Considerations for Next Generation 0νββ Experiments

J.F. Wilkerson

INT Workshop on 0νββ Seattle, WA
June 13, 2017
Searching for $0\nu\beta\beta$ Decay

Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions ($W$)

\[
T_{1/2}^{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2
\]

\[
m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|
\]

2015 NSAC Long Range Plan for Nuclear Science

Next Gen $\beta\beta$ Expt. Considerations
Next Generation Considerations

- Is there a preferred $0\nu\beta\beta$ isotope?
Sensitivity to $\langle m_{\beta\beta} \rangle$

For Ge, Te, Xe, Nd

uncertainty on NME$^2$

uncertainty on value of $g_A^4$

Signal of 1 cnt/t-y for corresponding values of NME and $g_A$

R.G.H. Robertson, MPL A 28 (2013) 1350021 (arXiv 1301.1323)
Isotopes have comparable sensitivities in terms of rate per unit mass.

R.G.H. Robertson, MPL A 28 (2013) 1350021 (arXiv 1301.1323)

Inverse correlation observed between phase space and the square of the nuclear matrix element.

The points in order of increasing abscissa value are: $^{48}$Ca, $^{150}$Nd, $^{136}$Xe, $^{96}$Zr, $^{116}$Cd, $^{124}$Sn, $^{130}$Te, $^{82}$Se, $^{76}$Ge, $^{100}$Mo and $^{110}$Pd.

gometric mean of the squared matrix element range limits & the phase-space factor evaluated at $g_A = 1$.
Next Generation Considerations

- Is there a preferred $0
\nu\beta\beta$ isotope?

  *No preferred isotope in terms of per unit mass - within current uncertainties on NME and $g_A$.*

- What is required to cover Inverted Ordering masses?
Sensitivity vs. Exposure for $^{76}\text{Ge}$

$$T_{1/2}^{0\nu} \text{ (background free)} \propto MT$$

$$T_{1/2}^{0\nu} \text{ (backgrounds)} \propto \sqrt{\frac{MT}{b\Delta E}}$$
$3\sigma$ Discovery vs. Exposure for $^{76}\text{Ge}$

IH minimum $m_{\beta\beta}$:
- GRPA
- SM
- IBM-2
- EDF

$^{76}\text{Ge} T_{1/2} 3\sigma$ DL [years]

Log-log plot showing the relationship between exposure [ton-years] and $^{76}\text{Ge} T_{1/2}$ for different backgrounds.

- Background free
- 0.1 counts/ROI/t/y
- 1.0 count/ROI/t/y
- 10.0 counts/ROI/t/y

J. Detwiler
Experimental searches for $0\nu\beta\beta$-decay

Most sensitive experiments to date using $^{76}\text{Ge}$, $^{130}\text{Te}$, and $^{136}\text{Xe}$ have attained results for $T_{1/2} > 5 \cdot 10^{25}$ to $10^{26}$ years.

(source mass) × (exposure times) of 30 - 125 kg-years

Covering IH region requires sensitivities of $0\nu\beta\beta$ $T_{1/2} \sim 10^{27} - 10^{28}$ years

(2$\nu\beta\beta$ $T_{1/2} \sim 10^{19} - 10^{21}$ years)

<table>
<thead>
<tr>
<th>Half life (years)</th>
<th>~Signal (cnts/ton-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{25}$</td>
<td>500</td>
</tr>
<tr>
<td>$5 \times 10^{26}$</td>
<td>10</td>
</tr>
<tr>
<td>$5 \times 10^{27}$</td>
<td>1</td>
</tr>
<tr>
<td>$5 \times 10^{28}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$&gt; 10^{29}$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Next Generation Expts. aim for background of 0.1 cnts/t-y
Next Generation Considerations

• Is there a preferred $0\nu\beta\beta$ isotope?
  *No preferred isotope in terms of per unit mass - within current uncertainties on NME and $g_A$.*

• What is required to cover Inverted Ordering masses?
  *For a nearly ideal, background free experiment ~ 10 t-y*

• Experimental Considerations
Potential contributions to the background

• Primordial, natural radioactivity in the detector and array components: U, Th, K

• Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, $^{60}$Co, $^3$H, $^{39}$Ar, $^{42}$Ar, …)

• Backgrounds from the surrounding environment: external γ, (α,n), (n,α), Rn plate-out, etc.

