Progress in $0\nu\beta\beta$ decay search and the GERmanium Detector Array

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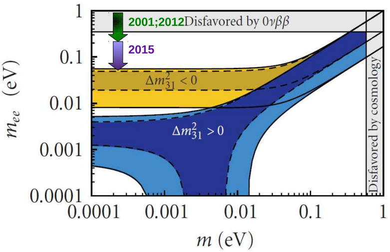
BeNu 2012 conference, September 17-21, 2012

The Abdus Salam International Centre for Theoretical Physics

Motivations for $0\nu\beta\beta$ decay search in 2012

Observation of $0\nu\beta\beta$ decay helps answering 3 fundamental questions:

1. Is lepton number conservation violated? Are neutrinos their own anti-particles ?
2. What is the absolute neutrino mass scale?
3. Is the neutrino mass spectrum degenerate, normal or inverted? (Hierarchy problem)



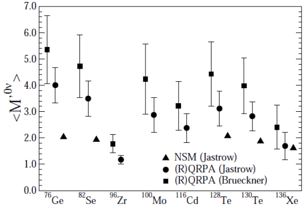
Observable: $0\nu\beta\beta$ decay rate $\rightarrow$ half-life $T_{1/2}$. If not observed, then quoting a lower limit of $T_{1/2}$ (90%C.L).

- Best limit in the past obtained by HdM (2001):
  $T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr; $\langle m_{\beta\beta}\rangle \leq 0.35$ eV
- KKDC claim (2004):
  $T^{0\nu}_{1/2} = 1.17\times10^{25}$ yr; $\langle m_{\beta\beta}\rangle \sim (0.23\text{-}0.59)$ eV
- New experiments:
  EXO-200 (2012):
  $T^{0\nu}_{1/2} > 1.6\times10^{25}$ yr, $\langle m_{\beta\beta}\rangle \leq 0.14\text{-}0.38$ eV
  Within 2015: $\langle m_{\beta\beta}\rangle \leq 0.05$ eV

Half-life correlation with effective Majorana neutrino mass

$$(T_{1/2})^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

with $G^{0\nu}$: phase space factor, $M^{0\nu}$: nuclear matrix element, $\langle m_{\beta\beta}\rangle = \left|\sum_j m_j U_{ej}^2\right|$



- $M^{0\nu}$ Calculations:
  - Improvements for NSM and QRPA:
    →Most QRPA discrepancies solved (`Simkovic F. et al, Phys.Rev.C 79 (2009)`)
    →Progress in understanding source of spread of NSM values (`Faessler A. et al,(2012)`)
  - New methods IBM, EDF, pHFB
- $Q_{\beta\beta}$ values: → Penning-traps (e.g. ^{130}Te: 5% shift)
- Cross sections for neutron reactions (e.g.^{207}Pb(n,n'γ): DEP of 3062 keV $\simeq Q_{\beta\beta}$ of ^{76}Ge)

Request: Larger number of measurement with different isotopes

→ Avoid (not well) known rare background events at $Q_{\beta\beta}$
→ NME uncertainties $\leq$30% for neutrino mass spectrum & CP violating phases
→ Mechanisms: Light vs. heavy Majorana neutrino exchange, RHC,...

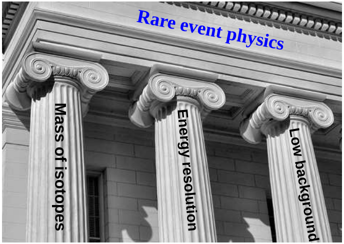
Progresses in experimental techniques

Determination of the half-life

$$T_{1/2} \propto \begin{cases} a \cdot \epsilon \cdot M \cdot T, & \text{background-free} \\ a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, & \text{if background is present} \end{cases}$$

with a: Abun./Enrich.; M: Mass;ϵ: act.volume; ΔE: e-res.; T: life-time; B: bkgd

Isotope	$Q_{\beta\beta}$ [keV]	nat.Abun. [%]	Experiment (operat./funded)	FWHM/E @ $Q_{\beta\beta}$ [%]	Mass [kg]
^{48}Ca	4273.7	0.19	Candles		0.35
^{76}Ge	2039.1	7.8	GERDA	0.1-0.2	15→35
			Majorana Dem.	0.1-0.2	30
^{82}Se	2995.5	9.2	SuperNEMO		7→100
			Lucifer		–
^{100}Mo	3035.0	9.6	MOON		480
			AMoRe		100
^{116}Cd	2809.1	7.6	Cobra		64
^{130}Tl	2530.3	34.5	CUORE	0.2	10→200
^{136}Xe	2457.8	8.9	EXO	4.0	175
			KamLand-Zen	9.8	330→1000
			NEXT		100
^{150}Nd	3367.3	5.6	SNO+		44

