SEARCHING FOR MATTER CREATION WITH GERDA AND BEYOND

L. Pertoldi <luigi.pertoldi@tum.de>
Erice • 19 June 2022
TU München, INFN Padova
**Why Neutrinoless Double-β Decay?**

"The search for $0\nu\beta\beta$ decay is one of the most compelling and exciting challenges in all of contemporary physics" \(^1\)

- $0\nu\beta\beta$ observation $\Rightarrow$ Majorana neutrino and Lepton Number Violation
- Lepton number $\leftrightarrow$ Barion number $\rightarrow$ new physics, baryogenesis?

### Light Neutrino Mass Mechanism

The (Majorana) neutrino that mediates $0\nu\beta\beta$ is the one that oscillates and the Standard Model is an effective theory (seesaw mechanism)

\[
(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2
\]

\(^1\)100+ papers per year with “$0\nu\beta\beta$” in the title [INSPIRE-HEP statistics]

---

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
All experiments measure the **total energy of the two emitted electrons**

\[ \text{necessary and sufficient for discovery} \]
THE GERDA EXPERIMENT
High-Purity Germanium detectors enriched in $^{76}$Ge

- source = detector $\rightarrow$ high efficiency
- pure $\rightarrow$ low intrinsic background 99.9999% Ge (6N)
- Ge crystal $\rightarrow$ outstanding energy resolution $0.1\%$ @ $Q_{\beta\beta}$ (FWHM)
- solid-state TPC $\rightarrow$ topological discrimination

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
**GERDA Phase II Setup**

- **35.6 kg** (later **44.2 kg**) of HPGe [EPJC 79 (2019) 11, 978, EPJC 81 (2021) 505]

- **Hybrid LAr light collection system**: WLS fibers / SiPMs / PMTs

- **μ-veto**: water Cherenkov, scintillating panels [EPJC 76 (2016) 298]

- **Ultra radio-pure** materials, small passive mass, deep underground

---

*Searching for matter creation with GERDA and beyond* • L. Pertoldi • 19 June 2022
• Data taken from Dec 2015 to Nov 2019 (~90% duty cycle, including upgrade works)
• Energy resolution: ~ 0.1% FWHM at $Q_{\beta\beta}$
• 103.7 kg yr of exposure selected for analysis, largest ever collected with $^{76}$Ge

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
• Bayesian multivariate fit of Monte Carlo predictions (with screening measurements as priors)
• $Q_{\beta\beta}$ dominated by $\beta$ from $^{42}$K (from $^{42}$Ar in LAr), $\alpha$ from $^{210}$Po, $\gamma$ from $^{228}$Th and $^{238}$U chains
• Results are input to several physics analyses and inform future experiments (LEGEND)
SEARCHING FOR MATTER CREATION WITH GERDA AND BEYOND

L. Pertoldi
19 June 2022
- Point-contact detectors: two-sided univariate A/E cut
- Coaxial detectors: artificial neural network and risetime cut
- 0νββ signal efficiency: 90% (70% for coaxials)

Referenced: *EPJC 82 (2022) 284*
• Anti-coincidence between HPGe trigger and SiPM/PMT data (≥ 0.3 p.e. in a 5 μs window)
• Extremely low event rate at $Q_{\beta\beta}$ of $\sim 5 \cdot 10^{-4}$ cts / (keV kg yr) $\rightarrow$ quasi-background-free
• Few events at $Q_{\beta\beta}$ $\rightarrow$ “simple” background-model-free analysis

~ 0.5 counts per FWHM in full exposure!
“One of the world’s best-performing 0νββ experiments”

- $5.2^{+1.6}_{-1.3} \times 10^{-4}$ cts / (keV kg yr) at $Q_{0ν}$
- No signal in 127.2 kg yr of exposure
- $T_{0ν}^{1/2} > 1.8 \times 10^{26}$ yr (90% C.L. frequentist)
- $\langle m_{ββ} \rangle < 79$–180 meV (NME uncertainty)
Results from other experiments

- $^{136}\text{Xe}$, $^{76}\text{Ge}$ (and $^{130}\text{Te}$) place the most stringent limits
  - Note: $^{76}\text{Ge}$ limits on $\langle m_{\beta\beta} \rangle$ are weakened by a less favorable phase space factor