• μ-induced backgrounds generated at depth: Cu, Pb(n,n’ γ), ββ-decay specific(n,n),(n,γ), direct μ

• 2 neutrino double beta decay (for 1000 kg, impact depends on resolution)

• neutrino backgrounds (for 1000 kg, can be a contribution)
Reducing Backgrounds - Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non “source” materials
  - Clean (low-activity) shielding
  - Fabricate ultra-clean materials (underground fab in some cases)
  - Go deep — reduced µ’s & related induced activities

- Utilize background measurement & discrimination techniques
  \(0\nu\beta\beta\) is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions
  - Energy resolution
  - Active veto detector
  - Tracking (topology)
  - Particle ID, angular, spatial, & time correlations
  - Fiducial self-consistent fits
  - Single site / multi site fitting
  - Granularity [multiple detectors]
  - Pulse shape discrimination (PSD)
  - Ion Identification
### 3σ Discovery: Exposure vs. Background

#### Discovery: Exposure vs. Background

- **Background [c/ROI-t-y]**
  - $10^{-4}$
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^0$
  - $10^1$
  - $10^2$
  - $10^3$

- **I0 min. 3σ DL Req. Exposure [ton-years]**
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^0$
  - $10^1$
  - $10^2$
  - $10^3$

#### Materials:
- $^{76}$Ge (87% enr.)
- $^{136}$Xe (90% enr.)
- $^{130}$Te (nat.)

#### Experiment Goals:
- GERDA-I
- NEXT 100 goal
- EXO-200 (Nature 2019)
- CUORE-0 (PRL 2015)
- NEMO-3 ($^{100}$Mo, PRD 2015)

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**J. Detwiler**

Next Gen $\beta\beta$ Expt. Considerations
3σ Discovery : Exposure vs. Background

Next Generation Goal

\[ \sigma \] Discovery : Exposure

- Background \([c/ROI-t-y]\)
  - \(4 \times 10^{-4}\)
  - \(10^{-3}\)
  - \(10^{-2}\)
  - \(10^{-1}\)
  - \(1\)
  - \(10\)
  - \(10^2\)
  - \(10^3\)

- DL Req. Exposure \([\text{ton-years}]\)
  - \(10^{-4}\)
  - \(10^{-3}\)
  - \(10^{-2}\)
  - \(10^{-1}\)
  - \(1\)
  - \(10\)
  - \(10^2\)
  - \(10^3\)

- \(^{76}\text{Ge} (87\% \text{ enr.})\)
- \(^{136}\text{Xe} (90\% \text{ enr.})\)
- \(^{130}\text{Te} \text{ (nat.)}\)

- \(100\) goal
- NEXT 100 goal
- CUORE / SNO+ goal
- GERDA-II
- MAJORANA DEMONSTRATOR
- CUORE-0 (PRL 2015)
- CUORE-3 (\(^{100}\)Mo, PRD 2015)
- NEMO-3 (\(^{100}\)Mo, PRD 2015)

J. Detwiler

Next Gen \(\beta\) Expt. Considerations

\(\beta\beta\)-Decay Workshop, INT, Seattle
June 13, 2017
Next Generation Considerations

- Is there a preferred $0\nu\beta\beta$ isotope?
  
  *No preferred isotope in terms of per unit mass - within current uncertainties on NME and $g_A$.*

- What is required to cover Inverted Ordering masses?
  
  *For a nearly ideal, background free experiment ~ 10 t-y*

- Experimental Considerations
  
  - **Backgrounds** - higher Q value (especially above $^{208}$Tl line) is good.
  
  - **Enrichment** - $^{130}$Te (34.5% nat. abundance) has an advantage.
  
  - **$2\nu\beta\beta$ rate (irreducible background)** - $^{76}$Ge $^{130}$Te, $^{136}$Xe are the best (longest $T_{1/2}$), but impact depends on resolution.

No clear leader. Need to evaluate on expt.-by-expt. basis. Backgrounds and resolution are critically important, in particular for discovery capable measurements.
Discovery of $0\nu\beta\beta$-decay

• **Evidence**: a combination of
  - Correct peak energy
  - Single-site or localized energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background ($3\sigma$ discovery)
  - Full energy spectrum (backgrounds) understood.