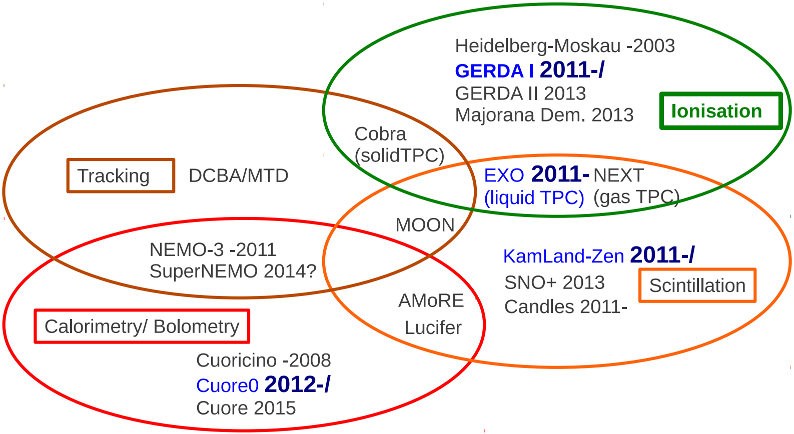


Request: Larger number of measurement with different isotopes

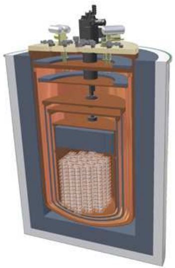
→ Avoid natural radioactivity: stay above ^{208}Th and ^{214}Bi lines
→ Advantages of single isotopes: better ΔE, scalability/enrichment of isotope mass
→ Measurements: independent techniques with $\leq$30% precision

Isotopes and experimental techniques for $0\nu\beta\beta$ decay search

- Selected isotopes: 8 out of 35 ($\leftarrow$ nat.Abun., $Q_{\beta\beta}$, $G^{0\nu} \propto (Z, Q^5_{\beta\beta})$, chem.prop.)
- Techniques: ion., scint.(gas,liq.), track./TPC(gas,liq.,solid), cal./bolo.



The CUORE experiment



Detectors and cryostat

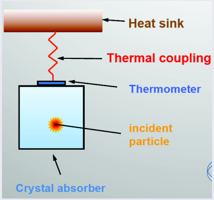
- TeO_2 crystals cooled down to ∼10 mK with He within a multi-layer copper cryostat
- Isotopic nat. abundance of ^{130}Te: 34.1% (no enrichment!)

Shielding

- Inner Roman lead layer and outer lead layer
- Ra barrier and neutron shield
- 1400 m overburden (3500 m w.e.) at LNGS

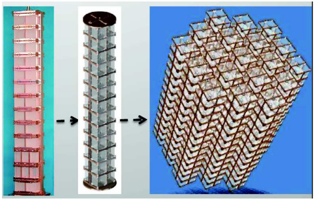
Concept: DBD Source = Absorber

Bolometric technique



- TeO_2 absorbs energy deposition E by particle
- Energy deposition E registered by a thermistor (NTD Ge) as temperature increase:
  Signal: $\Delta T = E/C$, C: capacity
  Time constant $= C/G$; G: thermal coupling
  Need: → low-heat C → mK + diele.diamagn.mat.
- Very good energy resolution achievable:
  ∼5 keV @$Q_{\beta\beta}$ (2527 keV), corr.FWHM/E=0.2%

Scaling of the CUORE project

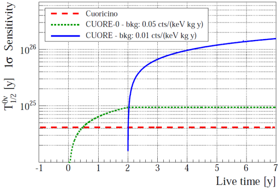


1. **Cuoricino** (Cuore Demonstrator) (2003-2008):
   - 1 tower; 62 crystals; ^{130}Te: 11.3 kg
   - Achieved BI = 0.169±0.006 cts/(keV·kg·yr); most prob.: surface α's
   - Limit for $0\nu\beta\beta$ half-life of ^{130}Te (90% C.L.):
     $T^{0\nu}_{1/2} > 2.8\times10^{24}$ yr, $\langle m_{\beta\beta}\rangle < 0.30\text{-}0.71$ eV
     (E. Andreotti et al., Astropart. Phys. 34 (2011))
2. **Cuore-0** (2012-2014):
   - 1.tower of 19-tower Cuore assembly; 52 crystals; ^{130}Te: 11 kg
     → Control detector-production chain for Cuore (recontamination)
     → As stand alone experiment: Improve BI to 0.11-0.05 cts/(keV·kg·yr)
3. **Cuore (2014-2019)**:
   - 19 towers; 988 crystals; ^{130}Te: 206 kg
   - Goal BI: 0.01 cts/(keV·kg·yr)

