STAGED IMPLEMENTATION TOWARDS A LARGE-SCALE $^{76}$Ge NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENT

Stefan Schönhert, TU München

NDM15, Jyväskylä, Finland, June 1-5, 2015
\[ \sin^2(\theta_{12}) = 0.318 \text{ (best-fit)} \]

\( g_A = 1.25, \quad \langle m_{\text{ee}} \rangle = 17.5 \text{ meV}, \) bars from variation of nucl matrix element calc & \( \pm 3\sigma \) vari. of U, \( \Delta m^2 \) from DOE Nuclear Science Advisory Committee report on 0\( \nu \beta \beta \) (24 April 2014)

N.B.: 17 meV is useful benchmark, but plenty of physics opportunities on the way towards \( 10^{27} \) yrs....
Why $^{76}\text{Ge}$?

From DOE Nuclear Science Advisory Committee report on 0nbb (24 April 2014):
list of highly desirable design features of any next-generation double beta decay search

- Very low, and preferably flat, background within the spectral region of interest, relative to the signal size anticipated at the half-life sensitivity goal; **YES**

- Good energy resolution with excellent energy calibration, to enhance a potential signal above backgrounds & to minimize the 2νββ tail underneath the 0νββ peak; **YES**

- Ability to scale the experimental approach to larger masses at realizable cost, as needed to maximize the discovery potential within the inverted hierarchy region; **YES**

- Tracking capability to enhance identification of 0νββ decay event topology; **YES**

- A favorable 0νββ Q-value to enhance the phase space factor and provide a region of interest above many of the gamma ray lines from U- and Th-chain contaminants; **NO** but low A compensates (more mole/kg, larger matrix elements, smaller gA quenching, ...)

- Ability to remove or replace the enriched isotope without affecting detector performance, in order to verify the reality of a possible non-null signal. **YES**
Staging: not a new concept

required for ‘background free’ exp. with $\Delta E \sim 3$ keV (FWHM): $O(10^{-3})$ $O(10^{-4})$ counts/(kg·y·keV)

⇒ reduction of background by factor $10/100/1000$ w.r. to precursor exps. for bgd free operations

S. Schönhert (TUM): Towards a large-scale $^{76}$Ge experiment – NDM, June 4, 2015
The $^{76}$Ge-experiments: GERDA & Majorana-Demonstrator

**GERDA**
- Bare $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / $H_2O$
- Phase I: 17 kg (HdM/IGEX) - completed
- Phase II: 38 kg enriched in $^{76}$Ge

**Majorana-Demonstrator (MJD)**
- Array(s) of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- 30 kg enriched in $^{76}$Ge

**Physics goals:** degenerate mass range
**Technology:** study of bgds. and exp. techniques

**LoI**
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for future large scale $^{76}$Ge experiment selecting the best technologies tested in GERDA and Majorana

Also interests / discussion in China (Jin Ping)
GERDA Phase I results

GERDA 13-07

90% lower limit ($T_{1/2}^{0ν}$)

$T_{1/2}^{0ν} > 2.1 \cdot 10^{25}$ yr

PRL 111 (2013) 122503

S. Schönert (TUM): Towards a large-scale $^{76}$Ge experiment – NDM, June 4, 2015
### Comparison and reach of current Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass [kg]* (total/FV)</th>
<th>FWHM [keV]</th>
<th>Background &amp; [cnt/mol yr FWHM]</th>
<th>$T_{1/2}$ limit $[10^{25} \text{ yr}]$ after 4 yr</th>
<th>$&lt;m_{ee}&gt;$ limit [meV]</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerda II</td>
<td>Ge 35/27</td>
<td>3</td>
<td>0.0004</td>
<td>15</td>
<td>80-190</td>
<td>-2019</td>
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<tr>
<td>MajoranaD</td>
<td>Ge 30/24</td>
<td>3</td>
<td>0.0004</td>
<td>15</td>
<td>80-190</td>
<td>-2019</td>
</tr>
<tr>
<td>EXO-200</td>
<td>Xe 170/80</td>
<td>88</td>
<td>0.03</td>
<td>6</td>
<td>80-220</td>
<td>-2019</td>
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<tr>
<td>KLZen</td>
<td>Xe 383/88 (600/??)</td>
<td>250</td>
<td>0.03</td>
<td>20</td>
<td>44-120</td>
<td>-2018</td>
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<tr>
<td>NEXT</td>
<td>Xe 100/80</td>
<td>17</td>
<td>0.0036</td>
<td>6</td>
<td>100-200</td>
<td>-2020</td>
</tr>
<tr>
<td>Cuore</td>
<td>Te 600/206</td>
<td>5</td>
<td>0.02</td>
<td>9</td>
<td>50-200</td>
<td>-2019</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te 2340/160</td>
<td>270</td>
<td>0.02</td>
<td>9</td>
<td>50-200</td>
<td>-2020</td>
</tr>
</tbody>
</table>