• **More direct confirmation**: very difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay(s)

• **Convincing**
  - Observe $0\nu\beta\beta$ in several different isotopes, using a variety of experimental techniques that meet the above definition of evidence
### 0νββ decay Experiments - Efforts Underway

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Isotope</th>
<th>Technique</th>
<th>mass (0νββ isotope)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANDLES</td>
<td>Cu-48</td>
<td>305 kg CaF₂ crystals - liq. scint</td>
<td>0.3 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>CARVEL</td>
<td>Cu-48</td>
<td>⁴⁰CaWO₄ crystal scint.</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>GERDA I</td>
<td>Ge-76</td>
<td>Ge diodes in LAr</td>
<td>15 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>GERDA II</td>
<td>Ge-76</td>
<td>Point contact Ge in LAr</td>
<td>31</td>
<td>Operating</td>
</tr>
<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>Ge-76</td>
<td>Point contact Ge</td>
<td>25 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>LEGEND</td>
<td>Ge-76</td>
<td>Point contact</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>NEMO3</td>
<td>Mo-100</td>
<td>Foils with tracking</td>
<td>6.9 kg</td>
<td>Complete</td>
</tr>
<tr>
<td></td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>0.9 kg</td>
<td></td>
</tr>
<tr>
<td>SuperNEMO Demonstrator</td>
<td>Se-82</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>Construction</td>
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<tr>
<td>LUCIFER (CUPID)</td>
<td>Se-82</td>
<td>ZnSe scint. bolometer</td>
<td>100 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>AMoRE</td>
<td>Mo-100</td>
<td>CaMoO₄ scint. bolometer</td>
<td>1.5 - 200 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>LUMINEU (CUPID)</td>
<td>Mo-100</td>
<td>ZnMoO₄ / Li₂MoO₄ scint. bolometer</td>
<td>1.5 - 5 kg</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>COBRA</td>
<td>Cd-114,116</td>
<td>CdZnTe detectors</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>CUORICINO, CUORE-0</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
<td>10 kg, 11 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>CUORE</td>
<td>Te-130</td>
<td>TeO₂ Bolometer</td>
<td>206 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>CUPID</td>
<td>Te-130</td>
<td>TeO₂ Bolometer &amp; scint.</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>SNO+</td>
<td>Te-130</td>
<td>0.3% natTe suspended in Scint</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>EXO200</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>79 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>nEXO</td>
<td>Xe-136</td>
<td>Xe liquid TPC</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>KamLAND-Zen (I, II)</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>380 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>KamLAND2-Zen</td>
<td>Xe-136</td>
<td>2.7% in liquid scint.</td>
<td>750 kg</td>
<td>Upgrade</td>
</tr>
<tr>
<td>NEXT-NEW</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>5 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>NEXT</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>100 kg - ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>PandaX - 1k</td>
<td>Xe-136</td>
<td>High pressure Xe TPC</td>
<td>~ ton</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>DCBA</td>
<td>Nd-150</td>
<td>Nd foils &amp; tracking chambers</td>
<td>20 kg</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>
0νββ Detection Techniques

Ionization

- Tracking & Cal:
  - SuperNEMO
  - PandaX-III

- Crystals:
  - GERDA
  - MAJORANA
  - COBRA

TPC:
- nEXO
- NEXT

Scintillation

- Liquid:
  - KamLAND-Zen
  - SNO+

Phonons

- CUPID (LUCIFER Lumineu, ...), AMoRE

Bolometer:
- CUORE
Next generation ton scale experiments

- Active international collaborations building on current efforts.
  - $^{76}$Ge : LEGEND, HPGE crystals, ~ton (builds on GERDA & MAJORANA)  
  - $^{82}$Se : SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale  
  - $^{100}$Mo : AMoRE : CaMoO$_4$ scint. bolometer, 200 kg scale  
  - $^{136}$Xe : nEXO — Liquid TPC, 5 tons  
    - NEXT — High pressure gas TPC, ton scale  
    - PandaX - III — High pressure gas TPC, ton scale  
    - KamLAND-Zen — $^{136}$Xe in scintillator, 800 kg scale  
    - LZ — nat$^{136}$Xe liquid TPC, 7 tons, operating 2019  
  - $^{130}$Te : CUPID (CUORE with Particle ID) — Bolometer - Scintillation  
    - SNO+ Phase I & II — $^{130}$Te in scintillator  