Status and sensitivity of Cuore-0/Cuore

Installation of Cuore-0

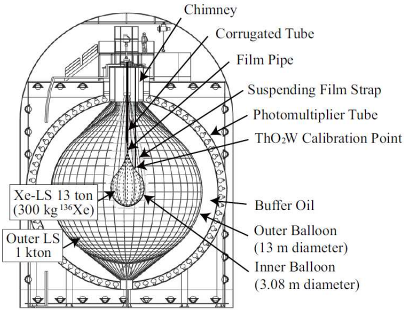
(spring/summer 2012)



- **Cuore-0**:
  - Installation in cryostat completed; cooling-down and data-collection start forseen within **July 2012**
  - With BI=0.05 cts/(keV·kg·yr), 2 yr run (90%C.L.):
    $\rightarrow T^{0\nu}_{1/2} > 5.9\times10^{24}$ yr, $\rightarrow \langle m_{\beta\beta}\rangle <$ 0.17-0.39 eV
- **Cuore**:
  - Crystals almost all arrived at LNGS
  - Radiopurity of all crystals measured; extrapolation to BI for Cuore:
    $\rightarrow$ from bulk: 1.1×10^{-4} cts/(keV·kg·yr)
    $\rightarrow$ from surface: 4.2×10^{-3} cts/(keV·kg·yr)
  - With BI=0.01 cts/(keV·kg·yr), 5 yr run:
    $\rightarrow T^{0\nu}_{1/2} > 1.6\times10^{25}$ yr, $\langle m_{\beta\beta}\rangle <$ 0.04-0.09 eV

The KamLAND-Zen experiment

KamLAND-Zen is 'embedded' within KamLAND using Xe-loaded LS



Inner balloon (R=1.54 m, 25 μm thick)

- 13 t of Xe-loaded LS:
  - Decane 82.3%, PC 17.7%, PPO 2.7 g/l
  - Xe $\sim$3 wt% (320 kg)
- ^{136}Xe enrichment: 90.9%

1000 t KamLand LS (R=6.5 m)

- Dodecane 80%, PC 20%,PPO 1.36 g/l
- Active shield: ext.γs, int.γs from IB/Xe-loaded LS

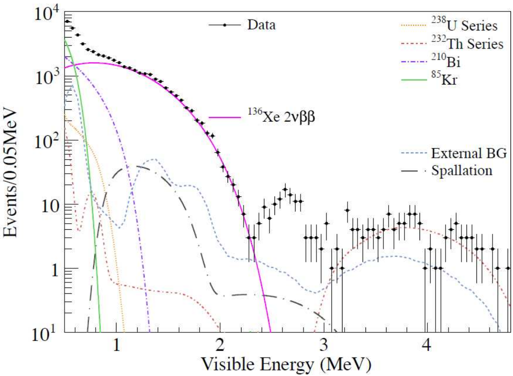
SSS and 3.2 kt water tank

- SSS: 1879 PMTs detecting scintillation light
- Water tank: neutron moderator and muon Cherenkov detector

Advantages of using a) Xe-loaded LS b) in KamLAND

- Xe: soluble in LS (Raghavan R., PRL72 1411 (1994))
- Xe: high isotopic enrichment, extraction and purification
- Use existing ultra-pure detector; low-energy anti-neutrino measurements can continue

Measurement of $2\nu\beta\beta$ half-life of ^{136}Xe



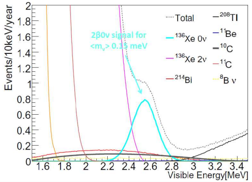
- Fitregion: [0.5;4.8] MeV; includes 80% of the $2\nu\beta\beta$ spectrum
- Exposure for ^{136}Xe alone: 38.4 kg·yr (112.3 d; 125 kg ^{136}Xe)
- $2\nu\beta\beta$ events: ~35500 events; rate: (80.9±0.7) cts/(d·ton) in Xe-loaded LS

