Review of double beta decay experiments: Present status and near future

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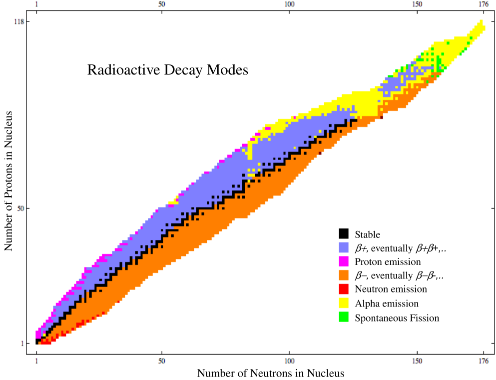
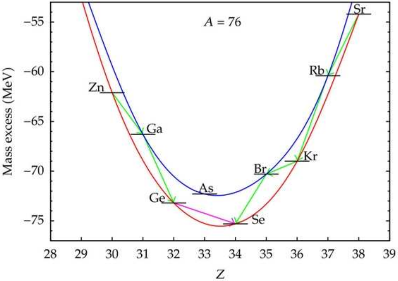
Searching for the double beta decay



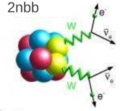


Towards the valley of stability:

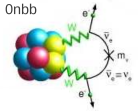
- Second-order nuclear transition that can occur between two odd-odd isobars:
  → single β decay energetically forbidden
  → Among competing channels ($\beta^-\beta^-$, $\beta^+\beta^+$, ECβ^+, ECEC) $\beta^-\beta^-$ has highest rates
- 35 candidates in Nature; examples:
  ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe

Double beta decay: $2\nu\beta\beta$ versus $0\nu\beta\beta$

2nbb



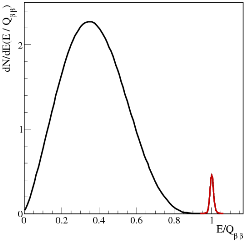
0nbb



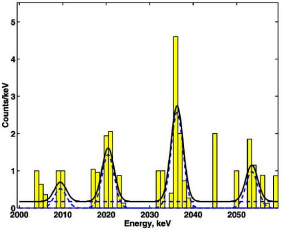
Role of neutrinos in $\beta\beta$ decay:

1. $2\nu\beta\beta$ decay
   → Allowed by Standard Model
   → Signature: β -like spectrum
   → Observed in 12 candidates: O($T_{1/2}$)=10^{18}-10^{24} yr
   (Longest-lived decay processes observed in Nature)
2. $0\nu\beta\beta$ (or $0\nu\chi^0(\chi^0)\beta\beta$) decay
   → Not allowed by Standard Model
   → Signiture: Full energy peak at $Q_{\beta\beta}$
   → One claim (in ^{76}Ge) by subgroup of
   Heidelberg-Moskow collaboration (HdM)

Expected experimental signature from $2\nu\beta\beta$ and $0\nu\beta\beta$ decays



Claim: observed signal in ^{76}Ge at $Q_{\beta\beta}$=2039 keV
`Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198`



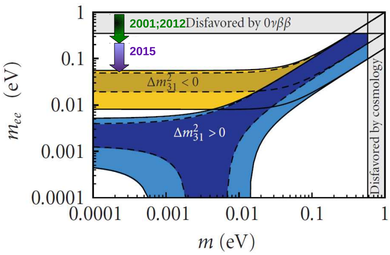
Motivations for $0\nu\beta\beta$ decay search

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

1. Is lepton number conservation violated ($\Delta L=2$)? Are neutrinos their own anti-particles ?
   → If yes, physics beyond the Standard Model of Elementary Particles with impact up to cosmology
2. What is the absolute neutrino mass scale ?
   → Neutrino-oscillations reveal only squared mass-differences of neutrino mass eigenstates
3. Is the neutrino mass spectrum degenerate, normal or inverted ?
   → Atm./solar/reactor neutrino oscillation experiments allow different scenarios (Hierarchy problem)
   → Measurement of 'effective' neutrino mass which is very rich of information:

$$\langle m_{ee}\rangle = \left|\Sigma\, |U_e i|^2\, m^i e^{i\alpha_i}\right|$$

with $U_e i$ neutrino mixing matrix, m^i neutrino mass eigenstate, α_i CP-violating Majorana phases



