Outgassing setup at ORNL



Example of residual gas analyzer mass spectrum

2. Radiopurity measurements :

- Only radiopure materials will be selected as a potential candidate for encapsulation phase of germanium detectors, < 1 μBq per component.
- ICP-MS and gamma ray spectrometry will be performed on samples.

3. Optical measurements :

The encapsulation would leverage the LAr veto system of the LEGEND-1000 and hence every specimen will undergo optical testing.

Measurements for optical response of encapsulation material :
(i) Refractive index (ii) Peak emission wavelength
(iii) Reflectivity (iv) Light attenuation
(v) Wave shifting properties.

4. Mechanical measurements :

The encapsulation will remain in the detector for significantly longer period of time (10 yr) in cryogenic liquid at LEGEND-1000.

Measurement of ultimate tensile strength of each specimen will be performed at cryogenic conditions.

5. Cryogenic measurements :

- Encapsulation sample will be tested in liquid argon.
- Testing the encapsulated germanium detector in enriched argon with ^{42}Ar in a custom build cryostat with a VUV optical readout.

We are planning to produce ^{42}Ar at Notre Dame accelerator as:

^{40}Ar(^{7}Li^{3+}, α p)^{42}Ar

All of the testing procedures of encapsulation and fabrication will be performed at ORNL.

References:

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[6] N. Abgrall et al. (LEGEND), arXiv: 2107.11462 (2021)
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