KamLAND-Zen $2\nu\beta\beta$ half-life result (May 2012):

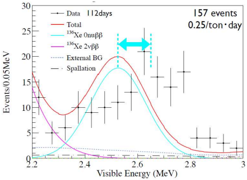
$T^{2\nu}_{1/2} = 2.30 \pm 0.02 \pm 0.12\,(\text{stat+sys}) \times 10^{21}$ yr (arXiv:1205.6372)

Limit for $0\nu\beta\beta$ half-life of ^{136}Xe

Expected spectrum

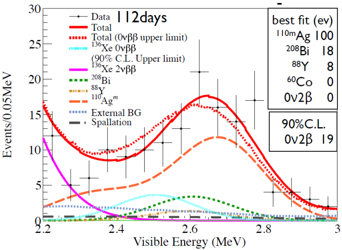


Measured spectrum



Unexpected peak at 2.6 MeV

- Rate stable in time, → non-shortlived radioisotopes
- Non-compatible with $Q_{\beta\beta}$ of ^{136}Xe
- Check 'all' nuclei ($\mathcal{O}(10^3)$) and decay paths ($\mathcal{O}(10^6)$)
  →Remaining candidates: ^{110m}**Ar**, ^{208}Bi, ^{88}Y, ^{60}Co



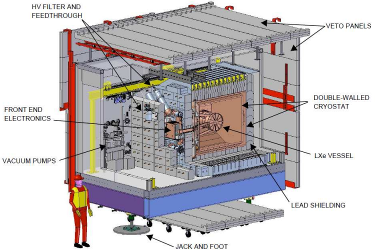
$T^{0\nu}_{1/2}$ result (May 2012: arXiv:1205.6372)

$T^{0\nu}_{1/2} > 6.2\times10^{24}$ yr, $\langle m_{\beta\beta}\rangle < 0.26$-$0.54$ eV at 90%C.L.

- Purification of Xe-loaded LS ongoing; → lower background ^{110m}Ar (,^{208}Bi,^{88}Y) background by 100×
- 600 kg Xe already in the Kamioka mine, → first $\beta\beta$ 1-ton experiment (?)
- Increased amount of Xe and cleaner balloon (less ^{214}Bi)

The EXO-200 experiment

Concept: DBD source = Detector

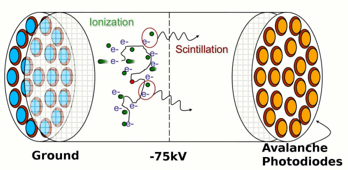


Detector design and background reduction

- LXe Vessel in ultra-radiopure copper cryostat filled with high-purity heat transfer fluid HFE7000
- Lead shield
- 4 plastic scintillators as active muon vetos
- 700 m overburden (1600 m w.e.) at WIPP lab, Carlsbad, NM

Detection principle

Medium: 175 kg of LXe; ^{136}Xe enrichment: 80.6% **Detection principle**:



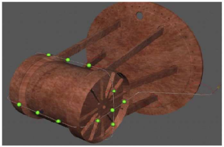
- Collection charge wires measure ionized electrons
- Large Area Avalanche Photodiodes (APDs) measure 178 nm scintillation light

Gain from:
Drifttime:
→ Position reconstruction res.: X,Y: 18 mm; Z: 6 mm
→ Distinguish single $\beta/\beta\beta$'s from multiple γ's clusters:
Ionisation vs. Scintillation:

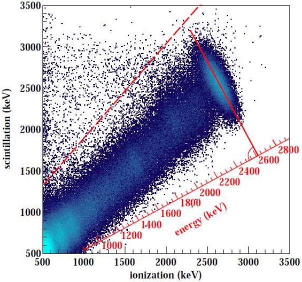
→ Discrimination of α from $\beta/\beta\beta/\gamma$

Calibrations with ^{60}Co, ^{137}Cs, ^{228}Th sources

Calibration points



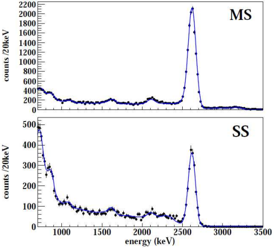
Ionisation vs. Scintillation (^{228}Th source)



