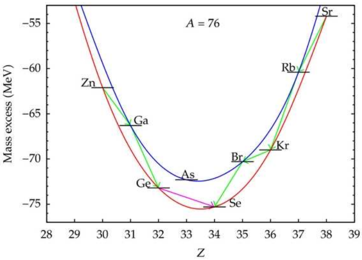
$0\nu\beta\beta$ decay search in 2013: Status and advancements

Werner Maneschg

Max-Planck-Institut für Kernphysik, Heidelberg

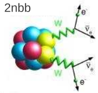
2013 International Workshop on Baryon and Lepton Number Violation:
From the Cosmos to the LHC
April 8-11, 2013, MPI-K Heidelberg, Germany

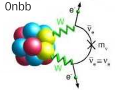
Searching for the rare neutrinoless double beta decay



Towards the valley of stability:

- Second-order nuclear transition that can occur between two odd-odd isobars:
  $\rightarrow$ single β decay energetically forbidden
  $\rightarrow$ Among partly ompeting alternatives ($\beta^-\beta^-$, $\beta^+\beta^+$, 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

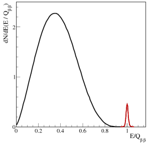




Role of neutrinos in $\beta\beta$ decay:

1. $2\nu\beta\beta$ decay
   $\rightarrow$ Allowed by Standard Model
   $\rightarrow$ Signature: β -like spectrum
   $\rightarrow$ 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
   $\rightarrow$ Signiture: Full energy peak at $Q_{\beta\beta}$
   $\rightarrow$ Lepton-number violation (ΔL=2), thus not allowed by Standard Model
   - Note: One claim (in ^{76}Ge) by subgroup of Heidelberg-Moskow Collaboration

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



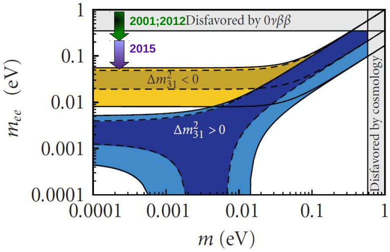
Motivations for $0\nu\beta\beta$ decay search

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

1. Is lepton number conservation violated? 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).

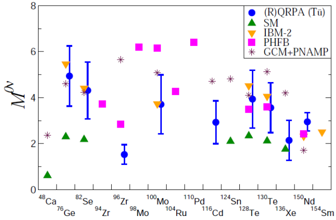
- Best limit in the past obtained by HdM (2001):
  $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr; $\langle m_{ee} \rangle \leq 0.35$ eV
- KKDC claim (2004):
  $T^{0\nu}_{1/2} = 1.17 \times 10^{25}$ yr; $\langle m_{ee} \rangle \sim (0.23\text{-}0.59)$ eV

$0\nu\beta\beta$ decay formalism

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:
    $\rightarrow$Most QRPA discrepancies solved
    $\rightarrow$Progress in understanding source of spread of NSM values
  - New methods IBM, EDF, pHFB
- $Q_{\beta\beta}$ values:
  $\rightarrow$ 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

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

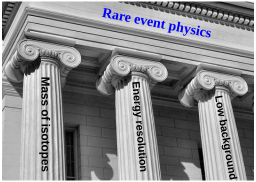
Progresses in experimental techniques

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 (oper./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}Te	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+(orig.)		44

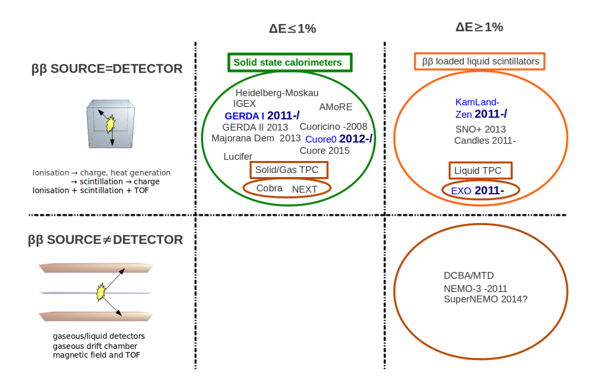


Request: Larger number of measurement with different isotopes

→ 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 $\lesssim$30% precision

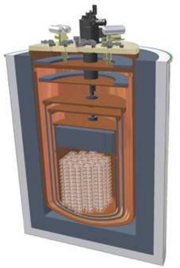
Isotopes and experimental techniques for $0\nu\beta\beta$ decay search