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

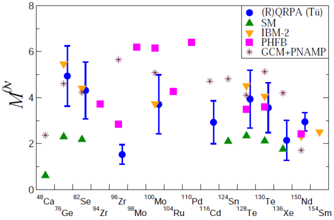
- Best limit in the past obtained by HdM (2001):
  $T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr; $\langle m_{ee}\rangle \leq 0.35$ eV
- KKDC claim (2004):
  $T^{0\nu}_{1/2} = 1.17\times10^{25}$ yr; $\langle m_{ee}\rangle \sim (0.23\text{-}0.59)$ eV

$0\nu\beta\beta$ decay formalism: a difficult nuclear physics problem

Half-life correlation with effective Majorana neutrino mass

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

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
    →Progress in understanding source of spread of NSM values
  - 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)

Theory's demand for a larger number of measurements with different isotopes

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

Experimental sensitivity and constraints

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 ([counts/kg/keV/yr] around region-of-interest)

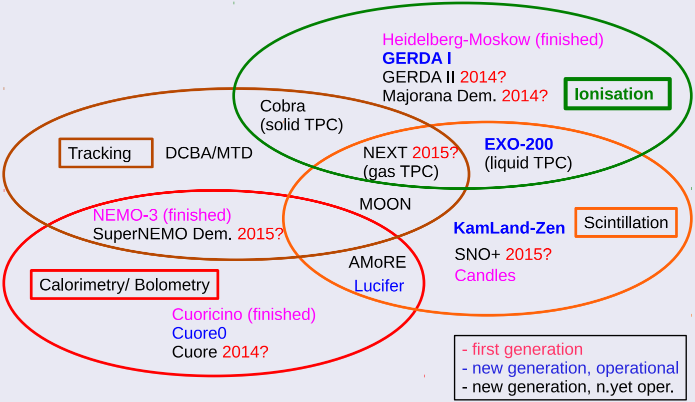
Isotope	$Q_{\beta\beta}$ [keV]	nat. abundance [%]	annual production [ton]	Experiment (oper./funded)	FWHM/E @ $Q_{\beta\beta}$ [%]	Mass [kg]
^{48}Ca	4273.7	0.19	5×10^5	Candles		0.35
^{76}Ge	2039.1	7.8	10	GERDA	0.1-0.2	15→35
				Majorana Dem.	0.1-0.2	30
^{82}Se	2995.5	9.2	250	SuperNEMO		7→100
				Lucifer		–
^{100}Mo	3035.0	9.6	2.5×10^4	MOON		480
				AMoRe		100
^{116}Cd	2809.1	7.6	1.5×10^3	Cobra		64
^{130}Te	2530.3	34.5	50	CUORE	0.2	10→200
^{136}Xe	2457.8	8.9	1.5	EXO	4.0	175
				KamLand-Zen	9.8	330→1000
				NEXT		100
^{150}Nd	3367.3	5.6	500	SNO+(orig.)		44

Motivations for a larger number of experiments and isotopes:

→ Reduction of background: detector segmentation, particle tracking, pulse shape, $Q_{\beta\beta}$ above lines of ^{228}Th
→ Advantages of single isotopes: better ΔE, enrichment of isotope, scalability (detector size, world annual production, prize)
→ Avoid/reduce systematics: independent techniques, measurements with $\leq$30% precision

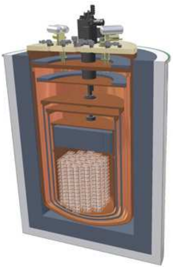
Isotopes and technologies for $0\nu\beta\beta$ decay search

- Selected best isotope candidates: 8 out of 35 (← nat. abundance, $Q_{\beta\beta}$, $G^{0\nu} \propto (Z, Q^5_{\beta\beta})$, chem. properties)
- Techniques and their advantages:



- Source=Detector: large isotopic masses possible and scalable (10-100 kg now, 1 ton near future)
- Source≠Detector: Tracking particle momenta → Topology of events and mechanisms
- Liquid scintillator detectors: multi-functional, largest target masses, purification strategies
- Solid state detectors achieve the best energy resolution: FWHW/E at $Q_{\beta\beta}$=0.15%

The CUORE experiment



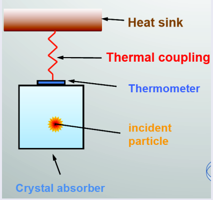
Location: LNGS, Assergi, Italy

Detectors, cryostat, and shield

- 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!)
- Energy resolution: 0.2% in ROI !
- Inner Roman lead layer and outer lead layer
- Ra barrier and neutron shield
- 1400 m overburden, corresponding 3500 m w.e.

Concept: **DBD Source = Absorber**

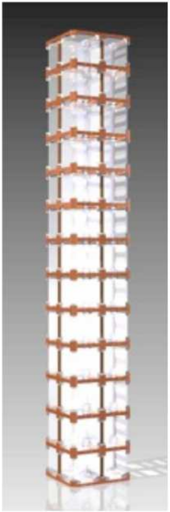
Bolometric technique



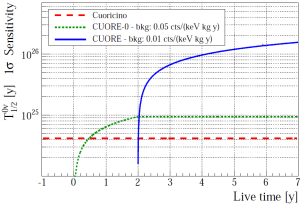
- TeO_2 absorbs energy deposition E by particle
- Energy deposition E registered by a thermistor (NTD Ge) as temperature increase:
  Signal: $\Delta T = E/C$, C: capacity
  Time constant $= C/G$; G: thermal coupling
  Need: → low-heat C → mK + diele.diamagn.mat.
- Very good energy resolution achievable: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

Status and sensitivity of CUORE

Cuore-0 tower



Cryostat of Cuore-0



- **Cuore-0** (2012—2014):
  - 1 tower with 52 crystals, 39 kg ^{130}TeO$_2$, 11 kg ^{130}Te
  - Data collection: 2011-2014, blinded
  - Achieved background: BI=0.02 cts/(keV·kg·yr)
  - Expected after 3 yr run:

  → $T^{0\nu}_{1/2}$ >5.9×10^{24} yr, →$\langle m_{\beta\beta} \rangle$ <0.17-0.39 eV

- **Cuore** (2015—2020):
  - Detector mass: 19 'Cuore-0' towers, 988 kg ^{130}TeO$_2$, 206 kg ^{130}Te
  - Status: All towers assembled, radiopurity of all crystals measured
  - Expected sensitivity:
  - With BI=0.01 cts/(keV·kg·yr), expected after 5 yr run:

  → $T^{0\nu}_{1/2}$ >1.6×10^{26} yr, $\langle m_{\beta\beta} \rangle$ <0.04-0.10 eV

The GERDA experiment

Concept: DBD source = Detector

Location: LNGS, Assergi, Italy

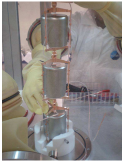
Setup and background reduction:

- 1.4 km overburden, corresponding 3500 m w.e.
  → Reduction of cosmic-muon flux by six orders of magn. down to $\sim 1\,\mu/(m^2 \cdot h)$ (PB)
- Water tank and plastic scintillator
  - R=5 m, h=9.0 m, 590 m^3 ultra-pure water
  → water acts as neutron moderator/absorber (PB)
  → both components act as muon Cherenkov veto (AB)
- Large volume cryostat:
  - R=2 m, h=5.9 m, 64 m^3 LAr
  → LAr acts as cooling medium for diodes
  → LAr attenuates external radiation (PB)
  → LAr scintillation light planned to be used an background rejection (AB)
- GERmanium Detector Array:
  - Operating bare diodes in LAr (-198^{o}C) using low-mass, ultra radiopure Cu holders (PB)
  - Detectors enriched in ^{76}Ge
  - Coincidence modus and pulse shape tracing (AB)
  - **Phase I** (2011-2013): 1-string and 3-string arms with each 3 detectors
  - **Phase II** (start: begin 2015): One 7-string arm

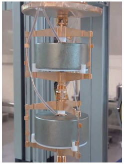
PB = passive background rejection
AB = active background rejection