Determination of number of SSE/MSE for a spectral component

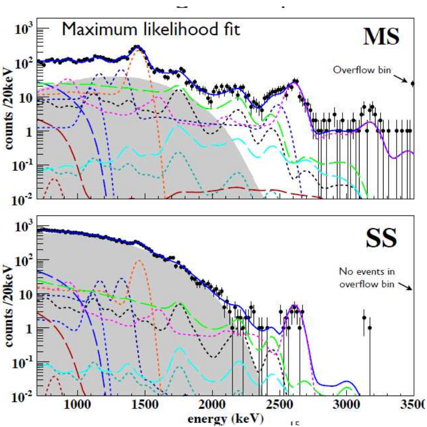
- $\beta/\beta\beta$'s are mostly SSE, **but** can also populate MSE spectrum due to bremsstrahlung (γ's mostly MSE)
- Contribution to SSE/MSE spectra to be simulated for all spectral components $\rightarrow$ MC tested with calibrations:

Example: Region around 2.6 MeV ^{208}Tl-line



$\rightarrow$ MC and data in good agreement

Measurement of $2\nu\beta\beta$ half-life of ^{136}Xe



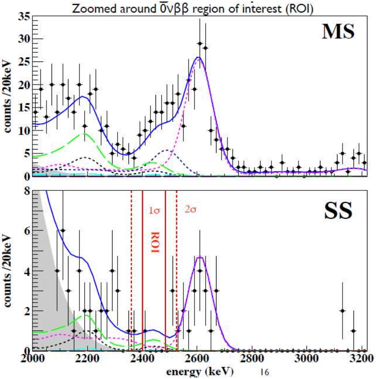
- Rejection of peripheral background by fiducial Volume cut:
  → Active mass of 98.5 kg of LXe (^{136}Xe: 79.4 kg)
  → LXe exposure after 120.7 d: 32.5 kg·yr
- SSE $2\nu\beta\beta$ spectrum:
  → spectrum contains ~22000 $2\nu\beta\beta$ events above 0.7 MeV
  → S/B ratio of ~10/1 !
  → SSE spectrum: 82.5% of $2\nu\beta\beta$ events (MC calc.)

Results for $T^{2\nu}_{1/2}$ [$\times 10^{21}$ yr]

EXO-200 (May 2012): 2.23±0.02±0.22 (stat+sys) arXiv:1205.5608
Agrees with KamLAND-Zen (May 2012): 2.30±0.02±0.12 (stat+sys) arXiv:1205.6372

Contradicts DAMA/LXe: >10 yr (90%C.L.) (R. Barnabei et al., Phys.Lett.B 546 (2002) 23)

Limit for $0\nu\beta\beta$ half-life of ^{136}Xe



$0\nu\beta\beta$ results after 120 d with 98.5 kg of LXe (May 2012):

- Observed background: 1(5) events within 1(2)σ around $0\nu\beta\beta$ ROI
  $\rightarrow$ BI=0.0015 cts/(keV·kg·yr) $\rightarrow$ within specs!
- $T^{0\nu}_{1/2} > 1.6\times10^{25}$ yr, $\langle m_{\beta\beta}\rangle < 0.14$-$0.38$ eV (90% C.L.)

The GERDA experiment

Plastic scintillator

- active muon veto

Clean room (cl.10000)

- access to detector insertion lock system

Water tank

- R=5 m, h=9.0 m, 590 m^3 ultra-pure water
- acts as neutron moderator/absorber
- acts as muon Cherenkov veto

Concept: DBD Source = Detector

Background reduction:

- material screening
- graded passive shielding;
- active vetos;
- operation of bare Ge diodes in LAr
- Particle identification techniques

Ge detector array

- 1-string and three arm with each 3 detectors (Phase I)
- up to ∼12 strings (depending on final design for Phase II)

Large Cryostat

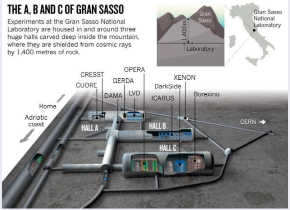
- R=2 m, h=5.9 m, 64 m^3 LAr
- Acts as cooling medium
- Acts as passive shielding
- Will act as active background suppresion using scintillation (Phase II)

GERDA: construction milestones

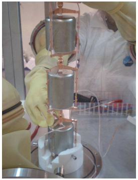
1. **LoI**: 2004
2. **R&D**: since 2004 (i.e. material screening, testing bare Ge diodes in LAr etc.)
3. **Construction**: 2008-2010
   - cryostat & cryogenic infrastructure
   - water tank & muon veto
   - clean-room and lock system

Location in Hall A at LNGS

(3500 m w.e.)