* total = element mass, FV = $0\nu\beta\beta$ isotope mass in fiducial volume (incl. enrichment fraction)

& mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

N.B.: values are design numbers except for EXO-200 and Kamland-Zen
Key developments: novel p-type HPGe detectors

Modified BEGe (GERDA)
(Similar results with MJD ppc)

Signal shape provides clear topology for event-by-event signal ID / bgd discrimination:
- **SSE/MSE** discrimination
- **Surface** events:
  - n+ slow pulses
  - p+: ‘amplified’ current pulses

**SSE** signal-like
**MSE** bgd-like (MSE γ’s)

**p+** bgd-like
(p+ surface α, β)

**n** bgd-like
(n+ surface β, 42K)

DEP: 90%
0νββ-like
γ-bgd: 11%
Key developments: novel p-type HPGe detectors
Key developments: high-purity copper

Underground production and machining of high-purity electroformed copper

$^{232}\text{Th} < 0.06 \mu\text{Bq/kg}$

$^{238}\text{U} < 0.10 \mu\text{Bq/kg}$
Key developments: liquid argon scintillation veto

Calibration with $^{228}\text{Th}$ source

- near source
- far source

LArGe test stand @ LNGS

LAr spiked with $^{42}\text{Ar}(^{42}\text{K})$

- Bare BEGe (scaled)
- With nylon MS PMT cut
- 89% acc. PSD + PMT cut
- 73% acc. PSD + PMT cut
Key developments: liquid argon scintillation veto
Key developments: liquid argon scintillation veto & PSD

$^{228}$Th calibration in GERDA during May commissioning run: factor 400 suppression @ $Q_{\beta\beta}$
Sensitivity: GERDA & MJD

Data | mass [kg] | $\epsilon$ | background $\frac{cts}{keV\cdot kg\cdot yr}$ | FWHM [keV]
--- | --- | --- | --- | ---
**GERDA Phase I:**
coaxial | 12.2 | 0.62 | $1.1 \cdot 10^{-2}$ | 4.4
BEGe | 2.8 | 0.66 | $0.5 \cdot 10^{-2}$ | 2.9
**GERDA Phase II:**
coaxial | 17.7 | 0.62 | $1 \cdot 10^{-3}$ | 4.0
BEGe | 20 | 0.65 | $1 \cdot 10^{-3}$ | 2.5
**Majorana Demonstrator:**
mod1 | 20 | 0.65 | $0.8 \cdot 10^{-3}$ | 3.0
mod2 | 10 | 0.65 | $0.8 \cdot 10^{-3}$ | 3.0

Sensitivity study by M. Agostini
Sensitivity: GERDA & MJD combined

<table>
<thead>
<tr>
<th>Data set</th>
<th>mass [kg]</th>
<th>background $\frac{\text{cts}}{\text{keV} \cdot \text{kg} \cdot \text{yr}}$</th>
<th>FWHM [keV]</th>
</tr>
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<td>GERDA Phase I:</td>
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<td>GERDA Phase II:</td>
<td></td>
<td></td>
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<td>coaxial</td>
<td>17.7</td>
<td>$1 \cdot 10^{-3}$</td>
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<td></td>
</tr>
<tr>
<td>mod1</td>
<td>20</td>
<td>$0.8 \cdot 10^{-3}$</td>
<td>3.0</td>
</tr>
<tr>
<td>mod2</td>
<td>10</td>
<td>$0.8 \cdot 10^{-3}$</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Possible next step beyond GERDA Phase II and MJD: deploy 200 kg in GERDA cryostat

See also B. Schwingenheuer’s presentation at LNGS, April 15

Bare detectors à la GERDA

7 strings in Phase II
up 19 strings fit into Ø 500 usable Ø of cryostat ~550
space for LAr veto Ø ~520?
calibration sources

16 BEGe / string
→ 300 detectors / 200 kg

Pool $^{76}$Ge material from GERDA & MJD
→ procure addition 140 kg $^{76}$Ge
3yr for enrichment & detector production
1yr for installation

S. Schönert (TUM): Towards a large-scale $^{76}$Ge experiment – NDM, June 4, 2015
Possible next step beyond GERDA Phase II and MJD: deploy 200 kg in GERDA cryostat

Thin-wall copper container with integrated fiber-SiPM light instrumentation operated in LAr as coolant and active shield (artist’s view)

Modular design: mass can further be increased by denser packing and/or new infrastructure
Backgrounds: $^{238}$U & $^{232}$Th progenies

**Far sources** (cryostat, tank, rocks): $^{232}$Th $< 0.3$ cnt/(ROI t yr); $^{226}$Ra factor 5 less (for central location, no LAr veto, no PSD)


**Close sources** (cables, holders, VFE): dominate bgd; efficiently suppressed with LAr veto & PSD (prelim: x400 for $^{208}$Tl; x10 for $^{214}$Bi)