- Selected best isotope candidates: 8 out of 35 ($\leftarrow$ 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 $\rightarrow$ 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



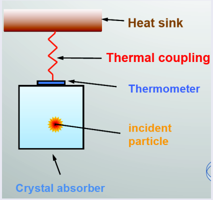
Location: LNGS, Assergi, Italy

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

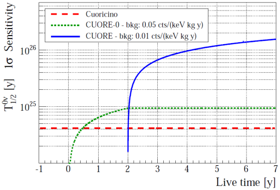


- TeO_2 absorbs energy deposition E by particle
- Energy deposition E registered by a thermistor (NTD Ge) as temperature increase:
  Signal: $\Delta T = E/C$, C: capacity
  Time constant $= C/G$; G: thermal coupling
  Need: → low-heat C → mK + diele.diamagn.mat.
- Very good energy resolution achievable: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

Status and sensitivity of Cuore-0/Cuore

Installation of Cuore-0

(spring/summer 2012)



- **Cuoricino** (2003—2008):
  - 12 kg 130Te
  - Main purpose: identify and disentangle backgrounds (cryostat, copper/crystal surfaces)
- **Cuore-0** (2012—2014):
  - Installation in cryostat completed, but cooling-down problems since May 2012
  - August 2012 first calibration, recently real data-acquisition started
  - 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** (2014—2019):
  - Crystals arrived at LNGS; first two towers should be glued in May 2013
  - 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

Concept: DBD source = Detector

Location: LNGS, Assergi, Italy

Setup and background shielding:

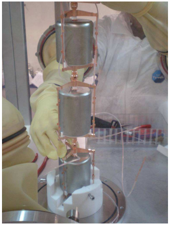
- 1.4 km overburden, corresponding 3500 m w.e.
  → Reduction of cosmic-muon flux by six orders of magn. down to $\sim 1\,\mu/(m^2 \cdot h)$ (PB)
- Water tank and plastic scintillator
  - R=5 m, h=9.0 m, 590 m^3 ultra-pure water
  → water acts as neutron moderator/absorber (PB)
  → both components act 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:
  - 1-string and 3-string arms with each 3 detectors (Phase I)
  - One 7-string arm (design for Phase II)
  - Accessible via a clean room (class 10000) (PB)
  - Operating bare diodes in LAr using low-mass holders (PB)
  → $0\nu\beta\beta$ source = Detector, enriched in ^{76}Ge
  - coincidence modus and pulse shape tracing (AB)

PB = passive background rejection
AB = active background rejection

Data acquisition and handling, and detector performance:

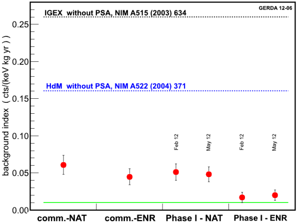
- Technology: Refurbished co-axial HPGe detectors, 6 ^{76}Ge enriched (HdM, IGEX) for ∼15 kg, 3 natural (GTF)
- Since July 2012: added 5 enriched Phase II BEGe prototype detectors for ∼3.5 kg
- Energy resolution of co-axial diodes: stable at 4.5-5.1 keV (FWHM) for 2614.5 keV
- Background index (BI)* for co-axial diodes: ∼0.02 cts/(keV·kg·yr)
  * BI:= $Q_{\beta\beta}$=2039 keV of ^{76}Ge ± 100 keV (minus 40 keV blinded region)
- Collected statistics: ∼19 kg·yr (March 2013) (lifetime ∼90%)
- Data blinding of $Q_{\beta\beta}$ region: automatic blinding of $Q_{\beta\beta}$ region applied since January 11, 2012;
  → Unblinding planned for summer 2013 !