Phase I: Installed detectors

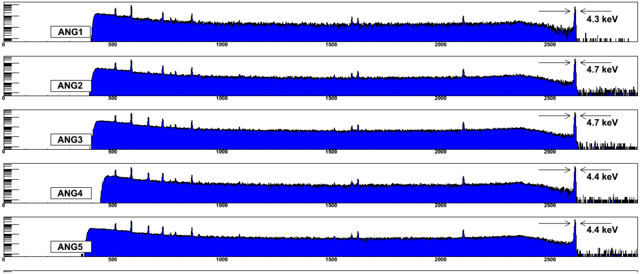


- **Technology**: refurbished co-axial HPGe detectors from HdM, IGEX and GTF experiments
- **Mass**:
  1. 6 enriched (^{76}Ge: ~86%): 14.63 kg: ANG2-ANG5, RG1, RG2; (ANG1 and RG3: drawing leakage current after installation and thus excluded from DAQ)
  2. 3 natural (^{76}Ge: 7.83%): 7.59 kg: GTF112, GTF45, GTF32
- **Operation**: bare diodes in LAr on low-mass holders

→ Commissioning phase: 2010-2011

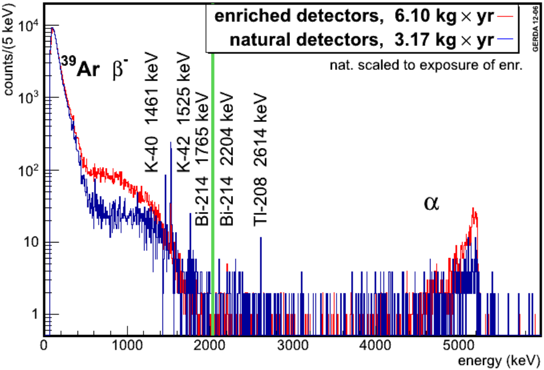
→ Start of Phase I data collection: November 9, 2011

Phase I: detectors' performance and stability



- **Energy resolution**: 4.5-5.1 keV (FWHM) @ 2614.5 keV; 4.5 keV @ 2039 keV
- **Stability I**: Constant energy resolution and no significant shift of energy scale
  → Duty cycle 'high',i.e. ∼95% in (DAQ start - June 2012); effectively ∼80% due to 1 run rejected after temperature instabilities in clean room.
  → Exposure for enriched detectors until September 6, 2012: 9.55 kg·yr
- **Stability II**: No significant increase of leakage current !

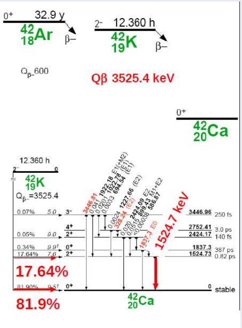
Phase I: Energy spectra for natural and enriched diodes



- **Background index at $Q_{\beta\beta}$**: 'low', however unexpected ^{42}Ar background
- **Pulse shape discrimination**: no PSD technique applied so far
- **Blinding**: **automatic blinding** of $Q_{\beta\beta}$ region in (2039±20) keV region applied since January 11, 2012

Phase I: ^{42}Ar background

^{42}Ar Level scheme



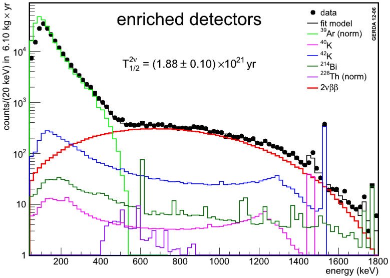
- **Problematics**:
  1. ^{42}Ar: long-lived ($T_{1/2}$=32.9 y)
  2. ^{42}K: β decay into ^{42}Ca: $Q_{\beta-}$=3525.4 keV, E_γ=1524.7 keV (81.9% Emis.Prob.)
  3. Expected concentration: <41 μBq/kg at 90% C.L. (`V.D. Ashitkov et al., Inst.Exp.Tech.46(2003)153`) **However**: collection of ions through E-field from HV
- **Improvement**: 60 μm thin cylindrical Cu foil around strings → Background reduction: 3 ×

Preliminary measurement of ^{42}Ar:

In GERDA: 92.8±5.2(syst)4.5±(stat) μBq/kg

In R&D setup LArGe: consistent result using a different method

Phase I: Measurement of $2\nu\beta\beta$ half-life of ^{76}Ge



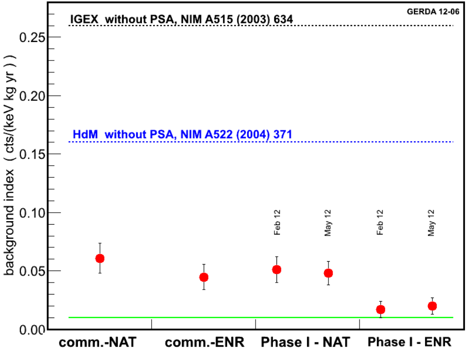
- **Fit**: region (600-1800) keV; May 2011-Nov 2012; only enriched detectors →S/B∼8/1 !
- **Free parameters**: ^{40}K, ^{42}K, ^{214}Bi, $T^{2\nu}_{1/2}$, active mass, enrichment

Results for $T^{2\nu}_{1/2}$ [$\times 10^{21}$ yr]

Preliminary GERDA result: 1.88±0.10 (sys+stat)
Comparison to weighted average of previous measurements: 1.50±0.10

(A. Barabash, Phys.Rev.C, 81 (2010) 035501)

Phase I: Achieved Background Index at $Q_{\beta\beta}$ of ^{76}Ge



- **BI definition**: $Q_{\beta\beta}\pm 100$ keV (minus blinded 40 keV region)
- **Achieved BI**: $0.020^{+0.006}_{-0.004}$ cts/(keV·kg·yr)
  → Design BI of 0.01 cts/(keV·kg·yr) almost reached !
- **GERDA Phase I vs. HdM**: continuum around $Q_{\beta\beta}$ and most gamma lines are 1 order of magnitude less intense
- ^{42}**Ar**: non-problematic for Phase I

Preparations for GERDA Phase II

Goal of Phase II: Lowering the BI to $\leq 0.001\,\mathrm{cts/(keV{\cdot}kg{\cdot}yr)}$

Determination of the half-life

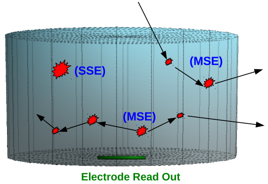
$$T_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, \quad \text{(if background is present)}$$

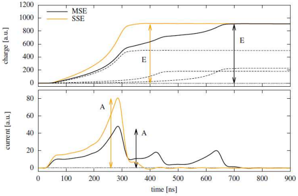
where:

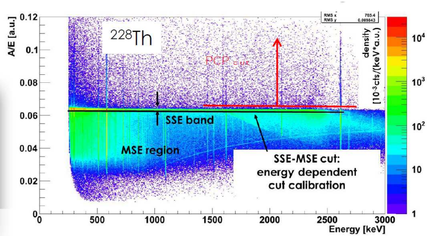
- **a**: Abundance of $0\nu\beta\beta$ candidate isotope $\rightarrow$ Enrichment
- ϵ: Efficiency $\rightarrow$ precise characterisation via dedicated acceptance tests
- **M**: Mass $\rightarrow$ Increasing target mass
- **T**: DAQ life-time high duty cycle
- **ΔE**: energy resolution $\rightarrow$ Novel detector technology with improved resolution
- **B**: Background
  $\rightarrow$ Avoid cosmogenic activation of germanium
  $\rightarrow$ Pulse shape discrimination using novel detector technology
  $\rightarrow$ Instrumentation to detect LAr scintillation light

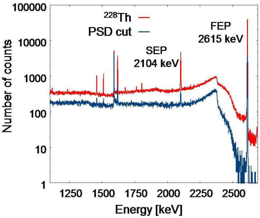
GERDA Phase II detectors

- **Goal**: Background rejection in the bulk by distinguishing single-site events (SSE) from multi-site events (MSE); additionally, surface events on the p^+ (i.e. amplified current pulses) and n^+ (i.e. slow pulses) contact can be discriminated
- **Solution**: Unsegmented Broad Energy germanium detectors (BEGe) with enhanced pulse shape discrimination (PSD) properties









Status: BEGe detector procurement

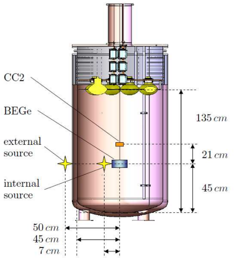
- **Crystal pulling** at Canberra in Oak Ridge, TN (USA): accomplished
- **Diode production** at Canberra in Olen (BE): ongoing
  → 12 out of 30 crystal slices converted into diodes
  → diode acceptance tests on-site at SCK, Mol (BE): ongoing
  → 5 BEGe's (3.63 kg) in GERDA since July 7, 2012 for tests and intrinsic background studies
- **Expected additional mass**: ∼20 kg

