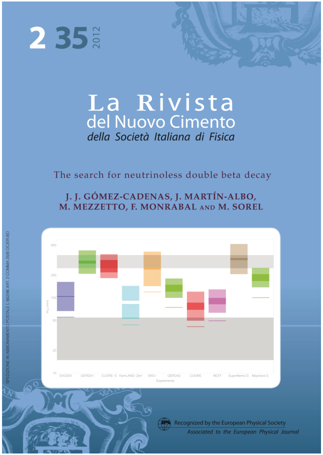
Mauro Mezzetto
Istituto Nazionale di Fisica Nucleare, Sezione di Padova

“ The next round of double beta decay experiments”

To which level will the several experiments starting this year push the sensitivity to double beta decays?



Introduction

An experiment detecting a $\beta\beta$0nu signal would:

- Discover a new type of spinor of the the standard model Lagrangian: Majorana nature of neutrinos.
- Non conservation of the Leptonic Number
- Measure of absolute ν mass
- Determine the neutrino mass hierarchy ONLY if the measured mass falls below the inverted mass limit
- Open new mechanisms for CP violation in the leptonic sector and possibly provide indications about the Majorana CP phases

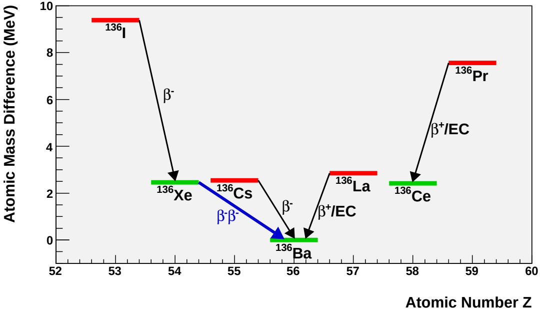
An experiment reporting a null result:

- Determine the Dirac nature of neutrinos ONLY if the sensitivity is below the inverted hierarchy region AND some external experiment has determined that the hierarchy is inverted

It is evident that the target mass scale sensitivity for double beta decay experiments is the inverted region mass scale: $15 - 50$ meV.

$\beta\beta 2\nu$ decays

$$(Z, A) \to (Z + 2, A) + 2\ e^- + 2\ \overline{\nu}_e,$$



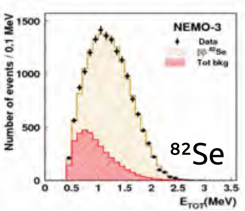
Atomic masses of $A = 136$ isotopes. The red (green) levels indicate odd-odd (even-even) nuclei. The arrows β^-, β^+, $\beta^-\beta^-$ indicate nuclear decays accompanied by electron, positron and double electron emission, respectively. The arrows EC indicate electron capture transitions.

- First considered by Maria Goeppert-Mayer in 1935
- First detected in 1950 using geochemical techniques
- First direct observation in $^{82}\mathrm{Se}$, using a TPC in 1987.

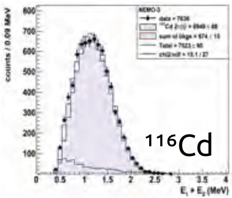
Current best direct measurements of $\beta\beta2\nu$ decays

See A.R. Barabash Phys.Rev. C81 (2010) 035501

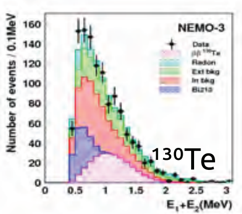
Isotope	$T^{2\nu}_{1/2}$ (year)	Experiments
^{48}Ca	$(4.4^{+0.6}_{-0.5}) \times 10^{19}$	Irvine TPC, TGV, NEMO3
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	PNL-USC-ITEP-YPI, IGEX, H-M
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	NEMO3, Irvine TPC, NEMO2
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	NEMO2, NEMO3
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$	NEMO3, NEMO-2, Irvine TPC
^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$	NEMO3, ELEGANT, Solotvina, NEMO2
^{130}Te	$(6.8^{+1.2}_{-1.1}) \times 10^{20}$	CUORICINO, NEMO3
^{136}Xe	$(2.11 \pm 0.21) \times 10^{21}$	EXO-200, Kamland-Zen
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$	Irvine TPC, NEMO3



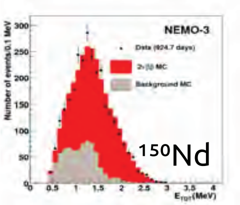
9.6 ± 0.1 (stat) ± 1.0 (sys) x 10^{19} y
[preliminary result]



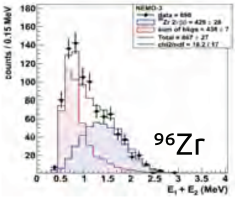
2.88 ± 0.04 (stat) ± 0.16 (sys) x 10^{19}
[preliminary result]



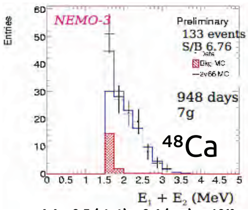
7.0 ± 0.9 (stat) ± 1.1 (sys) x 10^{20} y
[Phys. Rev. Lett. 107, 062504 (2011)]



9.11 ± 0.25 (stat) ± 0.63 (sys) x 10^{18} y
[Phys. Rev. C 80, 032501 (2009)]



2.35 ± 0.14 (stat) ± 0.16 (sys) x 10^{19} y
[Nucl. Phys. A 847 (2010)]

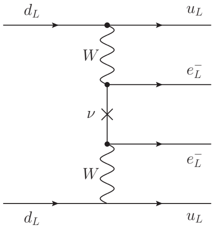


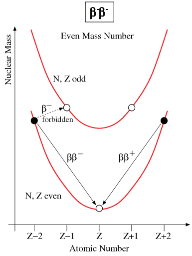
4.4 ± 0.5 (stat) ± 0.4 (sys) x 10^{19} y
[preliminary result]

World best catalogue of $\beta\beta2\nu$ half-lifes **first direct detection for ^{130}Te**

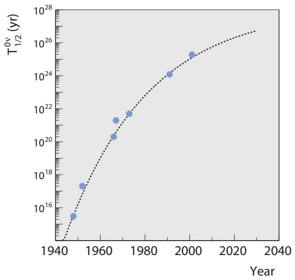
$\beta\beta0\nu$ decays

$$(Z, A) \rightarrow (Z+2, A) + 2\ e^-$$



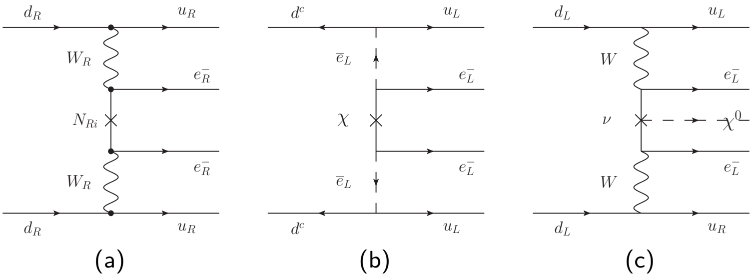


- Key test originally proposed by G. Racah (1937): $n \rightarrow p + e^- + \overline{\nu} \rightarrow (\overline{\nu} = \nu) + n \rightarrow p + e^- + p + e^-$
- $\beta\beta0\nu$ first proposed by W.H. Furry in 1939.
- $\sim$ 65 years of experimental limits. First experimental limit in 1948 by E.L.Fireman, Phys.Rev. 74, 1238 (1948): geiger tubes detecting $Sn^{124} \rightarrow Te^{124}$ with a limit of $T_{1/2} \geq 3 \cdot 10^{15}$ yr (in 1949 the same experiment reported a positive result . . .).



