The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay (LEGEND)

Michael Willers
Lawrence Berkeley National Laboratory
19.02.2019

Photo by Jacek Dylag (Unsplash)
A very short introduction to neutrinoless double beta decay

Two-neutrino double beta decay ($2\nu\beta\beta$)
- Only decay possible in certain isotopes ($^{76}\text{Ge}$, $^{82}\text{Se}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, ...)
- Predicted by the Standard Model
- Observed experimentally!

Neutrinoless double beta decay ($0\nu\beta\beta$)
- Violates lepton number by 2 units $\rightarrow$ new physics
- Determines the nature of the neutrino $\rightarrow \nu = \bar{\nu}$
- Can provide information on the $\nu$ mass
- so far unobserved

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$

Example: light neutrino exchange
The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

**LEGEND mission:** “The collaboration aims to develop a phased, $^{76}$Ge based double-beta decay experimental program with discovery potential at a half-life beyond $10^{28}$ years, using existing resources as appropriate to expedite physics results.”

53 institutions
About 250 scientists
• $Q_{\beta\beta} = 2039$ keV

• Excellent energy resolution
  → 2.2 - 3 keV FWHM at $Q_{\beta\beta}$

• Very high detection efficiency
  → source = detector

• Enrichment to > 88% in $^{76}$Ge possible

• Excellent background rejection
  → pulse shape & detector granularity

• Very low backgrounds achieved
The MAJORANA DEMONSTRATOR and GERDA Experiments

MAJORANA DEMONSTRATOR @ SURF

• Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
• Low noise electronics improves pulse shape discrimination
• Low energy threshold (helps reject background, extended low-energy physics program (e.g. dark matter search))

GERDA @ LNGS

• Detectors ($^{76}$Ge) in liquid argon (LAr)
• LAr acts as an active shield (no Pb)
  → background tagging by LAr scintillation light & coincident signals

Both:
• Clean fabrication techniques
• Control of surface exposure (cosmogenic activation)

• Lowest background and best resolution 0νββ decay experiments
• Combined detector mass: ~ 65 kg of $^{76}$Ge
The MAJORANA DEMONSTRATOR and GERDA Experiments

**MAJORANA DEMONSTRATOR @ SURF**

- **Background**: $4.7 \pm 0.8 \times 10^{-3}$ cts/(keV kg yr)
- **Resolution (FWHM)**: 2.5 keV @ $Q_{\beta\beta}$
- **Sensitivity**: $4.8 \times 10^{25}$ yr (90% CL)
- **Limit**: $T_{1/2} > 2.7 \times 10^{25}$ yr

**GERDA @ LNGS**

- **Background**: $0.6 \pm 0.4 \pm 0.2 \times 10^{-3}$ cts/(keV kg yr)
- **Resolution (FWHM)**: 3 keV @ $Q_{\beta\beta}$
- **Sensitivity**: $1.1 \times 10^{26}$ yr (90% CL)
- **Limit**: $T_{1/2} > 0.9 \times 10^{26}$ yr

**LEGEND strategy**: select best technologies based on experiences of MAJORANA DEMONSTRATOR and GERDA, as well as contributions from other groups and experiments

DOI 10.5281/zenodo.1286900
DOI 10.5281/zenodo.1287604
The LEGEND Experiment

First stage (LEGEND-200):
- (Up to) 200 kg of detectors $^{(enr76}Ge$
- Utilise existing GERDA infrastructure at LNGS + modifications as needed
- Target exposure: 1 t yr
- BG goal: 0.6 cts / (FWHM t yr)
- Data-taking start in ~ 2021

Subsequent stages (LEGEND-1000):
- 1000 kg of detectors $(enr76Ge)$ (staged)
- BG goal: reduction to < 0.1 cts / (FWHM t yr)
- Location: TBD
→ required depth ($^{77m}Ge$) under investigation
LEGEND-200

• Utilise existing GERDA infrastructure at LNGS
• Large enough for 200 kg of enriched detectors
• \textit{Exposure}: 1 ton yr, \textit{Sensitivity} > 10^{27} \text{ yr}
• Background goal: 0.6 cts / (FWHM t yr)

• Modifications:
  • new electronics
  • raise clean room roof
  • new lock
  • new cabling, detector suspension, feedthroughs

• Detectors:
  • BroadEnergyGe (BEGe) detectors from GERDA
  • P-type Point Contact (PPC) detectors from MAJORANA
  • new inverted coaxial detectors (baseline 1.5 kg)

• Funding for LEGEND-200 almost secured, first orders for additional detectors placed!
• Data-taking start in ~ 2021
**LEGEND-200: larger enrGe detectors**

- GERDA BEGe: ~ 0.7 kg
- MJD PPCs: ~ 0.8 kg

Larger detectors → less cables, connectors and readout electronics → **lower background**