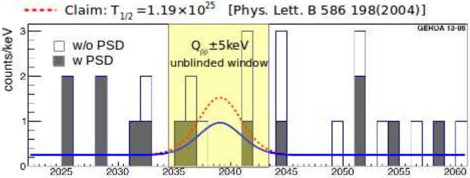
Results from GERDA Phase I

String with
co-axial Ge diodes



String with
Broad Energy Ge diodes





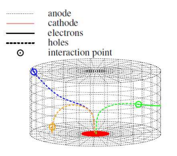
GERDA Phase I (2011-2013)

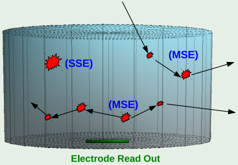
- Physics goal fullfilled: 21.6 kg·yr with BI≈0.01 cts/(kg·yr·keV) including pulse shape cuts (unprecedented !)
- Detector performance: excellent energy resolution at 0.2%, energy scale mostly very stable
- Data analysis: fully **blinded** (unprecedented !)
- Physics results:
  - **$T^{0\nu}_{1/2}$ >2.1×10^{25} yr (90% C.L.)**
  - combined Ge experiments: $T^{0\nu}_{1/2}$ >3.0×10^{25} yr (90% C.L.))
    → **HdM claim (2004) rejected at 99% level by GERDA alone**
    → Combined Ge experiments (HdM + IGEX + Gerda): $\langle m_{\beta\beta} \rangle$ <(0.2-0.4) eV

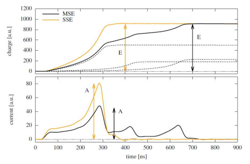
Upgrade to GERDA Phase II (planned start: begin 2015)

Assembly of new detectors:

- Novel technology: 30 ^{76}Ge enriched BEGe-type detectors for ~20 kg
  → Improved sensitivity expected due to: increased target mass, better energy resolution, enhanced pulse shape background discrimination, improved read-out electronics

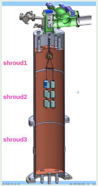


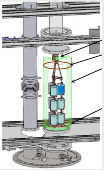




Exploitation of liquid argon scintillation light:

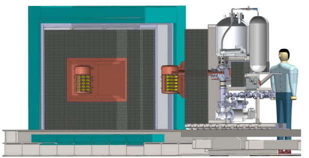
- Background detection: rejection of external background events via detection of scintillation light in liquid argon (λ=128 nm)
- Hybrid solution for read-out: Photomultiplier tubes + wavelength-shifter glass-fibres
- Envisioned BI (BEGe + light instr.): $\leq$0.001 cts/(keV·kg·yr), after 3 yr of data collection:
  → $T^{0\nu}_{1/2} > 1.5\text{-}2\times10^{26}$ yr, $\langle m_{\beta\beta}\rangle < 0.08\text{-}0.12$ eV

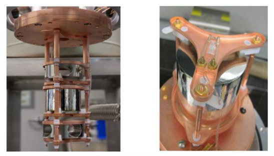




The Majorana Demonstrator

Concept: DBD source = Detector





`Location: Sanford UG lab, Lead, SD, USA (1.480 m overburden)`

R&D, design, goals and status:

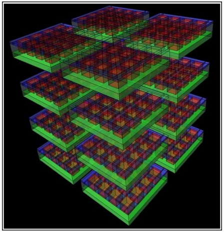
- P-type point contact Ge detectors (low noise, E-threshold at 0.5 keV → suitable also for dark matter search!)
- 40 kg (out of them 30 kg enriched in ^{76}Ge) germanium diodes in two large volume vacuum crystats (7 strings of 3-5 detectors each) within ultra-low background shield made of ultra-radiopure copper and lead.
- Demonstrate sensitivity: $\lesssim$0.001 cts/(keV·kg·yr) (like GERDA Phase II)
- Installation/commissioning of 1.cryostat in spring 2013, of 2.cryostat in fall 2014; data collection start in 2015

GERDA-Majorana cooperation:

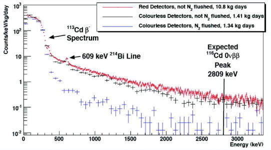
- Exchange of knowledge and technologies, joint Geant4-based simulation tool **MaGe**
- Intention for 100 kg-1 ton experiment; goal sensitivity: $\langle m_{\beta\beta} \rangle$ 0.02-0.12 meV (IH region)

The COBRA R&D project

Concept: **DBD source = detector**

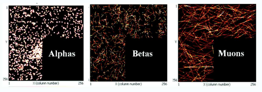


Location: LNGS, Assergi, Italy



Solid state TPC

- Large Array of CdZnTe semicond. detectors with goal sensitivity: $T_{1/2} > 10^{26}$ yr ($\langle m_{\beta\beta} \rangle$ 0.05 eV)
- Composition: 5 $0\nu\beta^-\beta^-$, + 4 EC/β^+, EC/EC candidates !
  Best candidate: ^{116}Cd: $Q_{\beta\beta}$=2809 keV; → enrichment
- Two modular designs (both operational at room temp.!):
  - CoPlanar Grid Detectors (CPG): little 'location' info (with PSA), $\Delta E < 2\%$, and simple read-out
  - Pixelated Detectors (PD): 3D 'location', particle ID if pixels small ($\sim$100 μm), $\Delta E < 1\%$, but complex read-out

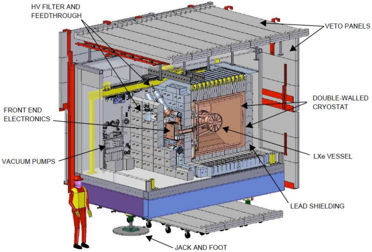


Status (2013/2014):

- Termination of coplaner grid with 64 10x10x10 cm^3 detectors
- MC/tests for 20x20x15 cm^3 detectors, 10^4 in final design
- MC/tests for shield options: multi-layer, liq. scint., water
- $2\nu\beta\beta$: 6 $T_{1/2}$ limits > 10^{20} yr, 7 new upper limits
- $0\nu\beta\beta$: achieved background at ^{116}Cd ROI for CPG: 5 cts/(keV·kg·yr) (2012)

The EXO-200 experiment

Concept: DBD source = Detector



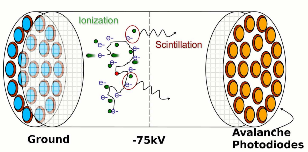
Detector design and background reduction

- 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, corresponding 1600 m w.e.

`Location: WIPP lab, Carlsbad, NM, USA`

Detection principle

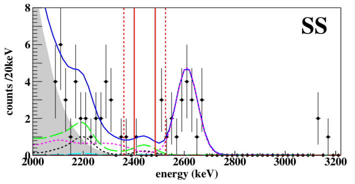
- Medium: 175 kg of LXe; ^{136}Xe enrichment: 80.6%
- Detection principle:



  - Collection charge wires measure ionized electrons
  - Large Area Avalanche Photodiodes (APDs) measure 178 nm scintillation light
- Gain information from:
  - Drifttime:
    → Position reconstruction res.: X,Y: 18 mm; Z: 6 mm
    → Distinguish single $\beta/\beta\beta$'s from multiple γ-ray clusters:
  - Ionisation vs. Scintillation:
    → Discrimination of α from $\beta/\beta\beta/\gamma$
    → Improve energy resolution down to 1.67%

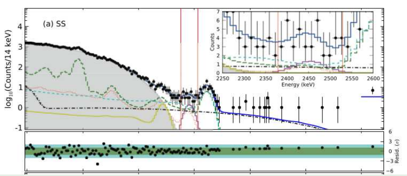
EXO-200: Limit for $0\nu\beta\beta$ half-life of ^{136}Xe

1. publication (May 2012) 120 d with 98.5 kg of LXe:



- Observed background: 1(5) events within 1(2)σ around $0\nu\beta\beta$ ROI → BI=0.0015 cts/(keV·kg·yr) → within specs
- Largest contaminant: ^{232}Th, ^{238}U, ^{137}Xe
- $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr, $\langle m_{\beta\beta} \rangle <$ 0.14-0.38 eV (90% C.L.)