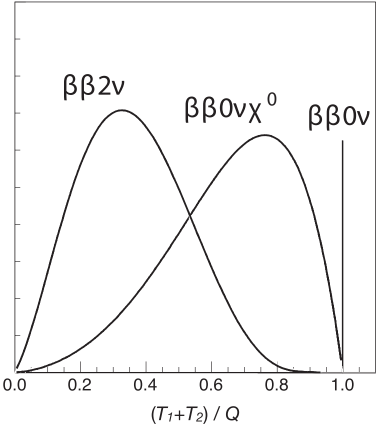
Alternative mechanisms for $\beta\beta0\nu$ decays

See W. Rodejohann: Int.J.Mod.Phys. E20 (2011) 1833-1930



- a) The Lorentz structure of the currents. Positive chirality currents mediated by a W_R boson can arise, for example, in left-right symmetric theories.
- b) The mass scale of the exchanged virtual particles. One example would be the presence of "sterile" neutrinos, either light or heavy, in the neutrino propagator, in addition to the three light, active, neutrinos. Another example would be the exchange of heavy supersymmetric particles.
- c) The number of particles in the final state. A popular example involves decay modes where additional Majorons, that is very light or massless particles which can couple to neutrinos, are produced in association with the two electrons.

Discrimination among different mechanisms



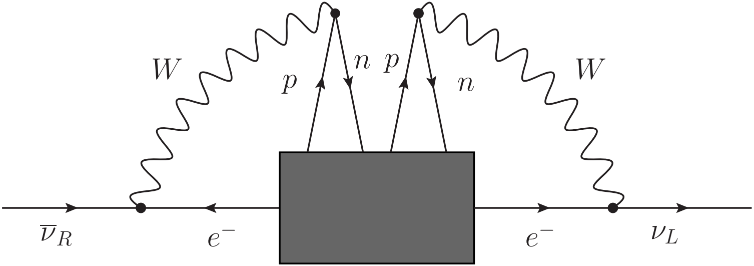
Spectra for the sum kinetic energy $T_1 + T_2$ of the two electrons, for different $\beta\beta$ modes: $\beta\beta 2\nu$, $\beta\beta 0\nu$, and $\beta\beta$ decay with Majoron emission.

1. Other observables (LHC, LFV, Katrin, cosmology,. . .)
2. Final state behaviour (e^- energies, angular correlations, spectrum,. . .)
3. Nuclear physics (multi-isotope, 0νECEC, $0\nu\beta^+\beta^+$,. . .)

From now on concentrate on Majorana neutrinos only.

The black box theorem

Schechter J. and Valle J. W. F., Phys. Rev. D, 25 (1982) 2951.



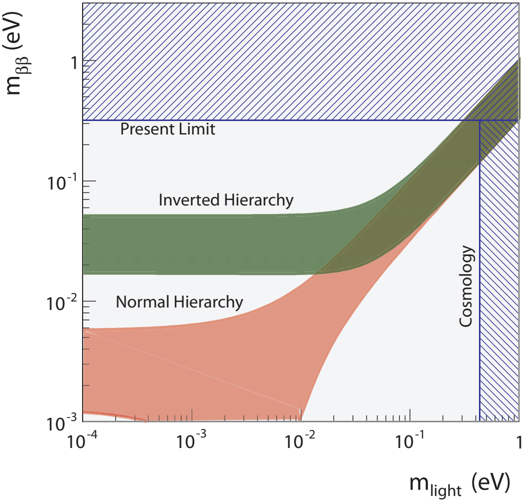
Whatever the mechanism, $\beta\beta0\nu$induces an effective Majorana mass term.

$\beta\beta0\nu$ and neutrino oscillations

$$m_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right| = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i\beta}|$$

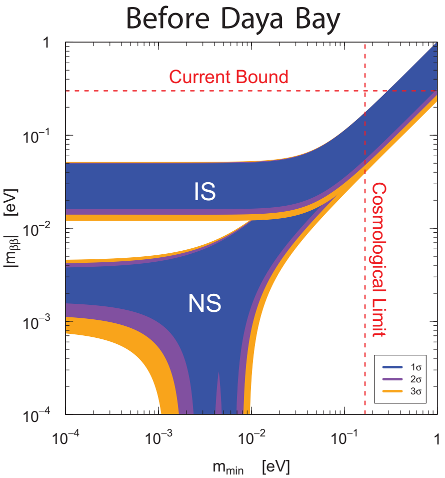
First proposed in
Vissani F., JHEP, 9906 (1999) 022,
see also Dueck, Rodejohann, Zuber,
Phys.Rev. D83 (2011) 113010

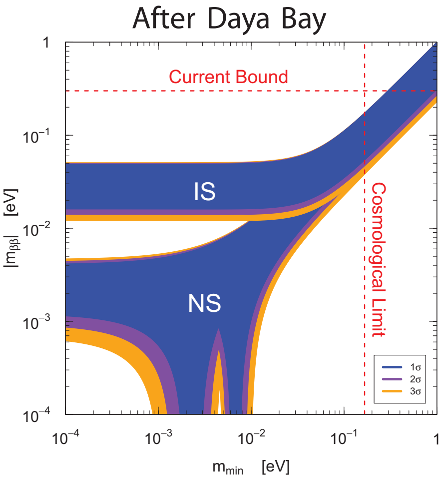
1. Uncertainties in the measured oscillation parameters;
2. Unknown neutrino mass ordering (normal or inverted);
3. Unknown phases in the neutrino mixing matrix (both Dirac and Majorana).



The effect of θ_{13}

From Bilenky, Giunti, arXiv:1203.5250





Existing experimental results

Isotope	$T^{0\nu}_{1/2}$ (years)	Experiment
^{48}Ca	$> 5.8 \times 10^{22}$	ELEGANT (2008)
^{76}Ge	$> 1.9 \times 10^{25}$	Heidelberg-Moscow (2000)
^{82}Se	$> 3.6 \times 10^{23}$	NEMO3 (2010)
^{96}Zr	$> 9.2 \times 10^{21}$	NEMO3 (2009)
^{100}Mo	$> 1.1 \times 10^{24}$	NEMO3 (2010)
^{116}Cd	$> 1.7 \times 10^{23}$	Solotvina (2003)
^{130}Te	$> 2.8 \times 10^{24}$	CUORICINO (2010)
^{136}Xe	$> 4.5 \times 10^{23}$	DAMA (2002)
^{150}Nd	$> 1.8 \times 10^{22}$	NEMO3 (2008)

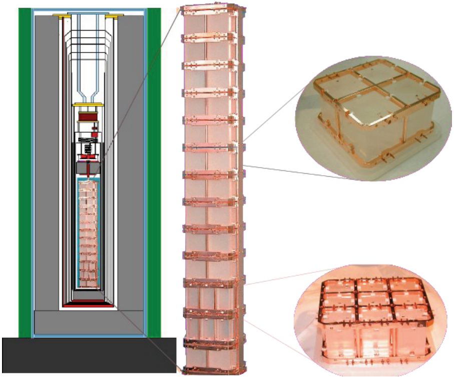
Current best limits on the half-life of $\beta\beta 0\nu$ processes for the most interesting isotopes. All values are at 90% CL.

Cuoricino Ref.[8]

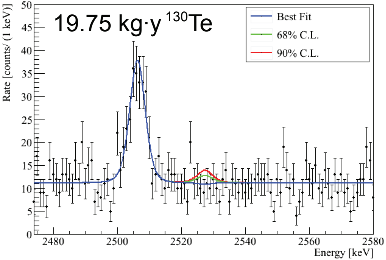
@LNGS 2003-2008

TeO_2 bolometric detector - with natural Te - 11.34 kg **^{130}Te** (34.167% i.a.)