- Experiments can be done in a staged (phased) approach. Most are considering stepwise increments.
- Isotope enrichment ($^{76}$Ge, $^{82}$Se, $^{136}$Xe) requires time and $s$.  
- Potential underground lab sites  
  - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L
KamLAND-ZEN $^{136}$Xe

- $^{136}$Xe (90% enr) in liquid scintillator, balloon R=1.5 m
- $Q_{\beta\beta}=2457.8$ keV; $\sigma \sim 114$ keV (4.6%)
- Phase II (PRL 117 082503 (2016))
  - 380 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 534.5 days, with 126 kg y exposure
  - $^{110m}$Ag contamination reduced by x10

$$T_{1/2} > 1.07 \times 10^{26} \text{ y (90\% CL)}$$

Sensitivity $$T_{1/2} > 5.6 \times 10^{25} \text{ y (90\% CL)}$$
KamLAND-ZEN $^{136}\text{Xe}$

Scintillation

(a) Period-2
- Data
- $^{110m}\text{Ag}$
- $^{238}\text{U} + ^{232}\text{Th} + ^{210}\text{Bi}$
- Total
- $^{210}\text{Po} + ^{85}\text{Kr} + ^{40}\text{K}$
- $(0\nu\beta\beta$ U.L.)
- IB/External
- $^{136}\text{Xe} 2\nu\beta\beta$
- Spallation
- $^{136}\text{Xe} 0\nu\beta\beta$
- (90% C.L. U.L.)

(b) Period-1

(c) Period-2

Visible Energy (MeV)

Events/0.05MeV

Figures show energy spectra and event distributions for KamLAND-ZEN $^{136}\text{Xe}$ with various decay processes and energy levels.
**KamLAND-ZEN $^{136}$Xe**

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  $T_{1/2} > 1.07 \times 10^{26}$ y (90% CL)

**Sensitivity** $T_{1/2} > 5.6 \times 10^{25}$ y (90% CL)

Unsuccessful new larger mini balloon deployment - 2016

Construction and deployment of new mini balloon with improved welding procedure for 800 kg (750 kg$_{iso}$) phase - 2017
KamLAND-Zen future

Higher energy resolution for reducing $2\nu$ BG → KamLAND2-Zen

Winston cone
light collection $\times 1.8$

high q.e. PMT
$17''\phi \rightarrow 20''\phi \cdot \varepsilon = 22 \rightarrow 30 +\%
light collection $\times 1.9$

New LAB LS
(better transparency)
light collection $\times 1.4$

expected $\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

target sensitivity: 20 meV

Far future:

Super-KamLAND-Zen
in connection with Hyper-Kamiokande

target sensitivity 8 meV
SNO+ $^{130}$Te (Phase I)

- 1357 kg $^{130}$Te (34.5% nat.) in liquid scintillator, Acrylic Vessel
- $Q_{\beta\beta}=2530.3$ keV; $\sigma \sim 82$ keV (4.6%)
- **Present (June 2017)** – water-filled data taking underway
  - measuring backgrounds
  - stable data taking, processing, data flow
  - invisible nucleon decay analysis
- **2017** – scintillator plant commissioning with LAB leading to scintillator filling, end of 2017
- **2018** – tellurium purification and synthesis
  - systems installation completed leading to Te purification and Te loading, late 2018

3.8 tonnes Telluric acid UG (half since 01/15); cosmogenic activity decaying

*First neutrino candidate: 2017-02-05, upward-going, no outward-looking PMTs triggered*
SNO+ $^{130}\text{Te}$ (Phase I)

The SNO+ technique:
- Large low-background detector
- Lower energy resolution of liquid scintillator compensated by large isotope mass loading

$T_{1/2}^{0\nu}$ sensitivity:
- 1 year: 0.8 $\pm$ 75 (59 – 144)*
- 5 years: 1.95 $\pm$ 48 (38 – 92)*

* Range due to NME models

LS cocktail: LAB + PPO (2g/L) + bisMSB (15mg/L) + Te (0.5%)

1-year backgrounds in ROI includes U/Th BiPo rejection cuts

Richard Ford (SNOLAB) CAP Congress, Kingston, 31-May-2017
NEXT $^{136}$Xe

- High pressure (10-15 bar) $^{136}$Xe TPC for high E-resolution + tracking capability
- $Q_{\beta\beta}=2457.8$ keV ; $\sigma \sim 7.3$ keV (0.3%)
- NEXT-NEW
  - 4.5 kg$_{iso}$, operating at Canfranc
- Planned: NEXT-100
  - 90 kg$_{iso}$, $b = 44 \, c/(ROI-t-y)$