String with co-axial HPGe diodes

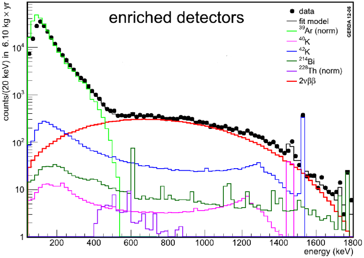


String with BEGe diodes

BI of Phase I co-axial detector



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



- **Fit region**: (600-1800) keV; May 2011-Nov 2012; only enriched detectors
- **Fit method**: binned maximum likelihood method with **free parameters**: ^{40}K, ^{42}K, ^{214}Bi, $T^{2\nu}_{1/2}$, active mass, enrichment
- **Background** is 'low': S/B∼8/1!
- **High ^{42}Ar background**, however, due to ion collection through E-field of diodes from applied HV.

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

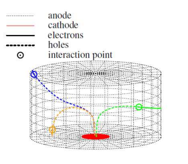
Preliminary GERDA result: $1.84^{+0.14}_{-0.10}$ (sys+stat)

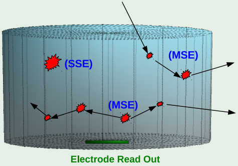
Comparison to previous measurements: superior signal-to-background ratio, trend towards higher $T^{2\nu}_{1/2}$, but in good agreement with the most recent results based on HdM data

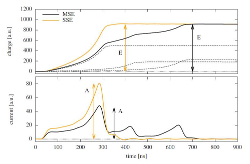
Upgrade to GERDA Phase II (planned start within 2013)

Assembly of new detectors:

- Novel technology: 25 ^{76}Ge enriched BEGe detectors for ∼17 kg:
  → Better sensitivity due to: increased target mass, better energy resolution, and enhanced pulse shape discrimination of **M**ulti-**S**ite background **E**vents ($0\nu\beta\beta$ events are **S**ingle-**S**ite **E**vents)

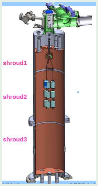


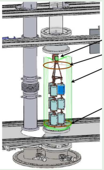




Scintillation light instrumentation:

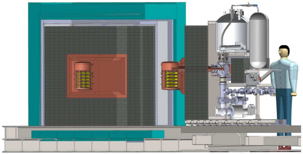
- Technique: Background rejection of external background events via detection of scintillation light in liquid argon (λ=128 nm)
- Options for read-out: PMT, Wavelength-shifter glass-fibre, large area avalanche photodiodes or UV sensitive SiPMs
- Envisioned BI (BEGe + Light instr): $\leq$0.001 cts/(keV·kg·yr)





The Majorana Demonstrator

Concept: DBD source = Detector



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

Detector setup and performance:

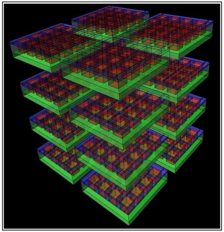
- P-Type point contact Ge detectors (also low noise, e-threshold below 1 keV → suitable for low-mass WIMP detection)
- 40 kg (out of them 30 kg enriched in ^{76}Ge) germanium diodes in a large volume vacuum crystat within ultra-low background shield made of ultrapure electro-formed copper and lead.
- Full commissioning in 2013: after 1 year: $T_{1/2} > 4 \times 10^{25}$ yr, address KKDC $0\nu\beta\beta$ observation claim

GERDA-Majorana cooperation:

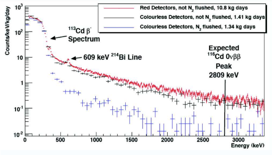
- Open exchange of knowledge and technologies
- Joint constant development of the Geant4-based simulation tool MaGe
- Common intention for 1-ton experiment; goal sensitivity: $\langle m_{\beta\beta} \rangle$: 0.04-0.12 meV (IH region)