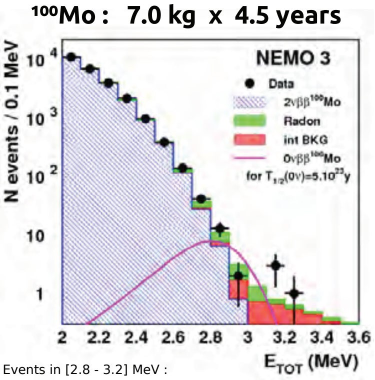
$N_{\beta\beta}$= 5.2x10^{25} ε ~ 87% ΔE/E (FWHM) ~ 0.24% Bkg ~ 0.17 c/keV/kg/y



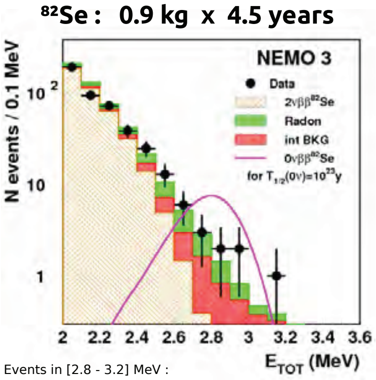
$T_{1/2}^{0\nu}$ > 2.8 x 10^{24} y @90%CL
$<m_{ee}>$ < 0.30 ÷ 0.71 meV [1-4]



$T_{1/2}^{0\nu}$ limit for decay on first 0^+ ^{130}Xe excited state also reported in Ref.[15]



Events in [2.8 - 3.2] MeV :
DATA = 18 Total MC = 16.4 ± 1.4



Events in [2.8 - 3.2] MeV :
DATA = 14 Total MC = 10.9 ± 1.3

$T_{1/2}^{\beta\beta0\nu} > 1.0 \times 10^{24}$ years (90 % CL)
$m_{\beta\beta} < 310 - 960$ meV

$T_{1/2}^{\beta\beta0\nu} > 3.2 \times 10^{23}$ years (90 % CL)
$m_{\beta\beta} < 940 - 2600$ meV

NME		
	QRPA	Kortelainen and Suhonen, Phys. Rev. C75 051303 (2007)
	QRPA	Simkovic et al., Phys. Rev. C77 045503 (2008)
	PHFB	Rath et al., Phys. Rev. C82 064310 (2010)
	QRPA	Kortelainen and Suhonen, Phys. Rev. C76 024315 (2007)
	IBM2	Barea and Iachello, Phys. Rev. C79 044301 (2009)
	SM	Caurrier at al., Phys. Rev. Lett. 100 052503 (2008)

Heidelberg-Moscow Experiment

@LNGS 1990-2003

5 p-type **HPGe detectors** - 86% enriched in ^{76}Ge – 11 kg ^{76}**Ge**

$N_{\beta\beta}$= **8.7x10^{25}** **ε ~ 80%** **ΔE/E (FWHM) ~ 0.15%** **Bkg ~ 0.11 c/keV/kg/y**

2001- whole collaboration [6]:

no 0νββ peak evidence
35.5 kg·y with PSA

$T^{0\nu}_{1/2}$ **> 1.9 x 10^{25} y @90% CL**

$<m_{ee}>$ < 0.22 ÷ 0.64 meV [1-4]

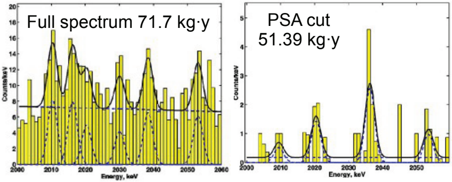
Part of the collaboration:

2001 [13]: **First claim for evidence at 2.2σ** with 54.98 kg·y statistics

2004 [12]: **Claim for evidence at 4.2σ** Added new statistics: 71.7 kg·y Bkg = 0.11 ± 0.01 c/keV/kg/y

2006 [11]: **Claim for evidence at > 6σ** New PSA methods partial statistics: 51.39 kg·y

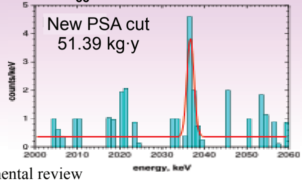
2004: Claim at 4.2 σ



2006: Claim at > 6 σ

$T^{0\nu}_{1/2}$ **≈ 2.2 x 10^{25} y**

$<m_{ee}>$ = 0.32 ± 0.03 eV



From half-lives to neutrino masses

$$[T_{1/2}^{0\nu}]^{-1} = \sum_{\text{spins}} \int |Z_{0\nu}|^2 \delta(E_{e1} + E_{e2} + E_f - M_i) \frac{d^3 p_1}{2\pi^3} \frac{d^3 p_2}{2\pi^3} \ .$$

$E_{1(2)}$ and $\vec{p}_{1(2)}$: total energies and momenta of the electrons
$E_f(M_i)$: energy of the final (mass of the initial) nuclear state
$Z_{0\nu}$: reaction amplitude, second order in the weak interaction (second order in G_F)
Leptonic part of the reaction amplitude:

$$-\frac{i}{4} \int \sum_k \frac{d^4 q}{(2\pi)^4} e^{-iq\cdot(x-y)} \overline{e}(x) \gamma_\mu (1-\gamma_5) \frac{q^\rho \gamma_\rho + m_k}{q^2 - m_k^2} (1-\gamma_5) \gamma_\nu e^c(y) \ U_{ek}^2 \ ,$$

Hadronic part of the reaction amplitude (impulse approximation: free nucleons):

$$J^{\rho\dagger} = \overline{\Psi} \tau^+ \left[g_V(q^2) \gamma^\rho - g_A(q^2) \gamma^\rho \gamma_5 - g_P(q^2) q^\rho \gamma_5 \right] \Psi \ ,$$

As first derived in: Doi M., Kotani T. and Takasugi E., Prog. Theor. Phys. Suppl., 83 (1985) 1

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q, Z) \ \left| M^{0\nu} \right|^2 \ m_{\beta\beta}^2 \ ,$$

$Q = M_i - E_f$, $G^{0\nu}(Q,Z)$ comes from the phase-space integral, nuclear matrix element:

$$M^{0\nu} \simeq \left(\frac{g_A}{1.25}\right)^2 \left(M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F\right)$$

with, to first order:

$$M^{0\nu}_F = \langle f | \sum_{a,b} H(r) \tau_a^+ \tau_b^+ | i \rangle$$

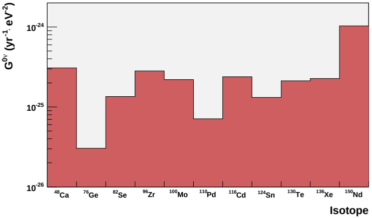
$$M^{0\nu}_{GT} = \langle f | \sum_{a,b} H(r) \vec{\sigma}_a \cdot \vec{\sigma}_b \tau_a^+ \tau_b^+ | i \rangle \ .$$

Phase Space Factor

$$G^{0\nu}(Q,Z) = (G_F V_{ud} g_A)^4 \left(\frac{1}{R}\right)^2 \frac{1}{\ln(2) 32\pi^5} \cdot \left(\int F(Z,E_{e1})F(Z,E_{e2}) p_{e1} p_{e2} E_{e1} E_{e2} \delta(E_0 - E_{e1} - E_{e2}) dE_{e1} dE_{e2} \right) .$$

$E_0 = Q + 2m_e = M_i - M_f$: available energy, p_{e1} (p_{e2}): electron 3-momenta, $F(Z,E)$ Fermi function for the nuclear Coulomb effect on the outgoing electrons, Z is the charge of the daughter nucleus.

$\beta\beta0\nu$ involves all multipolarities in the intermediate odd-odd $(A, Z+1)$ nucleus, and contains both a Fermi (F) and a Gamov-Teller (GT) part.
$\beta\beta2\nu$, involves only Gamov-Teller transitions through intermediate 1^+ states (because of low momentum transfer)
Phase space of $\beta\beta0\nu$ mode $\propto E_0^5$, $\beta\beta2\nu \propto E_0^{11}$



See Pantis G., Simkovic F., Vergados J. D. and Faessler A., Phys. Rev.C, 53 (1996) 695; Phys. Rev.C, 60 (1999) 055502

Nuclear Matrix Elements (NMEs)

Interacting Shell Model (ISM) The nucleons are moving independently in a mean field with a strongly attractive spin-orbit term.

$$U(r) = \frac{1}{2}\,\hbar\omega\, r^2 + D\,\vec{l}^{\,2} + C\,\vec{l}\cdot\vec{s}.$$

the harmonic oscillator (plus the surface correction $D\,\vec{l}^{\,2}$) part describes the bound nucleons

the spin-orbit part is added to give the proper separation of the subshells and explain the nuclear magic numbers

Residual two-body nucleon interaction among nucleons are added when the number of protons and neutrons depart from the magic numbers. As the number of valence nucleons increases, the direct application of the shell model becomes prohibitively difficult, and some approximation is needed

First, one usually assumes that the closed shells are inert. Second, one assumes that the important particle configurations in even-even nuclei are those in which identical particles are paired together in states with total angular momentum and parity $J^P = 0^+$ or $J^P = 2^+$. Third, one treats the pairs as bosons, much in the same way as Cooper pairs in a gas of electrons.

