Status of the LEGEND experiment

Mariia Redchuk on behalf of the LEGEND collaboration
What I want you to remember about
What I want you to remember about LEGEND

**LEGEND** = Large Enriched Germanium Experiment for Neutrinoless double beta Decay

1. **Neutrinoless double beta decay** ($0\nu\beta\beta$)
   - create matter without antimatter
   - lepton number violation
   - not observed yet

2. **Enriched germanium detectors**
   - leading material for $0\nu\beta\beta$ searches
   - excellent energy resolution
   - topological discrimination

3. **The LEGEND experiment**
   - indeed large
   - aims to observe $0\nu\beta\beta$ in germanium
   - or push the lower limit on decay half-life
   - synergy with other neutrino physics experiments
Neutrinoless double beta decay

\[ ^{n} \rightarrow ^{p} \quad W^{-} \rightarrow ^{e^{-}} \quad W^{-} \rightarrow ^{e^{-}} \quad ^{n} \rightarrow ^{p} \]
Neutrinoless double beta decay

Double beta decay \((2\nu\beta\beta)\)

\[
\begin{align*}
n &\rightarrow W^- & p \\
&\quad e & \bar{\nu} \\
&\quad e & \bar{\nu} \\
n &\rightarrow W^- & p \\
\end{align*}
\]

\[
\begin{align*}
76^{\text{Ge}} & \rightarrow 76^{\text{Se}} + 2e^- \ [ + 2\bar{\nu}_e ]
\end{align*}
\]

Dirac neutrino

\[\nu \neq \bar{\nu}\]

In nature we only observe \(\nu_L\) and \(\bar{\nu}_R\)

Majorana neutrino

\[\nu = \bar{\nu}\]

That's because they are simply just \(\nu_L\) and \(\nu_R\)

Neutrinoless double beta decay \((0\nu\beta\beta)\)

\[
\begin{align*}
n &\rightarrow W^- & p \\
&\quad e & \nu^M \\
&\quad e & \nu^M \\
n &\rightarrow W^- & p \\
\end{align*}
\]

Lepton number not conserved! Matter-antimatter asymmetry!
Some neutrino physics

Neutrino oscillation
flavor change during propagation

Neutrino mixing matrix
mathematical formalism & measurable parameters

New mixing matrix

\[
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha_1} & 0 \\
0 & 0 & e^{i\alpha_2}
\end{pmatrix}
\begin{pmatrix}
\nu_e \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix}
\]

Neutrino mass ordering
which mass state is the lightest?

Normal Ordering (NO)
Inverted Ordering (IO)
Back to neutrinoless double beta decay

Neutrino physics point of view

Majorana mass \( m_{\beta\beta} = | \sum U_{ei}^2 m_i | \)

Experimental point of view

0νββ signature \( Q_{\beta\beta} = M_{\text{init}} - M_{\text{final}} - 2m_e \)

Decay half-life

\( T_{1/2}^{0\nu\beta\beta} \sim \frac{Mt}{N^{0\nu\beta\beta}} \)

1σ sensitivity

in presence of background

\( T_{1/2}^{0\nu\beta\beta} \sim \sqrt{\frac{Mt}{BI \cdot \Delta E}} \)

Connection

\( m_{\beta\beta}^2 = (F^{0\nu} \cdot |M^{0\nu}|^2 \cdot T_{1/2}^{0\nu\beta\beta})^{-1} \)

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Neutrinoless double beta decay

\( n \rightarrow p + W^- + \nu^M + e^- \rightarrow p + W^- + \beta + \nu \)

Germanium experiment technology
Germanium detectors

- germanium crystal → semiconductor
- implanted p+ and n+ contacts → diode
- crystal fully depleted
- germanium serves as both detector and source of $2\nu\beta\beta/0\nu\beta\beta$

$^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- [ + 2\nu_e ]$

- particles deposit energy in the crystal
- electron-hole pairs drift towards respective contacts
- similar trajectories due to $E$ field profile → position-independent

- mirror charge on the p+ contact → signal
- reconstruct energy based on the pulse risetime and amplitude

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Germanium detectors

Window around $Q_{\beta\beta}$ is blinded!