2. publication (February 2014) 478 d with 98.5 kg of LXe:

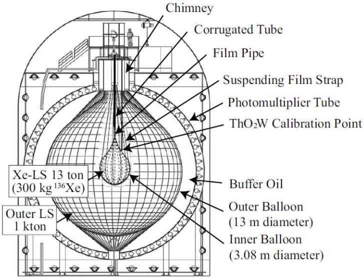


- Data set includes first 120 d
- Partial unblinding procedure applied
- Observed background: 31±5 events within 2σ around $0\nu\beta\beta$ → BI=0.0017 cts/(keV·kg·yr) → within specs
- $T^{0\nu}_{1/2} > 1.1 \times 10^{25}$ yr, $\langle m_{\beta\beta} \rangle <$ 0.19-0.45 eV (90% C.L.)

→ Background in 1. publication slighty underfluctuating, Reason for better sensitivity limit than in 2. publication, even though 4fold data set available.

The KamLAND-Zen experiment

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



`Location: Kamioka, Japan`

Overburden, 3.2 kt water tank, SSS

- 1000 m overburden, corresponding 2700 m.w.e.
- Water tank: neutron moderator and muon Cherenkov detector
- SSS: 1879 PMTs detecting scintillation light

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

Inner balloon (R=1.54 m, 25 μm thick)

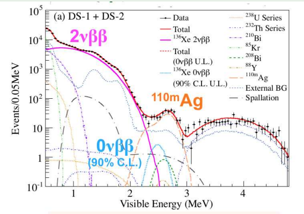
- 13 t of Xe-loaded LS:
  - Decane 82.3%, PC 17.7%, PPO 2.7 g/l
  - Xe $\sim$3 wt% (320 kg)
- ^{136}Xe enrichment: 90.9%

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

- Xe: soluble in LS, high isotopic enrichment, extraction and purification
- Use existing ultra-pure detector; low-energy anti-neutrino measurement continues (multipurpose)

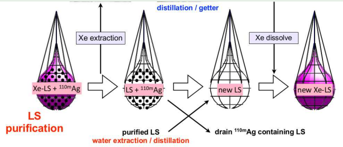
KamLAND-Zen: Limit for $0\nu\beta\beta$ half-life of ^{136}Xe

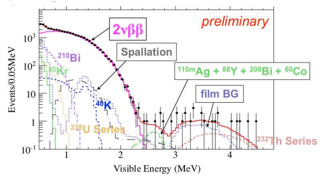
Phase 1 (publ. Feb. 2013)
Exposure: 86 kg·yr



- Unexpectedpeak at 2.6 MeV close to $Q_{\beta\beta}$ of ^{136}Xe; → rate 'stable' or long-lived
  → search for exotic candidates; most probable: ^{110m}**Ar** (Fukushima fallout), ^{208}Bi, ^{88}Y, ^{60}Co
- $T^{0\nu}_{1/2}$ >1.9×10^{25} yr (90% C.L.) (slightly better than EXO-200)

LS purification & Phase 2 (publ. June 2014)
115 d, 348 kg of ^{136}Xe





- $T^{0\nu}_{1/2}$ >1.3×10^{25} yr (90% C.L.) (preliminary)
- Combined Phases 1+2: >2.6×10^{25} yr (90% C.L.)
  $\langle m_{\beta\beta}\rangle$ <0.14-0.28 eV (90% C.L.)

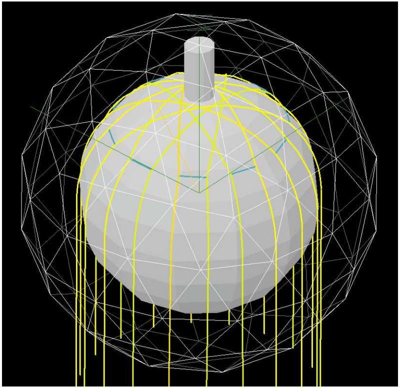
→ Near future: Up to 800 kg instead of 384 kg ^{136}Xe (first $\beta\beta$ 1-ton experiment ?)