Conceptually simple, but complicated in practice. The problem is reduced to diagonalizing a matrix in a sufficiently large basis ("valence space"). A limited valence space is used but all configuration of valence nucleons are included.

NMEs (II)

The Quasiparticle Random Phase Approximation (QRPA): The most important part of the residual interaction among nucleons is the *pairing force*. The pairing force accounts for the tendency of nucleons to couple pairwise to especially stable configurations, *i.e.* into nuclei with even N, even Z. This force favors the coupling of neutrons with neutrons, and protons with protons, so that the orbital angular momentum and spin of each couple adds to zero. As the result of the pairing force, the nuclear ground state is mainly composed of Cooper-like pairs of neutrons and protons coupled to $J^\pi = 0^+$ total angular momentum. In QRPA, the nucleon pairing is introduced via the *BCS theory* of superconductivity.

NMEs (III)

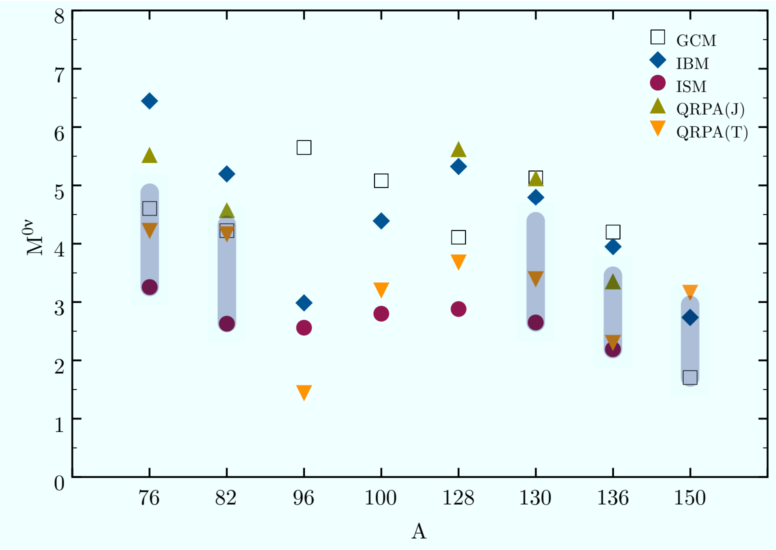
Generating Coordinate Method (GCM) Each nucleon has the tendency to align its orbit with the average field produced by all other nucleons. This preferentially gives rise to nuclei with deformed equilibrium shapes and collective rotational motion. A common representation of the shape of these nuclei is that of an ellipsoid.

Interacting Boson Model (IBM) A somewhat intermediate path between the "microscopic" view of nuclear structure (ISM) and the "collective" views (QRPA, GCM) mentioned above was opened by the *Interacting Boson Model*, IBM. In the interacting boson model, collective excitations of nuclei are described by bosons, and the microscopic foundation of such collective nuclear states is rooted in the shell model. As the number of valence nucleons increases, the direct application of the shell model becomes prohibitively difficult, and some approximation is needed. First, one usually assumes that the closed shells are inert. Second, one assumes that the important particle configurations in even-even nuclei are those in which identical particles are paired together in states with total angular momentum and parity $J^P = 0^+$ or $J^P = 2^+$. Third, one treats the pairs as bosons, much in the same way as Cooper pairs in a gas of electrons.

The physics motivated range (PMR)

Gomez-Cadenas J., Martin-Albo J., Sorel M., Ferrario P., Monrabal F. et al., JCAP, 1106 (2011) 007

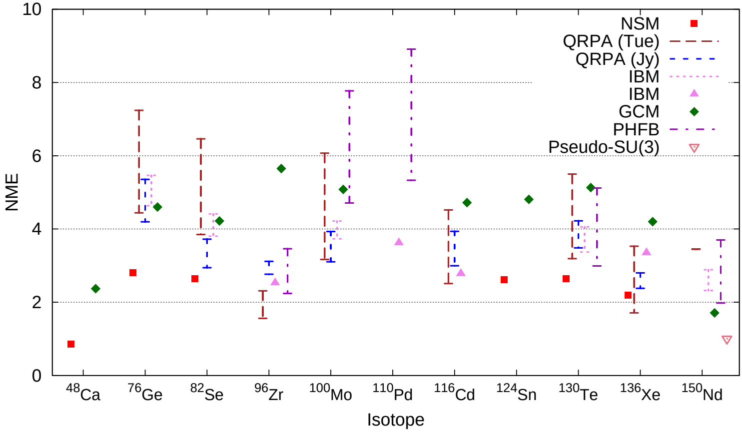
- The clear advantage of the ISM calculations is their full treatment of the nuclear correlations, while their drawback is that they may underestimate the NMEs due to the limited number of orbits in the affordable valence spaces. It has been estimated (Blennow M., Fernandez-Martinez E., Lopez-Pavon J. and Menendez J., JHEP, 07 (2010) 096,) that the effect can be of the order of 25%.
- The QRPA variants, the GCM in its present form, and the IBM are bound to underestimate the multipole correlations in one or another way. As it is well established that these correlations tend to diminish the NMEs, these methods should tend to overestimate them (Caurier E., Menendez J., Nowacki F. and Poves A., Phys. Rev. Lett., 100 (2008) 052503, Menendez J., Poves A., Caurier E. and Nowacki F., J. Phys. Conf. Ser., 267 (2011) 012058)



UCOM short range correlations. $g_A = 1.25$; the IBM-2 results are multiplied by 1.18 to account for the difference between Jastrow and UCOM, and the RQRPA are multiplied by 1.1/1.2 so as to line them up with the others in their choice of $r_0 = 1.2$ fm. The shaded intervals correspond to the proposed physics-motivated ranges.

Summarizing the NMEs (another way)

From Dueck, Rodejohann, Zuber, Phys.Rev. D83 (2011) 113010
Rescale different NMEs using common parameters: $g_A = 1.25$ and $r_0 = 1.2$ fm.



Experimental ingredients

$$N_{\beta\beta0\nu} = \log 2 \cdot \frac{M_{\beta\beta} \cdot N_A}{W_{\beta\beta}} \cdot \varepsilon \cdot \frac{t}{T^{0\nu}_{1/2}},$$

$M_{\beta\beta}$ mass of the $\beta\beta$ emitting isotope, N_A: Avogadro constant, $W_{\beta\beta}$: molar mass of the $\beta\beta$ isotope, ε: signal detection efficiency

$$M_{\beta\beta} = W_{\beta\beta} \cdot \frac{M}{W} \cdot a \cdot \eta$$

W: molecular weight of the molecule of the active material, a: isotopic abundance of the candidate $\beta\beta0\nu$ nuclide, η: the number of $\beta\beta0\nu$ element nuclei per molecule of the active mass.

For example, TeO_2 bolometric detectors with a natural isotopic abundance in $^{130}\mathrm{Te}$ are characterized by $W_{\beta\beta} = 129.9~\mathrm{g/mol}$, $W = 159.6~\mathrm{g/mol}$, $a = 0.34167$ and $\eta = 1$, such that $M_{\beta\beta} = 0.278M$.