$Q_{\beta\beta}(^{76}\text{Ge}) = 2039.061 \pm 0.007$ keV

Background index is computed based on the rest of the spectrum
Germanium detectors

Pulse shape discrimination

- Signal-like
- Multi-site
- p+ contact
- n+ contact

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Germanium experiments

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Germanium experiments

All analysis cuts

- Quality cuts
- Muon veto
- LAr veto

- Detector anti-coincidence
- Pulse shape discrimination

GERDA experiment

World leading background index

\[ BI = \frac{5.2 \pm 1.6}{1.3} \times 10^{-4} \text{ counts/keV kg yr} \]

Energy resolution

\[ \Delta E = (2.6 \pm 0.2) \text{ keV} \]
### Germanium experiments

<table>
<thead>
<tr>
<th>GERDA</th>
<th>MAJORANA Demonstrator</th>
<th>LEGEND-200 goal</th>
<th>LEGEND-1000 goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>44.2 kg</td>
<td>mass 29.7 kg</td>
<td>mass 200 kg</td>
</tr>
<tr>
<td>exposure</td>
<td>100 kg yr</td>
<td>exposure 75 kg yr</td>
<td>exposure 1000 kg yr</td>
</tr>
<tr>
<td>bkg idx</td>
<td>(5.2±1.6)×10^{-4} cts/(keV kg yr)</td>
<td>bkg idx (4.7±0.8)×10^{-3} cts/(keV kg yr)</td>
<td>bkg idx 2×10^{-4} cts/(keV kg yr)</td>
</tr>
<tr>
<td>resolution</td>
<td>(2.6 ± 0.2) keV</td>
<td>resolution (2.53 ± 0.08) keV</td>
<td>resolution 2.5 keV</td>
</tr>
</tbody>
</table>

**LEGEND-200 goal**
- Mass: 200 kg
- Exposure: 1000 kg yr
- Bkg idx: 2×10^{-4} cts/(keV kg yr)
- Resolution: 2.5 keV

**LEGEND-1000 goal**
- Mass: 1000 kg
- Exposure: 10 000 kg yr
- Bkg idx: 10^{-5} cts/(keV kg yr)
- Resolution: 2.5 keV

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Neutrinoless double beta decay

Germanium experiment technology

Status of the LEGEND experiment

\[ n \rightarrow p \quad W^- \rightarrow e^- \quad \nu^M \rightarrow e^- \quad n \rightarrow p \]
LEGEND baseline design

LEGEND-200  LEGEND-1000

Laboratori Nazionali del Gran Sasso

largest underground research center

INFIN

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LEGEND timeline and status

- **LEGEND timeline**
- **LEGEND timeline and status**

Detector characterization

- **Transfer of GERDA infrastructure to LEGEND**
  - Nov 2019

- **End of GERDA Phase II**
  - Oct 2019

- **Post-GERDA test @ LNGS, Italy**
  - Feb 2020

- **Preconceptual Design Report funding process initiated**
  - Aug 2020

- **LEGEND-200 commissioning**
  - Aug 2021

- **[LEGEND-1000]**
  - Fall 2021

**Major Milestones**

- **Transfer of GERDA infrastructure to LEGEND**
  - Nov 2019

- **End of GERDA Phase II**
  - Oct 2019

- **Post-GERDA test @ LNGS, Italy**
  - Feb 2020

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- **LEGEND-200 commissioning**
  - Aug 2021

**Key Points**

- Infrastructure
- GERDA, MAJORANA and new detectors
- Readout electronics and DAQ
- 1 month of physics data & calibrations
- $\Delta E = 2.2$ keV @ $Q_{\beta\beta}$