V. Alvarez et al.,
JINST 7, T06001 (2012),
arXiv:1202.0721

NEXT-100 (~100 kg)
[2018 - 2020’s]

NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, $\beta\beta2v$

NEXT-tonne (~1000 kg)
[future generation]

Neutrinoless double beta decay searches
**NEXT** \(^{136}\text{Xe}\)

- High pressure (10-15 bar) \(^{136}\text{Xe}\) TPC for high E-resolution + tracking capability
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**NEXT-100 (~100 kg)**
[2018 - 2020’s]

**NEXT-tonne (~1000 kg)**
[future generation]

**NEXT-NEW (~5 kg)**
[2015 - 2018]

- Underground and radio-pure operations, background, \(\beta\beta2v\)

**Scintillation - Ionization**

Neutrinoless double beta decay searches
Topological Reconstruction

- Observe the two stopping electron tracks emitted from common vertex, characteristic of double beta decays
  - Powerful handle for single-electron background suppression

>1.02 MeV $\gamma$-ray from Co-56 calibration source

Two 0.51 MeV annihilation $\gamma$-rays escape
PandaX-III $^{136}$Xe

- High pressure (10 bar) TPC using 90% enr $^{136}$Xe with Micro-MEsh Gaseous structure readout
- $Q_{\beta\beta} = 2457.8$ keV ; $\sigma \sim 31$ keV (1.3%)
- Five, 180 kg_{iso} modules, in large water shield
- Located at China Jinping Laboratory

X. Chen et al., arXiv:1610.08883
AMoRE $^{100}$ Mo

- $^{40}$Ca$^{100}$MoO$_4$ crystals (95% enr. $^{100}$Mo, depleted $^{48}$Ca) with bolometer (Metallic Magnetic Calorimeter) and light readout.
- $Q_{\beta\beta} = 3034.4$ keV
- Phases
  - AMoRE Pilot (1.5 kg) [2016-2017]
    - 6 crystals, operating at 8 mK
    - $\sigma (@2.6$ MeV$) \sim 4.6 - 5.8$ keV (0.2%)
  - AMoRE I (4.5 kg) [2017-2020]
  - AMoRE II (200 kg) [2020-2024]
    - Enriched material by 2018
    - Evaluating: Li$_2$MoO$_4$ and Na$_2$Mo$_2$O$_7$
- AMoRE Pilot and I at Yingyang Underground Laboratory, AMoRE at new UG lab, Astroparticle Research Facility at Handuk mine.
AMoRE $^{100}$ Mo

- $^{40}$Ca$^{100}$MoO$_4$ crystals (95% enr. $^{100}$Mo, depleted $^{48}$Ca) with bolometer (Metallic Magnetic Calorimeter) and light readout.
- $Q_{\beta\beta}=3034.4$ keV
- Phases
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**Discovery Sensitivity Comparison**

*Discovery probability of next-generation neutrinoless double-beta decay experiments*

Matteo Agostini, Giovanni Benato, and Jason Detwiler

arXiv:1705.02996v1

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**Red : Achieved Backgrounds; Black : Projected Backgrounds**

**Width of bands based on range of NME values**
Considerations for Next Gen $0\nu\beta\beta$-decay experiments

- Significant experimental progress since the 2015 long range plan.
  - Experiments have attained or are approaching sensitivities of $T_{1/2} > 10^{26}$ years, with substantially reduced backgrounds.

- Large international collaborations are moving forward with next generation experiments based on lessons learned from the current measurements.

- For discovery of $0\nu\beta\beta$, experiments require good energy resolution, low backgrounds (“background free”) and large exposures ($t$-$y$).

- Discovery will require observation by independent experiments, using different isotopes.

- Reduced uncertainties on NME and $g_A$ will have a critical impact on understanding sensitivity and discovery potential.
0νββ INT Workshop Discussions

• Sensitivity in the presence of backgrounds.

• Self-consistent fiducial vol. analysis (e.g. KamLAND-Zen).

• Bayesian vs. Frequentist approaches to sensitivity and discovery level.

• Incorporation of systematic uncertainties into overall estimates of sensitivity.