- $kg_{\beta\beta}$ as the mass unit to indicate one kilogram of $\beta\beta$ emitter mass (note that this is different from usual conventions).
- In principle the best quantity to express the $\beta\beta0\nu$ exposure, is neither kg·year nor $kg_{\beta\beta}$·year, but rather $n_{\beta\beta}$·year, where $n_{\beta\beta} = M_{\beta\beta} \cdot N_A / W_{\beta\beta}$ is the number of moles of the $\beta\beta$ nuclide. The reason is that 1 $kg_{\beta\beta}$ of, say, $^{76}\mathrm{Ge}$ contains almost twice as many $\beta\beta$ nuclides as 1 $kg_{\beta\beta}$ of $^{150}\mathrm{Nd}$.

The $\beta\beta0\nu$ killer: backgrounds

A background free experiment will report an upper limit in the $\beta\beta0\nu$ decay rate $(T^{0\nu}_{1/2})^{-1}$, or possibly in the more relevant physical parameter $m_{\beta\beta}$

$$m_{\beta\beta} = K_1 \sqrt{\frac{1}{\varepsilon \cdot M_{\beta\beta} \cdot t}}$$

Where K_1 is a constant that depends only on the isotope type, and on the details of the statistical method (and the confidence level) chosen to report such limit.
An experiment with background, assuming the sensitivity as a function of the background rate $\mathcal{S}(b) \propto \sqrt{b}$:

$$m_{\beta\beta} = K_2 \sqrt{\frac{b^{1/2}}{\varepsilon \cdot M_{\beta\beta} \cdot t}}$$

If the background b is proportional to the exposure $M_{\beta\beta} \cdot t$ and to an energy window ΔE around $Q_{\beta\beta}$:

$$b = c \cdot M_{\beta\beta} \cdot t \cdot \Delta E$$

with the background rate c expressed in counts/(keV · kg · year), then:

$$m_{\beta\beta} = K_2 \sqrt{1/\varepsilon} \left(\frac{c \cdot \Delta E}{M_{\beta\beta} \cdot t}\right)^{1/4}$$

Backgrounds limit dramatically the sensitivity of a double beta decay experiment, which improves only as $(M_{\beta\beta} \cdot t)^{-1/4}$ instead of the $(M_{\beta\beta} \cdot t)^{-1/2}$ expected in the background-free case.

Some consideration

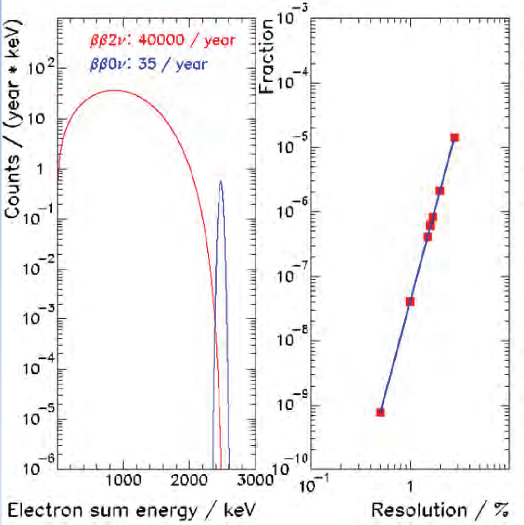
- To improve by one order of magnitude the sensitivity, in presence of backgrounds, the active mass should be improved by 4 (four) order of magnitudes ...
- For a given background level b, the background rate c will in general depend on the choice of the energy window ΔE. This is the case if the background energy spectrum around $Q_{\beta\beta}$ is not flat.
- For each experiment, define a ROI (Region Of Interest) centered at the $\beta\beta$ decay Q-value and extending for one FWHM of energy resolution, computing the experimental sensitivity at 90% confidence level. The effect of the FWHM selection (corresponding to 76% efficiency assuming gaussian resolution) is taken as a multiplicative factor to the experimental efficiency.
- $\beta\beta 2\nu$ is an irreducible background that can be limited only by ΔE.
- The background rate c will in general depend on $M_{\beta\beta}$ or better from the total mass of the target.
- Statistics: full Feldman-Cousins treatment, see Gomez-Cadenas J., Martin-Albo J., Sorel M., Ferrario P., Monrabal F. et al., JCAP, 1106 (2011) 007.

Distinguishing ^{136}Xe decay channels

Only by electron energy sum.

On the left: experimental limit on 2νββ rate + 0νββ claim with 1.5% energy resolution.

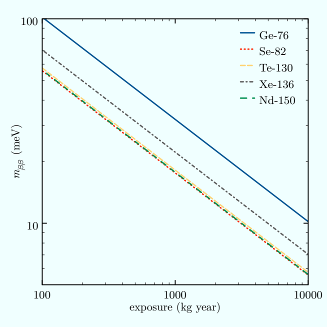
On the right: leakage of 2νββ events into the 0νββ peak increases with resolution to the 6th power!



Choice of the $\beta\beta$ isotope

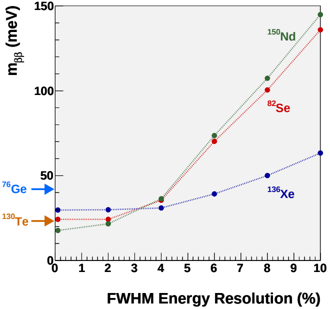
In nature, 35 naturally-occurring isotopes are $\beta\beta$ emitters. Which ones are the most favorable in terms of $\beta\beta0\nu$ searches?

1. Phase space $\times$ NME



Sensitivity of ideal experiments at 90% CL for different $\beta\beta$ isotopes. Since the yields are very similar, the sensitivities of $^{82}\mathrm{Se}$, $^{130}\mathrm{Te}$ and $^{150}\mathrm{Nd}$ overlap.

2. High $Q_{\beta\beta}$ puts the signal above the natural radioactivity backgrounds (below ~ 3 MeV).

3. 

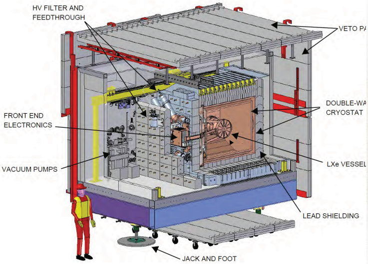
90% CL $m_{\beta\beta}$sensitivity as a function of FWHM energy resolution, for ideal experiments using five different isotopes, each with 100 kg$_{\beta\beta}$ of $\beta\beta$ emitter mass and 5 years of data-taking. The experiments are assumed to have perfect efficiency and to be affected only by $\beta\beta2\nu$ backgrounds. In practice, experiments using $^{76}\mathrm{Ge}$ and $^{130}\mathrm{Te}$ always feature an excellent energy resolution and are therefore not affected by $\beta\beta2\nu$ backgrounds, hence only the background-free sensitivity limit is shown in those cases, with an arrow.

4. Cost of the enrichment
5. Purity of the enriched material

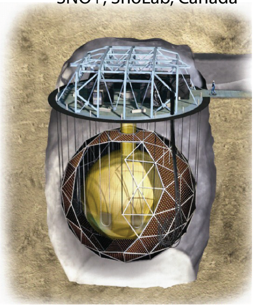
CONCLUSION: No magic isotope exists

Approved and funded experiments

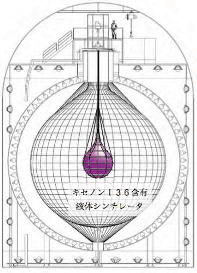
EXO-200, WIPP (US)