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LEGEND prospects in $0\nu\beta\beta$

Virtually **background free**!
Unambiguous discovery even with a **handful of counts**

In case of no discovery, push lower limit
2 orders of magnitude above current best

![Graph showing LEGEND prospects in $0\nu\beta\beta$](image)
LEGEND prospects in $0\nu\beta\beta$

**Discovery potential**

$$T_{1/2}^{0\nu\beta\beta} \sim \sqrt{\frac{M t}{B I \cdot \Delta E}}$$

**Limit setting**

$$m_{\beta\beta}^2 = \left( F_{0\nu} \cdot |M_{0\nu}|^2 \cdot T_{1/2}^{0\nu\beta\beta} \right)^{-1}$$

- $76\text{Ge (91% enr.)}$

- $T_{1/2}$ vs Exposure [ton-years]

- $m_{\beta\beta}$ vs $m_{\text{lightest}}$

- LEGEND goal

- Mass ordering experiments

- Background free regime

- $L_{1000}$, $L_{200}$, GERDA, Majorana

- Mass ordering:
  - NO
  - IO

- $m_{\text{lightest}} = \nu_3$

- $m_{\text{lightest}} = \nu_1$

- Cosmology & neutrino mass experiments

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What else can LEGEND do?

Alternative $0\nu\beta\beta$ mechanisms

Long-range mechanisms e.g. light Majorana neutrino

Short-range mechanisms = heavy particles
  - SUSY particles e.g. gluions or squarks
  - right-handed currents with heavy neutrinos or scalar fields e.g. Higgs
  - ...

Multiple mechanisms at the same time could be possible

LEGEND can probe short-range mechanisms beyond what other experiments can do

Other Beyond Standard Model searches

Fermionic Dark Matter
- Fractionally Charged Cosmic-rays
- Majoron emission
- Exotic Fermion Emission in $0\nu\beta\beta$ decay
- Lorentz violation
- Exotic Currents in $2\nu\beta\beta$ decay

Bosonic Dark Matter
- Solar axions
- WIMP searches
- Electron Decay
- Pauli Exclusion Principle Violation

$+\text{BSM physics in } ^{36}\text{Ar (ECEC)}$
What I want you to remember about LEGEND

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   - or push the lower limit on decay half-life
   - synergy with other neutrino physics experiments
More about LEGEND

LEGEND website
https://legend-exp.org

LEGEND Preconceptual Design Report
https://inspirehep.net/literature/1892243

Chat with me during the coffee break
Contact me if you have questions
mariia.redchuk@pd.infn.it

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9 countries • 47 institutions • 260 members

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THANK YOU!
Backup
"But if $\nu = \bar{\nu}$, does that mean $\nu$ can participate in inverse beta decay?"

For Majorana, there is no such thing as $\bar{\nu}$, just $\nu$, what matters is **helicity**

<table>
<thead>
<tr>
<th>Dirac</th>
<th>Majorana</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e^R + p \rightarrow n + e^+$</td>
<td>yes</td>
</tr>
<tr>
<td>$\nu_e^L + p \rightarrow n + e^+$</td>
<td>never</td>
</tr>
<tr>
<td>$\nu_e^R + p \rightarrow n + e^+$</td>
<td>never</td>
</tr>
<tr>
<td>$\bar{\nu}_e^L + p \rightarrow n + e^+$</td>
<td>yes but ~0% chance</td>
</tr>
<tr>
<td>$\nu_e^R + p \rightarrow n + e^+$</td>
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**Dirac**: so far, we have only observed $\nu_L$ and $\bar{\nu}_R$