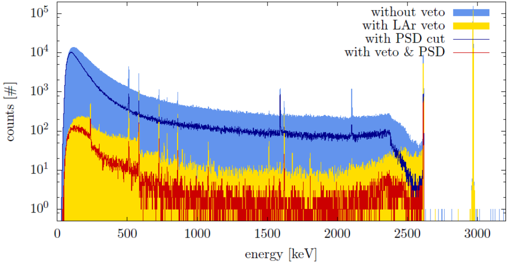
First 5 BEGe diodes: preliminary averaged results

	In Vacuum	In LAr
FWHW @ 2.6 MeV	2.35 keV	3.18 keV
PSD efficiency	DEP: 0.90 SEP: 0.09 FEP: 0.13 ROI: 0.38	DEP: 0.90 SEP: 0.11 FEP: 0.15 ROI: 0.46

GERDA Phase II: 'Light instrumentation'

- **Goal**: Background rejection via detection of scintillation light in liquid argon (λ=128 nm)
- **R&D** with LArGe test facility at LNGS





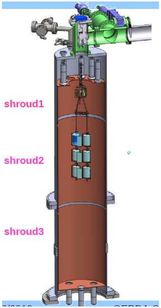
Results for ^{60}Co and ^{228}Th source (M. Heisel, Diss.2011)

source	position	LAr Veto	PSD	total
^{60}Co	int	27±2	76±9	3900±1300
^{228}Th	ext	25±1	2.8±0.1	129±15
	int	1180±250	2.4±0.1	5200±1300

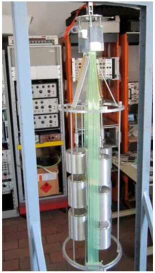
Preparations for Phase II: LAr scintillation read-outs

PMT teststand

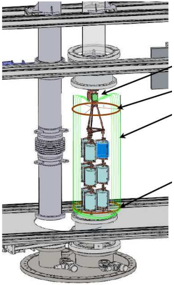
PMT Design



Glass-fibre teststand



Glass-fibre design

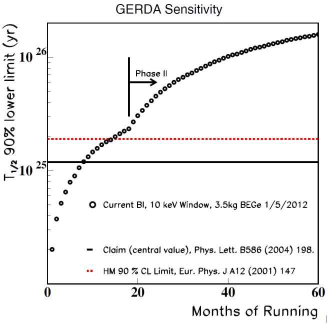


1. Option: PMT light instrumentation (based on LarGe experience)
2. Option: Wavelength-shifter glass-fibre with SiPMs
3. Option: large area avalanche photodiodes or UV sensitive SiPMs on custom-made low-activity substrates

→ Most advanced solution: combination of 1. and 2. option

Summary GERDA

1. **Phase I**:
   - Running since November 9, 2011;
   - Background index almost within specs
   - Exposure: ∼9.55 kg·y (September 6, 2012)
   - $2\nu\beta\beta$: New measurement of halflife of $T^{2\nu}_{1/2}$ in ^{76}Ge
   - Analysis: blinded in $Q_{\beta\beta}$ region; unblinding in spring 2013
2. **Phase II**:
   - Preparations ongoing (det.procurement, light instr., elec.readout)
   - Planned installation of new infrastructure: early 2013



Summary: status of $0\nu\beta\beta$ search experiments

- If range $\langle m_{\beta\beta}\rangle$=0.1-0.5 eV holds (if KK claim confirmed):
  → Observation by EXO-200, KamLAND-Zen (^{136}Xe) and GERDA (^{76}Ge) in (early) 2013
  → Other experiments that will be finalized in the next years will observed the $0\nu\beta\beta$ decay in other isotopes (SNO+ ^{150}Nd, Cuore in ^{130}Te,...)

  → Precision-experiments have to follow (to improve NME and understand exchange mechanisms)

- If range $\langle m_{\beta\beta}\rangle$=0.02-0.05 eV holds:
  → Necessity for large scale enrichment and lower background reduction
  → Possible experiments: Gerda Phase III and Majorana, Cuore marginally, KamLand-Zen(2),...

  → Discovery in 3-4 isotopes necessary to confirm the observation and to improve the theoretical nuclear calculations

2013+ will be exciting time for $0\nu\beta\beta$ search !