SNO+, SnoLab, Canada

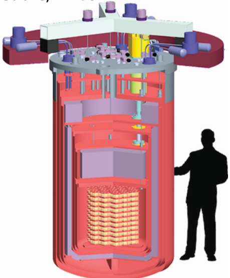


Kamland-Zen, Kamioka

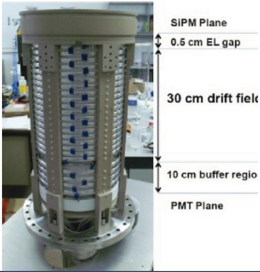


Gerda, LNGS

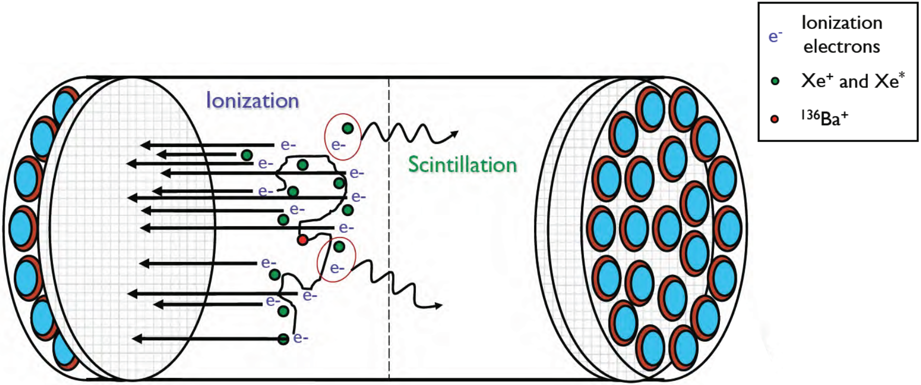
Cuore, LNGS



NEXT, Canfranc



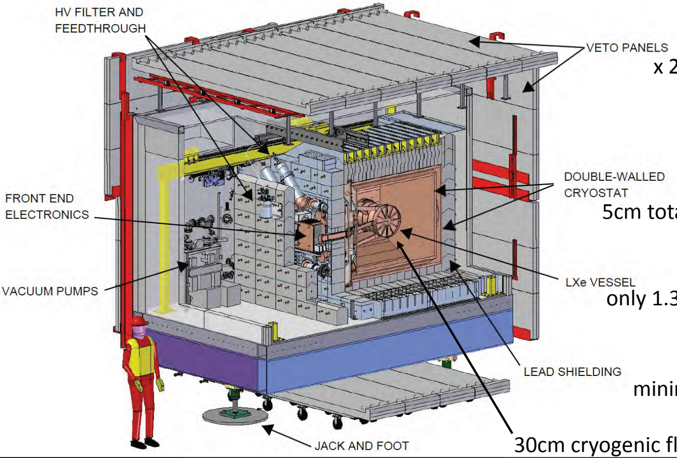
EXO-200



Ionization
Scintillation
e-
e- Ionization electrons
Xe+ and Xe*
136Ba+

EXO-200

arXiv:1202.2192v1 [physics.ins-det] 10 Feb 2012



x 29

5cm total thickness

only 1.37mm thick

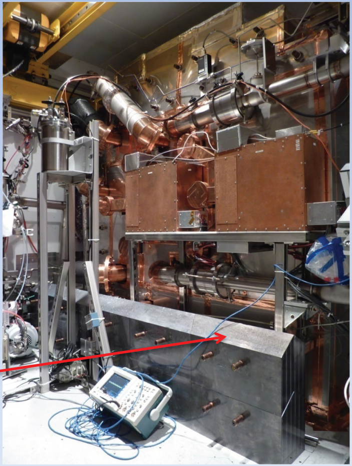
minimum 25cm

30cm cryogenic fluid

EXO–200 enriched low-background run in 2011

- EXO–200 filled with Enriched Xe; data taking began in spring 2011
- Drift field: E = -376 V/cm
- 31 live days
- Source calibration ~ 2 hrs each day to monitor purity, resolution, calibration, other detector effects
- Continuous xenon recirculation through commercial SAES purifiers at ~ 5 SLPM producing liquid xenon purity 210–280 μs
- Conservative fiducial volume ~ 63 kg chosen to reduce external low energy backgrounds
- Data collected were used for immediate measurement of the 2νββ $t_{1/2}$ of ^{136}Xe and to begin energy resolution studies
- Scintillation light for position reconstruction and PID only

Also still missing part of front lead enclosure

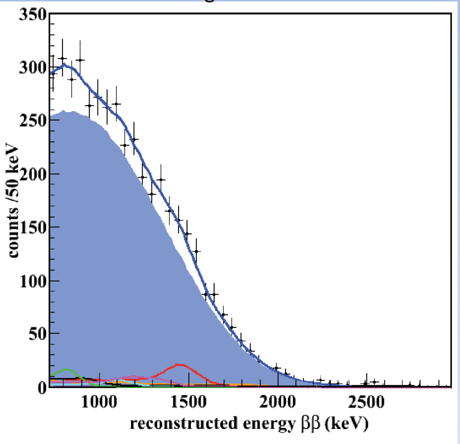


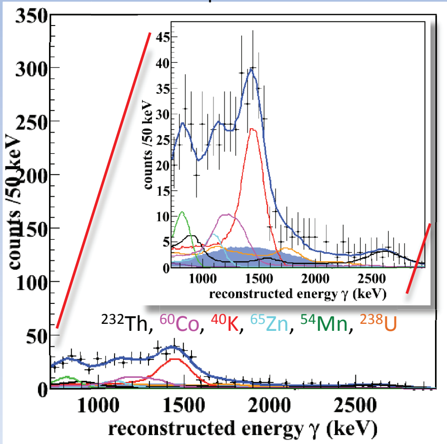
31 live-days of data 63 kg active mass Signal/Background 10:1

2νββ observation

single - cluster

multiple - cluster



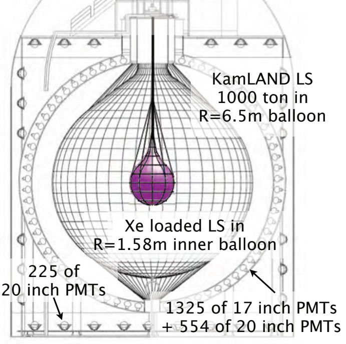


$t_{1/2}$ = 2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 sys) Phys. Rev. Lett. 107, 212501 (2011)

KamLAND-Zen(Zero neutrino double beta decay)

KamLAND-Zen :
Modification of KamLAND.
1,000 tons of highly purified liquid scintillator.
BIG & Low BG

^{136}Xe loaded LS → into KamLAND center with inner balloon(IB).



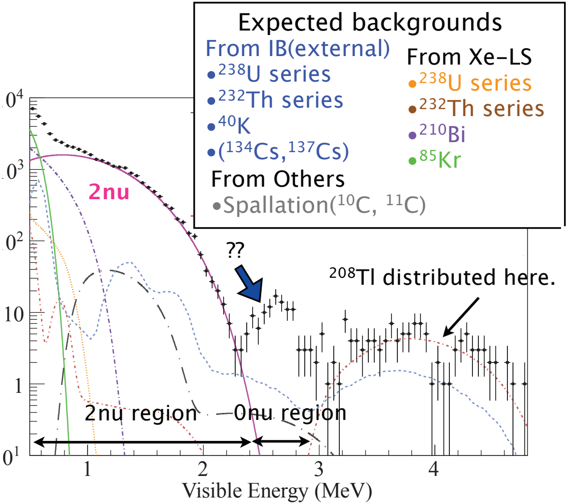
Double beta decay isotope
~300 kg of ^{136}Xe (91% enriched)
Largest amount for DBD experiment.
Already have another 200kg for next phase.
Q-value : 2.476MeV

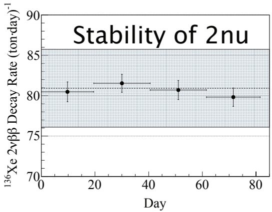
Target for 1st phase
Search for KKDC claim and Degenerated hierarchy.

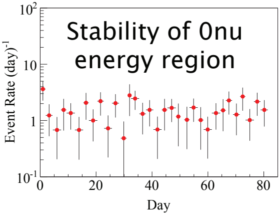
Why Xe?
- Soluble to LS ~3% by weight.
- easily extracted.
- Isotopic enrichment, purification established.

Schedule
2011 Aug. Modification
Sep. 24th, 2011 data taking start
Oct. 12th, 2011 -Jan 2nd, 2012.
77.6 days data for 1st result.