The COBRA R&D project

Concept: DBD source = Detector

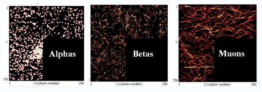


Location: LNGS, Assergi, Italy



Solid state TPC

- Large Array of CdZnTe semicond. detectors for 420 kg
  Goal sensitivity: $T_{1/2} > 10^{26}$ yr ($\langle m_{\beta\beta} \rangle$50 meV)
- Containing: 5 $0\nu\beta^-\beta^-$, and 4 EC/β^+, EC/EC candidates
  Best candidate: ^{116}Cd: $Q_{\beta\beta}$=2809 keV; $\rightarrow$ enrichment
- Two modular designs (both oper. 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

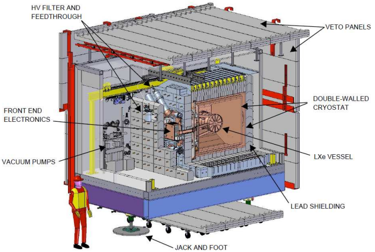


Status:

- MC/test for shield options: multi-layer, liq. scint., water
- Technical design report: expected within 2013
- $2\nu\beta\beta$: 6 $T_{1/2}$ limits $> 10^{20}$ yr, 7 new upper limits
- $0\nu\beta\beta$: achieved background for:
  Colorless passivated CPG at ^{116}Cd ROI: 5 cts/(keV·kg·yr)
  Large Volume PD in 2700-3000 keV: 0.9 cts/(keV·kg·yr)

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.

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Location:  WIPP lab, Carlsbad, NM, USA
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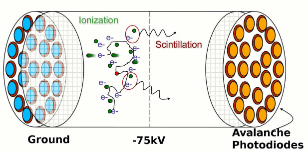
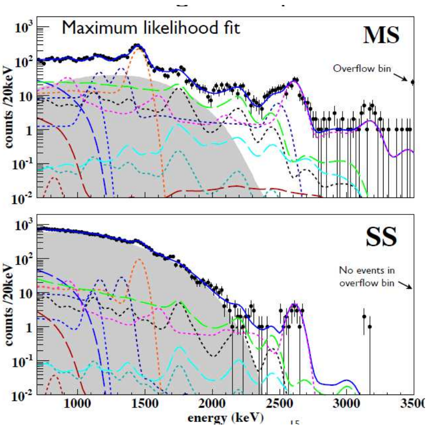
Detection principle

- 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:
    $\rightarrow$ Position reconstruction res.: X,Y: 18 mm; Z: 6 mm
    $\rightarrow$ Distinguish single $\beta/\beta\beta$'s from multiple γ-ray clusters:
  - Ionisation vs. Scintillation:
    $\rightarrow$ Discrimination of α from $\beta/\beta\beta/\gamma$
    $\rightarrow$ Improve energy resolution down to 1.67%

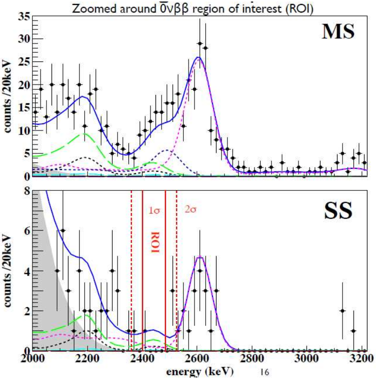
Measurement of $2\nu\beta\beta$ half-life of ^{136}Xe

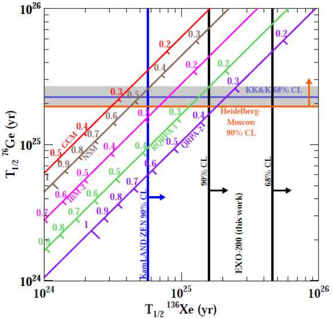


- Rejection of peripheral background by Fiducial Volume cut:
  $\rightarrow$ Active mass of 98.5 kg of LXe (^{136}Xe: 79.4 kg)
  $\rightarrow$ LXe exposure after 120.7 d: 32.5 kg·yr
- SSE $2\nu\beta\beta$ spectrum:
  $\rightarrow$ spectrum contains $\sim$22000 $2\nu\beta\beta$ events above 0.7 MeV
 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