→ Long term: KamLAND2-Zen (pressurized Xe, high energy resolution)

SNO+: another multipurpose experiment

SNO+ 'recycles' upgraded SNO infrastructure

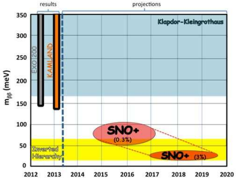
filled with Te-loaded LS



`Location: Sudbury, Ontario, Canada`

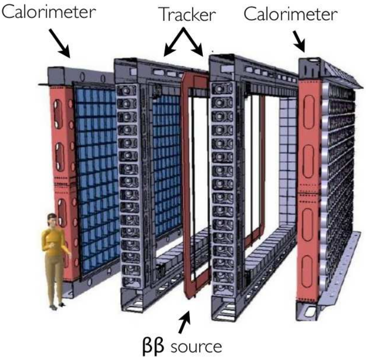
Detector setup

- 2000 m overburden, corresponding 6000 m w.e.
- Outer stainless steel frame (D=17.8 m), carring 9500 PMTs and acrylic vessel AV (907 m^3)
- Between PMTs and AV: 3 m thick ultrapure light water
- Upgrade of trigger/DAQ due to 45× more light
- Scintillator: 780 ton of acrylic-compatible linear alkylbenzene (LAB), hold down with ropes (buoyancy) installed in January 2013. Water filling (before scin. filling) starting in 9 days !
- Phase I: Original idea with ^{150}Nd rejected, March 2013 decision to change to ^{130}Te
  Spring 2014: 1st batch of Te purchased, HV test for PMTs, laser scatt. syst. tested
  - $\sim$0.3% of nat. Te (% ^{130}Te (800 kg)
  $\rightarrow \langle m_e ff \rangle$=0.05 eV (after $\sim$3 yr)
- Phase II: $\sim$3% of nat. Te $\rightarrow \langle m_e ff \rangle$=15 meV (full IH)



SuperNEMO: a tracking calorimeter

Concept: DBD Source $\neq$ Absorber



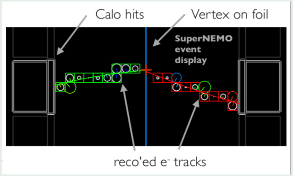
Location: Modane, France (tbc)

1700 m overburden, corr.4800 m w.e.

Detector description

- 3 main components:
  - Multiple $\beta\beta$ foil: ^{82}Se, ^{150}**Nd**, ^{48}Ca, ^{100}Mo...
  - Multiwire chamber: track reco., vertex reco.
  - Calorimeters: energy measurement

  → Unique full reco. of $\beta\beta$ kinematics!



Strategy

- NEMO-3: 7 kg ^{100}Mo: $T^{0\nu}_{1/2} > 1.1 \times 10^{24}$ yr (90% C.L.)
- SuperNEMO Demonstrator (planned start in 2015):
  - ^{82}Se main isotope; ener.res:8%→4% at 3 MeV
  - Lower background, 10× higher exposure
- SuperNEMO:
  - 20 Demonstrator modules using 100 kg ^{82}Se
  - Goal sensitivity: $T^{0\nu}_{1/2} > 10^{26}$ yr

  $\langle m_{\beta\beta} \rangle < 0.04\text{-}0.1$ eV (90% C.L.)

Summary of $0\nu\beta\beta$ decay search - part 1

Status in 2014:

- Flagship of several new $0\nu\beta\beta$ decay experiments under development, partly they have been completed. Several R&D projects for future upgrades or next generation experiments are in progress.
- In 2012/2013, three of the new experiments (EXO-200, KamLAND-Zen, GERDA) reached again sensitivities comparable/better than the previous most sensitive experiment Heidelberg-Moskau (HdM).
- The claim of observation by a subgroup of the HdM collaboration in 2002 was rejected with high probability.
- A lot of progresses in calculating the $0\nu\beta\beta$ nuclear processes were achieved.