Energy spectrum for 77.6 days data







(2.2 < E < 3.0 MeV, R< 1.2m)

High statistics for 2nu region.
Peak at the 0nu region. Signal or background?

cont'd

4 Candidates → Free parameters in fitting.

	decay	τ	Q-value[MeV]
^{110m}Ag	$\beta^- + \gamma$	360 days	3.01
^{88}Y	EC + γ	154 days	3.62
^{208}Bi	EC + γ	5.31×10^5 yr	2.88
^{60}Co	$\beta^- + \gamma$	7.61 yr	2.82

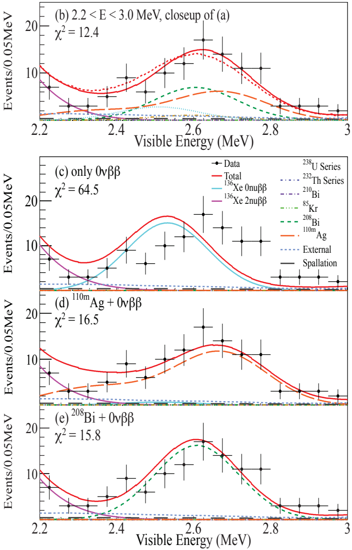
^{88}Y and ^{60}Co -> constrained by its half life and shape.

There is no clear evidence for existing BG.

difficult to determine each contribution separately by an ex-situ measurement.

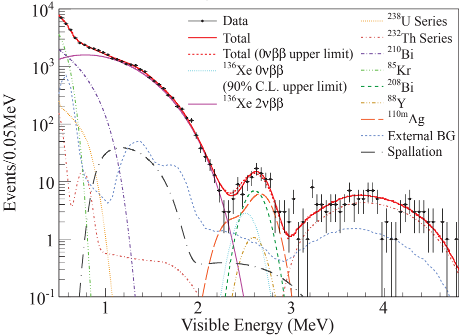
Possibility of Ag
- Spallation (gas made in Russia sent by airplane.).
- Included in the solder for Xe system.
  but no detection in Ge detector.
- Fukushima fallout contains Ag.
  Observed in the soil in Sendai(IB fabrication)
  with Ge detector.

Possibility of Bi
- Included in the solder for Xe system(same as Ag).
- ^{207}Bi/^{208}Bi ratio is small than expected.

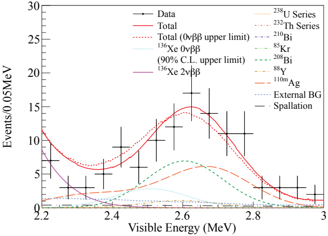


^{136}Xe 2νββ & 0νββ Half life

arXiv:1201.4664v1 [hep-ex]



- livetime 77.6 days.
- 129 kg of ^{136}Xe



$T^{2\nu}_{1/2}$=2.38±0.02(stat)±0.14(syst) ×10^{21} years

- high precision measurement.
- consistent with EXO result. $T^{2\nu}_{1/2}$=2.11±0.04(stat)±0.21(syst) ×10^{21} yr
- verification of discrepancy of $T^{2\nu}_{1/2}$. (DAMA result $T^{2\nu}_{1/2}$>1.0 × 10^{22} yr)

$T^{0\nu}_{1/2}$ > 5.7×10^{24} years at 90% C.L.

$\langle m_{\beta\beta} \rangle$ <0.3~0.6 eV QRPA, shell model – Top class measurement.

Near future plan

Expectation of reducing BG to improve limit.

- Filtration (with 50 nm filter) of LS.
- Done on middle of Feb. Waiting for Rn decay.

Peak remained ↓ / **NO Peak** →

- Other purification (distillation for LS & Xe)
- We already have distillation system, experience and technique.

NO Peak →

- Measurement going. Will present new limit.

If peak remained ↓

- Extraction of Xe from LS.
- Measure the left LS and its background.

Peak remained →

- Return Xe to LS (after purified).
- Options:
  Fabrication of new IB.
  – cleaner film.
  – larger radius.
  Pressurized Xenon
  – higher concentration.

NO peak ↓

- ...Peak is 0nu?

1

CUORE [18-20]

988 TeO_2 (34.167% ai ^{130}Te) **bolometers at ~ 10 mK in a granular structure** (741 kg mass)
@LNGS Phase-I: starts ~ end 2011 **Phase-II: ~ 2014** Future: enr., scintill. bolom...

ββ candidate: ^{130}Te **– Q** 2527.5 keV

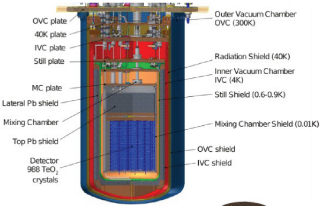
Source Mass:
Phase-I: 10.8 kg ^{130}Te – $N_{\beta\beta}$ 5.0 x10^{25}
Phase-II: **206 kg** ^{130}Te – $N_{\beta\beta}$ 9.6 x10^{26}

Projected Bkg:
Phase-I: 0.05 c/keV/kg/y
Phase-II: 0.01 c/keV/kg/y

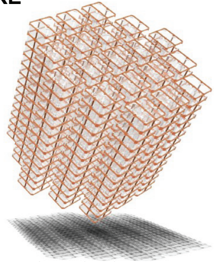
Resolution FWHM: ~ 0.2% @ROI

Sensitivity $T_{1/2}^{0\nu}$:
Phase-I: 4.2x10^{24} y in 1 y
Phase-II: 1.6x10^{26} y in 5 y

Sensitivity Phase-II $<m_{ee}>$:
$<m_{ee}> < 40 \div 94$ meV in 5y **– IH region**



CUORE



CUORE-0

LowNu11, Seoul Silvia Capelli - ββ0ν: experimental review 24

GERDA: Experimental Ideas

Challenges:

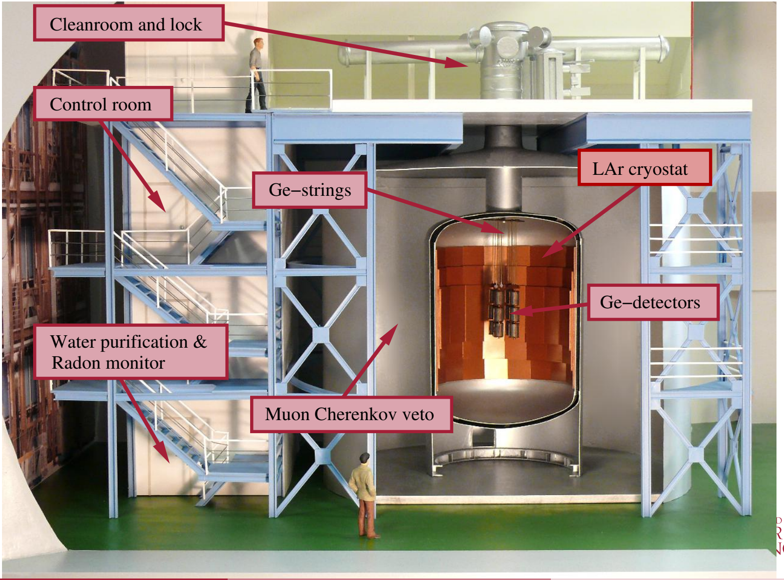
- Low rate: 0-10 cts/yr (Phase I)
- Expensive detectors, limited time
- Inherent background: cosmic muons, “dirty” materials, activation, ambient radioactivity

Solution: background reduction

- Naked Ge-diodes enriched to 86% shielded by low-Z materials
- Source = detector, resolution $\approx 0.1\%$
- LNGS: 3500 m.w.e.
  muons flux red. by $\approx 10^6$
- Pulse shape analysis