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

EXO-200 (May 2012): 2.23$\pm$0.02$\pm$0.22 (stat+sys) arXiv:1205.5608
Agrees with KamLAND-Zen (May 2012): 2.30$\pm$0.02$\pm$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)



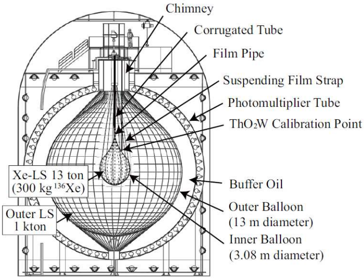


$0\nu\beta\beta$ results after 120 d with 98.5 kg of LXe (May 2012):

- 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 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

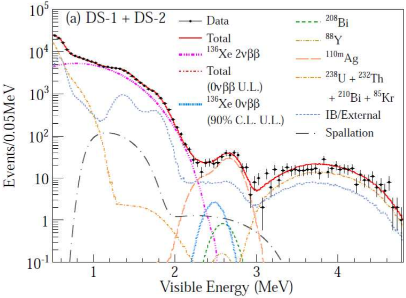
Inner balloon (R=1.54 m, 25 μm thick)

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

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



- Fit region: [0.5;4.8] MeV; includes 82% of the $2\nu\beta\beta$ spectrum
- Data-sets and $2\nu\beta\beta$ rate (February 2013: arXiv:1211.3863v2[hep-ex]):
  - DS-1: October 12, 2011 - filtration: → 82.9±1.1(stat)±3.4(syst) cts/(d·ton)
  - Filtration (February 2012): PTFE-based 50 nm filter; 2.3 full-volume exchange
  - DS-2: filtration - June 14, 2012: → 80.2±1.8(stat)±3.3(syst) cts/(d·ton
- Exposure for ^{136}Xe alone (both data-sets together: 89.5 kg·yr)

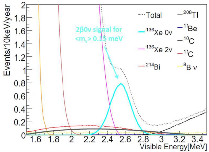
KamLAND-Zen $2\nu\beta\beta$ half-life result (May 2012):

$2\nu\beta\beta$ rate = (80.9±0.7) cts/(d·ton)

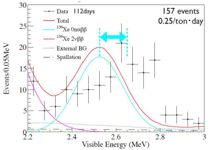
$T^{2\nu}_{1/2}$ = 2.30±0.02±0.12 (stat+sys)×10^{21} yr (arXiv:1205.6372)

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

Expected spectrum

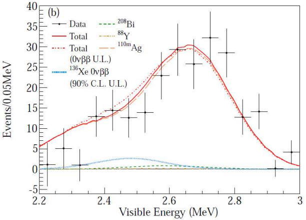


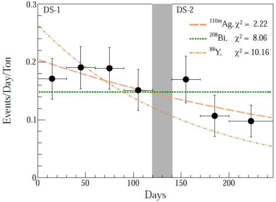
Meas. spec. (May 2012)



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



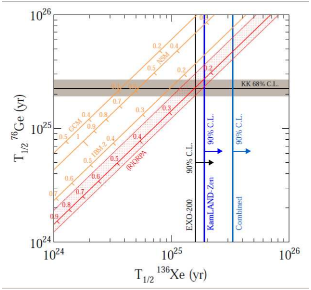


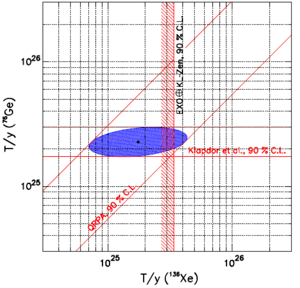
$T^{0\nu}_{1/2}$ result (February 2013)

$T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr
(EXO-200 result from 2012 ($\langle m_{\beta\beta}\rangle < 0.14$-$0.38$ eV (90% C.L.)) slightly improved)

- Purification ongoing: in late 2012 Xe removed from scintillator, LS being distilled, IB replacement
  → Expected 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 ?