GERDA Phase II: 0.5 cnt/(ROI t yr) dominated by $^{226}$Ra
no special Cu, PTFE production → for “200 kg Majorana copper / PTFE quality required
Backgrounds: $^{42}$K($^{42}$Ar)

LArGe test stand:
1 ton LAr doped with $^{42}$Ar, ~1000x conc. of $^{nat}$Ar BEGe det. in nylon cylinder, LAr veto with PMTs → bgd suppression factor SF = 15 from nylon → LAr veto + Ge det. pulse shape SF = 70 → expect in GERDA 0.6-2 cnt/(ROI t yr) for current n+ dead layer

for ”200 kg” add. SF by PSD or hardware (e.g thicker n+ dead layer or hybrid design)
Backgrounds: in-situ muon induced isotopes @ LNGS

**Direct muons:** muon veto (water Cherenkov & liquid argon) – no issue

**Muon induced** long-lived isotopes:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$</th>
<th>decay</th>
<th>$Q$ value [keV]</th>
<th>background [cnt/(ROI t yr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{74}$Ga</td>
<td>8.1 m</td>
<td>$\beta^-$</td>
<td>5368</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{75}$Ga</td>
<td>126 s</td>
<td>$\beta^-$</td>
<td>3392</td>
<td>0.01</td>
</tr>
<tr>
<td>$^{76}$Ga</td>
<td>33 s</td>
<td>$\beta^-$</td>
<td>7010</td>
<td>0.01</td>
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<tr>
<td>$^{77}$Ge</td>
<td>11.3 h</td>
<td>$\beta^-$</td>
<td>2702</td>
<td>0.1</td>
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<tr>
<td>$^{77m}$Ge</td>
<td>53 s</td>
<td>$\beta^-$</td>
<td>2861</td>
<td>0.1</td>
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<tr>
<td>$^{38}$Cl</td>
<td>37 m</td>
<td>$\beta^-$</td>
<td>4916</td>
<td>0.003</td>
</tr>
<tr>
<td>$^{40}$Cl</td>
<td>1.4 m</td>
<td>$\beta^-$</td>
<td>7482</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Most critical $^{77m}$Ge (w/o $\gamma$) - mitigation: triple coincidence: $\mu$, n-capture($\gamma$), $^{77m}$Ge-decay

S. Schönert (TUM): Towards a large-scale $^{76}$Ge experiment – NDM, June 4, 2015
Towards a large scale $^{76}\text{Ge}$ experiment

Envision a phased, stepwise implementation; e.g. $250 \rightarrow 500 \rightarrow 1000$ kg

J. Wilkerson, LRP Resolution Meeting April 18, 2015
A large scale staged $^{76}$Ge experiment: sensitivity vs. time

Assumptions:

<table>
<thead>
<tr>
<th>Data set</th>
<th>mass [kg]</th>
<th>$\epsilon$</th>
<th>background [cts/keV·kg·yr]</th>
<th>FWHM [keV]</th>
<th>time [start/stop]</th>
</tr>
</thead>
<tbody>
<tr>
<td>mod1</td>
<td>200</td>
<td>0.65</td>
<td>$1 \times 10^{-4}$</td>
<td>2.5</td>
<td>Jan 21 / Jan 31</td>
</tr>
<tr>
<td>mod2</td>
<td>200</td>
<td>0.65</td>
<td>$1 \times 10^{-4}$</td>
<td>2.5</td>
<td>Jan 22 / Jan 31</td>
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<tr>
<td>mod3</td>
<td>200</td>
<td>0.65</td>
<td>$1 \times 10^{-4}$</td>
<td>2.5</td>
<td>Jan 23 / Jan 31</td>
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<tr>
<td>mod4</td>
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<td>0.65</td>
<td>$1 \times 10^{-4}$</td>
<td>2.5</td>
<td>Jan 24 / Jan 31</td>
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<td>mod5</td>
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<td>0.65</td>
<td>$1 \times 10^{-4}$</td>
<td>2.5</td>
<td>Jan 25 / Jan 31</td>
</tr>
</tbody>
</table>

Sensitivity study by M. Agostini
Summary

$^{76}$Ge detector features:
- known technology (enrichment + diode production)
- best energy resolution
- lowest bgd in ROI per mol of isotopes
- flat background at Q value
- excellent PID through PSD and LAr-veto

→ important features for discovery
GERDA Phase II & Majorana Demonstrator start data taking soon

If current experiments meet specifications:
- possible next step: combine existing detectors and add new $^{76}$Ge
- GERDA infrastructure can in principle host 200 kg of Ge detectors
- Bare detectors in LAr - but also hybrid design conceived
- bgd reduction x3 relative to Phase II goal required to be ”background free”
- $T_{1/2}$ sensitivity for 90% CL limit $\sim 10^{27} \text{ yr}$

In parallel:
- Prepare for subsequent stages towards ton-scale experiment
- New infrastructure required