Designed and applied detector technologies

- Former technologies further optimized: e.g. Cuore, Gerda
- Combine different technologies for active background suppression; technology transfer among low background rare-event physics projects, e.g. $0\nu\beta\beta \leftrightarrow$ dark matter)
- Multifunctionality of low background detectors: e.g. KL→KL-Zen, SNO→SNO+
- Different technologies and isotopes are complementary:
  - Systematic uncertainties (from experiment, background modelling and nuclear calculations) can be reduced/ruled out
  - Discovery potential and sensitivity limits:
    - Solid state detectors: low mass, high resolution → signal discovery
    - Xe-experiments: high mass, low resolution → push limits

Summary of $0\nu\beta\beta$ decay search - part 2

Outlook:

- Excluding $\langle m_{\beta\beta}\rangle$=0.1-0.5 eV (degenerate hierarchy):
  → This parameter space is in the range of EXO-200, KamLAND-Zen (^{136}Xe) and GERDA (^{76}Ge); within the next 5 years, other experiments (with partly other isotopes) will reach similar sensitivities.
  → So far, no signal was found. The KKDC claim of signal observation was rejected with high probability.
- If range $\langle m_{\beta\beta}\rangle$=0.02-0.05 eV holds (inverted hierarchy):
  → Necessity for large scale enrichment, lower background reduction AND reliable identification of residual background
  → Possible experiments: nEXO, Gerda Phase III and Majorana, KamLand-Zen(2),...
  → Guessed start of commissioning of first experiments after 2020 (SNO+ with 3% Te)
  → Discovery in 2-3 isotopes necessary to confirm the observation
  → An ultimate precision-experiments (SuperNEMO- or NEXT-type) have to follow to improve NME and describe exchange mechanisms

2014+ will be exciting years for $\beta\beta$ decay experiments

searching for lepton number violation !

Back up

How to improve the sensitivity of a $0\nu\beta\beta$ experiment?

Example: GERDA's transition from Phase I to Phase II

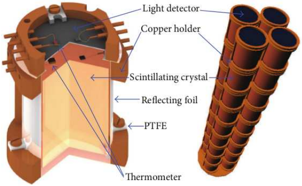
$$T_{1/2} \propto f_{76} \cdot \epsilon \cdot \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}, \quad \text{(if background is present)}$$

- **M** (Mass): → new Ge detectors added, old 15 + new 20 kg
- **T** (DAQ livetime): → larger DAQ period, 20 to 100 kg·yr
- f_{76} (Enrichement): → ^{76}Ge enrichment from 8% to 90%
- ϵ (Detector efficiency): Precise characterisation of detector
- **ΔE** (Energy resolution): → novel detector technologies with better ΔE (BEGe vs. coax) from 0.2% to 0.15%
- **B** (Background suppression) (most important!):
  - **Goal**: BI from 0.01 to 0.001 cts/(kg·yr·keV)
  - Minimize exposure to cosmogenic radiation → less cosmogenic-induced prompt signals and delayed radioisotope decays
  - Enhanced pulse shape discrimination of BEGe detectors
  - Read-out scintillation light in LAr of bckg events

R&D and next generation bolometers

- **Lucifer**:
  - Isotopes: 1. option ZnSe, enriched from 8.7 to 95% in ^{82}Se; 2. option $ZnMoO_4$
  - Technique: scintillation bolometry, → optimal for effective α-rejection
  - Goal of demonstrator (2010-2015): prove feasibility of BI $\sim$ 0.001 cts/kg/yr/keV
  - Crystal growth: problematic, only two suppliers, mass yield transfer still too low
- **Lumineu**:
  - Isotope: ^{100}Mo in $ZnMoO_4$
  - Technique: scintillation bolometry; scintillation detected by small 170 μm thick Ge detectors
  - Status 2014: prototype crystals with masses of 55-340 g produced and characterized
- **AmoRE**:
  - Begin of R&D: 2009
  - Isotopes: ^{100}Mo and ^{40}Ca in $CaMo0_4$
  - Status: low-background, high transparent crystals with up to 0.6 kg produced
  - Planned sensitivity: with 100 kg and 5 yr of data collection: $\rightarrow T^{0\nu}_{1/2} > 3\times10^{26}$ yr, $\langle m_{\beta\beta}\rangle < 0.02\text{-}0.06$ eV

Design for Lucifer



Crystal for AmoRE R&D (2013)