Combined results from the 136Xe experiments





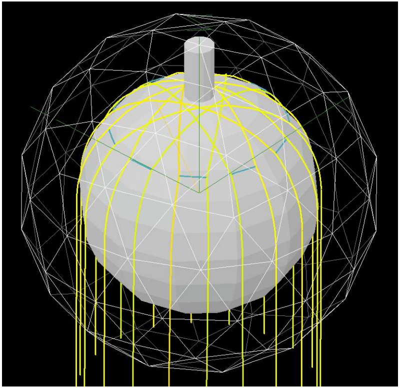
- Combination of the recent negative results from KamLAND-Zen and EXO-200 (arXiv:1211.3863v2 [hep-ex]):
  $T^{0\nu}_{1/2}$ >3.4×10^{25} yr, $\langle m_{\beta\beta}\rangle$ <0.12-0.25 eV at 90%C.L.
  → refutes the $0\nu\beta\beta$ detection claim in ^{76}Ge at >97.5% C.L. (for all NME, assuming light Majorana exchange mechanism)
- Some remarks about this result:
  - From QRPA calc.: $T_{1/2}(^{136}\text{Xe})$~3.4-4.3×10^{25} y needed for 90% C.L. to rule out ^{76}Ge claim ; however, some issues concerning the likelihood/χ^2 functions non-available from experiments (A. Faessler et al., arXiv:1301.1587v1 [hep-ph])
  - Some issues concerning the 1.(4σ) and 2.(6σ) ^{76}Ge KKDC claim (B. Schwingenheuer, arXiv:1210.7432 [hep-ex])

→ '...not yet the end of the story'

SNO+: a multipurpose experiment

SNO+ 'recycles' upgraded SNO infrastructure

filled with Te-loaded LS

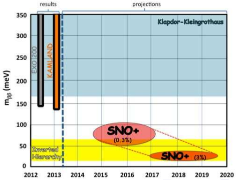


Location: Sudbury, Ontario, Canada

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 pursue ^{130}Te as prim. target isotope
  - ~0.3% of nat. Te (% ^{130}Te (800 kg)

  → $\langle m_e ff \rangle$=50 meV (after ~3 yr)
- Phase II: ~3% of nat. Te → $\langle m_e ff \rangle$=15 meV (full IH)



$0\nu\beta\beta$ search: Summary and some conclusions

Current Status

- In 2012/2013, after a dedade of R&D, we will have/have first results from several new generation $0\nu\beta\beta$ experiments: EXO-200, KamLAND-Zen, GERDA. Their sensitivies will are/will be similar/better than the best former experiment: HdM
- In the next years, other experiments using different techniques and $\beta\beta$ isotopes will become operational
- A lot of progresses in calculating the $0\nu\beta\beta$ nuclear processes were achieved

Outlook: Possible scenarios

- **If range $\langle m_{\beta\beta}\rangle$=0.1-0.5 eV holds (if KK claim confirmed):**
  → EXO-200, KamLAND-Zen (^{136}Xe) and GERDA (^{76}Ge) should observe the signal
  → Other experiments that will be finalized in the next years will observed the $0\nu\beta\beta$ decay in other isotopes (SNO+ PhaseI and Cuore in ^{130}Te,...)
  → Precision-experiments (SuperNEMO-type) have to follow (to improve NME and understand exchange mechanisms→SuperNEMO-type detectors)

- **If range $\langle m_{\beta\beta}\rangle$=0.02-0.05 eV holds:**
  → Necessity for large scale enrichment and lower background reduction
  → Possible experiments: nEXO, Gerda Phase III and Majorana, Cuore marginally, KamLand-Zen(2),...
  → Discovery in 3-4 isotopes necessary to confirm the observation and to improve the calculations of nuclear processes

2013+ will be exciting years for Lepton Number violating $\beta\beta$ decay search!