- Recent: KAMLAND-ZEN800 results:
  - $T_{1/2}^{0\nu} > 2.3 \cdot 10^{26}$ yr (90% C.L.)
  - $\langle m_{\beta\beta} \rangle < 36$–156 meV
  - (GERDA has still the best sensitivity)
Not only 0νββ
• \( \beta\beta \) event survival probability > 97% (random coincidences)
• Cleaner, high-statistics \( 2\nu\beta\beta \) spectrum \( \rightarrow \) precision SM test bench
• Need a model for signal and background after the cut

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
MODELING THE LIQUID ARGON DETECTOR RESPONSE (LIGHTS OFF)
• Bayesian multivariate fit of Monte Carlo predictions *(with screening measurements as priors)*
• $Q_{\beta\beta}$ dominated by $\beta$ from $^{42}$K (from $^{42}$Ar in LAr), $\alpha$ from $^{210}$Po, $\gamma$ from $^{228}$Th and $^{238}$U chains
• Results are input to several physics analyses and inform future experiments *(LEGEND)*

---

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
• Little or no light from $\beta$ and $\alpha$ surface events (but suppressed by pulse-shape cut)
• $\gamma$ from $^{228}\text{Th}$ and $^{238}\text{U}$ efficiently suppressed (99.7% and 85%, respectively)
• Can now use model to isolate and study $2\nu\beta\beta$ events
Searching for new physics with $\beta\beta$ events

- BEGe detectors - 32.8 kg yr
- Best-fit model (no exotic physics signal)
- Standard Model $2\nu\beta\beta$ decay
- Background
- $0\nu\beta\beta$ (n=1) 90% C.L.
- $0\nu\beta\beta$ (n=2) 90% C.L.
- $0\nu\beta\beta$ (n=3) 90% C.L.
- $0\nu\beta\beta$ (n=7) 90% C.L.
- Sterile neutrino ($m_N=600$ keV) 90% C.L.
- Lorentz Violation 90% C.L.

Counts / (10 keV)

Energy (keV)

600 800 1000 1200 1400 1600 1800 2000

40K 42K 214Bi

SM $2\nu\beta\beta$

Majoron emission

Limits

Search for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
The Future
50 YEARS OF DOUBLE BETA DECAY WITH $^{76}\text{Ge}$

https://github.com/gipert/0vbb-ge76-history

Background index (cts/(keV⋅kg⋅yr))

$T_{0\nu}^{1/2}$ lower limit (yr)

Background index (cts/(keV⋅kg⋅yr))

$T_{0\nu}^{1/2}$ lower limit (yr)

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
“...an era in which a discovery could come at any time!”

\[ m_{\beta\beta} = 18.4 \pm 1.3 \text{ meV} \]
“The collaboration aims to develop a phased, $^{76}\text{Ge-based}$ double-beta decay experimental program with discovery potential at a half-life beyond $10^{28}$ yr, using existing resources as appropriate to expedite physics results.”

**LEGEND-200**

- 200 kg of $^{\text{enr}}\text{Ge}$ (×5 yr), in GERDA cryostat
- Funded, under commissioning
- $B \sim 2 \cdot 10^{-4}$ cts / (keV kg yr) $\implies T_{1/2}^{0\nu} > 10^{27}$ yr

**LEGEND-1000**

- 1 ton of $^{\text{enr}}\text{Ge}$ (×10 yr), awaiting funding
- $B < 10^{-5}$ cts / (keV kg yr) $\implies T_{1/2}^{0\nu} > 10^{28}$ yr
- Cover full $\langle m_{\beta\beta} \rangle$ inverted ordering region

[Link to LEGEND-200](https://legend-exp.org/200)

[Link to LEGEND-1000](https://legend-exp.org/1000)
50 YEARS OF DOUBLE BETA DECAY WITH $^{76}$Ge

Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022

GERDA (BEGe)  Majorana (PPC)  LEGEND (ICPC)

electric field & isochores

performant $\checkmark$ & small $\times$ < 1 kg

2-3 kg
Searching for matter creation with GERDA and beyond • L. Pertoldi • 19 June 2022
Wrapping up

**GERDA:**

- has searched for $0\nu\beta\beta$ in a *quasi-background-free* regime
- has led the worldwide effort by providing *strong half-life limits*
- has demonstrated the *maturity of germanium technology* for a ton-scale project

**The scientific community:**

- has acknowledged the search for $0\nu\beta\beta$ as *one of the most compelling challenges in contemporary physics*
- strives for international funding for *ton-scale $0\nu\beta\beta$ experiments*

**Legend:**

- has a low-risk path to meeting its background goal and is *optimized for discovering $0\nu\beta\beta*
- will pioneer the exploration of *new energy frontiers beyond the inverted ordering scenario*