**Majorana**: they are simply just $\nu_L$ and $\nu_R$
<table>
<thead>
<tr>
<th>notation</th>
<th>chirality</th>
<th>$p(l^-)$</th>
<th>$p(l^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L^D$</td>
<td>L</td>
<td>$1 - \left(\frac{m_\nu}{2E}\right)^2$</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_R^D$</td>
<td>R</td>
<td>$\left(\frac{m_\nu}{2E}\right)^2$</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{\nu}_L^D$</td>
<td>L</td>
<td>0</td>
<td>$\left(\frac{m_\nu}{2E}\right)^2$</td>
</tr>
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<td>$\bar{\nu}_R^D$</td>
<td>R</td>
<td>0</td>
<td>$1 - \left(\frac{m_\nu}{2E}\right)^2$</td>
</tr>
<tr>
<td>$\nu_L^M = \bar{\nu}_L^M$</td>
<td>L</td>
<td>$1 - \left(\frac{m_\nu}{2E}\right)^2$</td>
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**Dirac**: so far, we have only observed $\nu_L$ and $\bar{\nu}_R$

**Majorana**: they are simply just $\nu_L$ and $\nu_R$
Neutrino observables

\[ m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right| \]

Effective Majorana mass

\[ m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2} \]

"Incoherent sum" of \( \nu_e \) mass eigenstates ("mass of electron neutrino")

\[ \Sigma \text{ or } m_{\text{cosm}} = \sum m_i \]

Sum of neutrino masses cosmological/astrophysical observable

![Graph showing neutrino mass spectrum with LEGEND goal highlighted.](image)
Two-neutrino and neutrinoless double beta decay

- 35 naturally occurring isotopes which can decay through $2\nu\beta-\beta$- with forbidden or suppressed $\beta-$ decay

- Only 6 for $2\nu\beta+\beta+$, small Q values and much longer livetimes

Limits by present-generation experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Exposure [kg-yr]</th>
<th>$T_{1/2}^{0\nu}[10^{25}$ yr]</th>
<th>$m_{\beta\beta}[\text{meV}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA [77]</td>
<td>$^{76}\text{Ge}$</td>
<td>127.2</td>
<td>18</td>
<td>79 – 180</td>
</tr>
<tr>
<td>Majorana [78]</td>
<td>$^{76}\text{Ge}$</td>
<td>26</td>
<td>2.7</td>
<td>200 – 433</td>
</tr>
<tr>
<td>KamLAND-Zen [79]</td>
<td>$^{136}\text{Xe}$</td>
<td>594</td>
<td>10.7</td>
<td>61 – 165</td>
</tr>
<tr>
<td>EXO-200 [80]</td>
<td>$^{136}\text{Xe}$</td>
<td>234.1</td>
<td>3.5</td>
<td>93 – 286</td>
</tr>
<tr>
<td>CUORE [81]</td>
<td>$^{130}\text{Te}$</td>
<td>1038.4</td>
<td>2.2</td>
<td>90 – 305</td>
</tr>
</tbody>
</table>
Alternative mechanisms for $0\nu\beta\beta$

Long-range mechanisms e.g. light Majorana neutrino

$$T_{1/2}^{0\nu\beta\beta} \sim m_{\beta\beta}$$

Short-range mechanisms = heavy particles

- SUSY particles e.g. gluions or squarks
- Right-handed currents with heavy neutrinos or scalar fields e.g. Higgs
- ...

Multiple mechanisms at the same time could be possible

Let’s see if we observe $0\nu\beta\beta$!

$$T_{1/2}^{0\nu\beta\beta} \sim 10^{26–27} \text{ yr}$$

Possible to see in LHC and determine dominant (short-range) mechanism
Germanium detectors

- e- do not contribute much since they drift through a volume of low field strength
- n+ → diffused lithium, p+ → ion-implanted boron
- >$10^5$ e-h pairs / MeV

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• Longer drift times → optimal PSD
Waveforms

Pulse on the p+ contact (simulation)

DAQ waveform (characterization data)
Pulse shape discrimination

Fits in 30-keV slices
- SSE
- MSE
- total

→ obtain $\mu$ and $\sigma$ for each slice for each detector
The LEGEND experiment

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