**New concept:** Inverted Coaxial Point-Contact Ge detectors (ICPC) DOI 10.1016/j.nima.2011.10.008

- Combines advantages of Coaxial and BEGe/PPC detectors: high mass / lower depletion voltage / excellent pulse shape discrimination
- Large mass of up to 3 kg (R&D for 6 kg ongoing) → "production" ~ 1.5 kg
- Orders for LEGEND-200 detectors placed early 2019!
**Baseline Design:** Combine LAr-operated preamplifier of GERDA with the ultra-clean Low Mass Front-End of MAJORANA DEMONSTRATOR

→ Preamplifier (CC4) developed by **INFN / University of Milan, Italy**
→ Low Mass Front-End (LMFE) developed by **Lawrence Berkeley Laboratory**

- Based on current GERDA preamplifier (CC3)
- Differential output
- Operation in LAr

Amorphous germanium feedback resistor $R_f$ (few GΩ in LAr)

Feedback and pulser ($C_F$ and $C_P$): stray capacitance between traces

Bare die JFET: Moxtek MX11

Sputtered Ti/Au traces

Fused silica substrate / Suprasil

+ new cables (Axon pico-Coax) & connectors
+ new LMFE mount
**LEGEND-1000**

- Detector array: 1 t of $^{76}$Ge(enr)
- Separate arrays, each payload ~ 200 - 250 kg
- Exposure: 10 t yr
- Sensitivity: $>10^{28}$ yr
- Background target: < 0.1 cts / (FWHM t yr)
- Location: TBD (studies concerning cosmogenic background from $^{77m}$Ge ongoing)
- Potential to use depleted underground Ar is investigated ($^{42}$Ar background)
  - $\rightarrow$ divide LAr volume into small depleted volumes surrounding detectors and large natural LAr volume
- Many R&D efforts $\rightarrow$ very high mass detectors, ...
LEGEND - Discovery Potential

$^{76}\text{Ge (88\% enr.)}$

$T_{1/2, 3\sigma, DS \text{ [years]}}$

10^3 - 10^30

10^29 - 10^28

10^27 - 10^26

10^25 - 10^24

10^{-3} - 10^{-1}

10^{-1} - 10^1

10^1 - 10^3

Exposure [ton-years]

IO $m_{\text{min}}^\text{eff}$ range

Background free

0.1 counts/FWHM-t-y

1.0 count/FWHM-t-y

10 counts/FWHM-t-y

LEGEND-1000

LEGEND-200

GERDA / MJD
LEGEND - Exclusion Sensitivity

$^{76}$Ge (88% enr.)

$T_{1/2}^{90\% \text{ Sensitivity}}$ [years]

Exposure [ton-years]

LEGEND-1000

LEGEND-200

GERDA / MJD

$\text{IO m}^\text{min}_{\text{FWHM}} \text{ range}$

- Background free
- 0.1 counts/FWHM-t-y
- 1.0 count/FWHM-t-y
- 10 counts/FWHM-t-y
LEGEND - Schedule

- **2018**
  - GERDA (100 kg yr)
  - Majorana (75 kg yr)

- **2019**
  - LEGEND-200 Purchase Isotope
  - Fabricate Detectors
  - Install New Lock, Calibration, infrastructure

- **2020**
  - Install Detectors

- **2021**
  - LEGEND-200 Data runs

- **2022**
  - LEGEND-1000 Design/Build 2021-2029

**Ton-Scale Down-Select Process**
Conclusions & Outlook

• Discovery of $0\nu\beta\beta$ would have far-reaching consequences in particle physics
  → $\nu = \bar{\nu}$ / Lepton Number Violation

• The next generation of $0\nu\beta\beta$ decay experiments will require reduced backgrounds and increased detector mass

• $^{76}$Ge detectors have demonstrated the lowest backgrounds and best energy resolution
  → well suited technology for ton-scale $0\nu\beta\beta$ experiment

• LEGEND will build upon the success of MJD and GERDA
  → pursue a staged approach: starting with 200 kg (LEGEND-200) and gradually increasing (LEGEND-1000)

• Funding for LEGEND-200 almost secured, first orders for additional detectors placed!

• Design studies and R&D for LEGEND-1000 ongoing
Acknowledgements

• We appreciate the support of our sponsors:
  • German Federal Ministry for Education and Research (BMBF)
  • German Research Foundation (DFG), Excellence Cluster Universe
  • German Max Planck Society (MPG)
  • U.S. National Science Foundation, Nuclear Physics (NSF)
  • U.S. Department of Energy, Office of Nuclear Physics (DOE-NP)
  • U.S. Department of Energy, Through the LANL, LBNL & ORNL LDRD programs (LDRD)
  • Italian Instituto Nazionale di Fisica Nucleare (INFN)
  • Swiss National Science Foundation (SNF)
  • Polish National Science Centre (NCN)
  • Foundation for Polish Science
  • Russian Foundation for Basic Research (RFBR)
  • Research Council of Canada, Natural Sciences and Engineering
  • Canada Foundation for Innovation, John R. Evans Leaders Fund

• We thank our hosts and colleagues at LNGS
• We thank the ORNL Leadership Computing Facility and the LBNL NERSC Center
Thank you for your attention!