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

GERDA: Experimental Setup



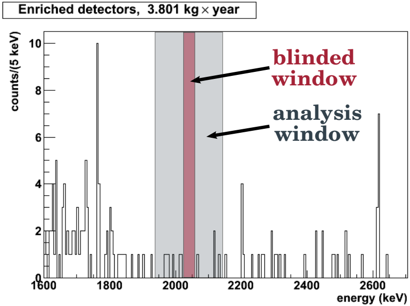
GERDA Current Status

- **data taking** since Nov. 2011
- 8 enr. detectors, 2 taken out (14.6 kg enr. + 7.6 kg nat.)
- **blinding** since Jan. 2012 ($Q_{\beta\beta} \pm 20$ keV)
- **unblinding** once sufficient exposure / BI reached

current ^{enr}BI, 3.8 kg y

$0.017\ ^{+0.009}_{-0.005}$ cts/(keV kg y)

≈10 times better than HdM
no PSD applied yet

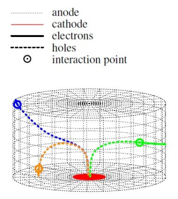


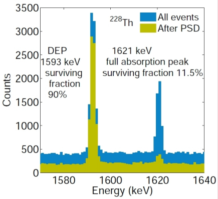
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Future BG Reduction

Pulse Shape Discrimination

- PPC / BEGe detectors
- inhomog. field
- MSE discrimination



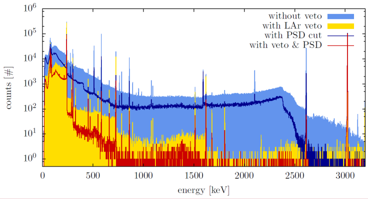


[M. Agostini et. al.;(JINST), 6 (2011) P03005]

[M. Barnabé Heider et.al., (JINST), 5 (2010) P10007]

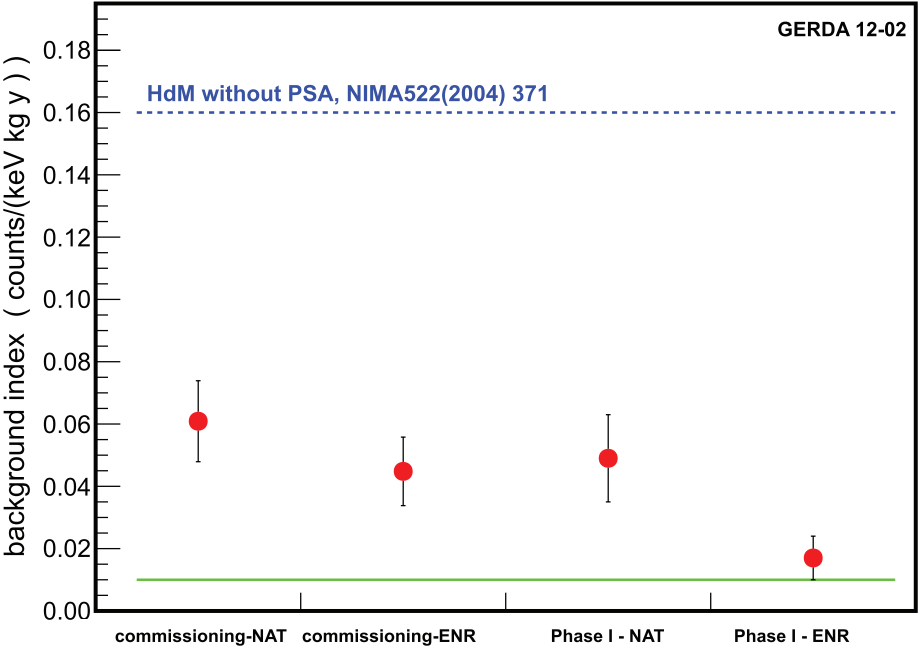
LAr Instrumentation / LArGe

- utilize scintillation of LAr
- Active veto system
- multiple designs studied:
  $\Rightarrow$ PMT / WLS fibers
  $\Rightarrow$ no additional BG



[M.Heisel; PhD thesis]

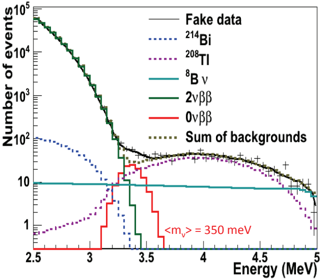
Courtesy of A. Bettini

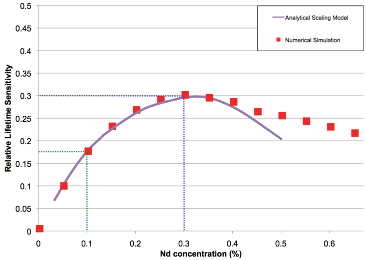


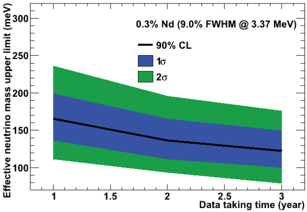
M. Chen talk at Lownu, Seoul, 11/2011

Double Beta Decay with ^{150}Nd

- 44 kg ^{150}Nd (0.1% loading)
- investigating 0.3% loading, found to be the optimum amount
- pursuing Nd isotope enrichment possibilities





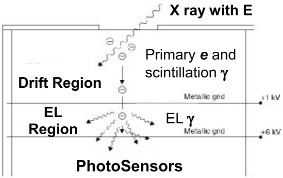


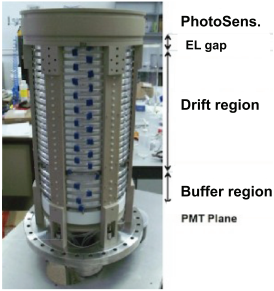
Next

119 kg High Pressure Gas-^{enr}Xe EL TPC (~ 90% of ^{136}Xe) **at 15 bar** with double read-out **(ion+scint/EL)** allowing **good ΔE** + event **3D tracking** and **topology** for a **free bkg exp**.
@SLC Next-1: on-going Next-100: ~ 2015 Future 1t?

ββ candidate: ^{136}Xe **– Q** 2476 keV

Source Mass:
~ 90 kg FMass ^{136}Xe – $N_{\beta\beta}$ 4.0 x10^{26}

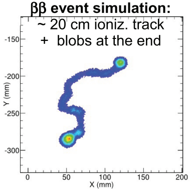




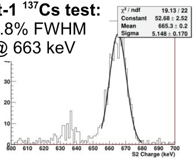
Bkg Strategy:
- low activity materials / GasXe purity monitor
- conventional screening techniques
- 3 cuts: FV + ROI + topology

Projected Bkg: ~ $2\cdot10^{-4}$ c/keV/kg/y

Projected FWHM: ~ 1% @ROI (EL!)



Next-1 ^{137}Cs test:
~ 1.8% FWHM
@ 663 keV



Target Sensitivity:
Next-100: <m_{ee}> ~ 89 meV @6y
Next-100+Next-1t: <m_{ee}> ~ 38 meV @6y (3+3) – **IH region**

SuperNEMO

20 modules of **tracker-calorimeter** with 40 mg/cm^2 source foil each (~5 kg ^{82}Se each).
@LSM   Demonstrator (1 module) start-up ~ 2013   Full: start-up ~2014

ββ candidate: ^{82}Se **– Q** 2995 keV

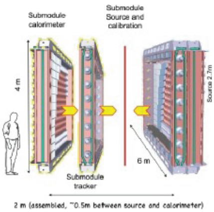
Source mass:
Demonstrator: 5 kg ^{82}Se - $\mathbf{N}_{\beta\beta}$ 1.8 x10^{25}
Full: 100 kg ^{82}Se - $\mathbf{N}_{\beta\beta}$ 7.3 x10^{25}

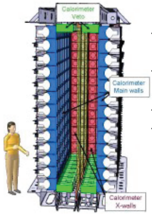
Bkg Strategy:
- Standard shieldings
- Low ^{208}Tl/^{214}Bi contam. in source foils
- tracking
- $2\nu\beta\beta$ reduced with better ΔE

Measured ΔE: ~4 % @ROI
with best calorimeter/PMT choice

Target Sensitivity:
Demonstrator: KK claim within 2015
Full: $T_{1/2}^{0\nu}$ ~ 1.2 x10^{26} 90%CL @ 5y
$\langle m_{ee} \rangle$ ~ 40-105 meV @ 5y **– IH region**

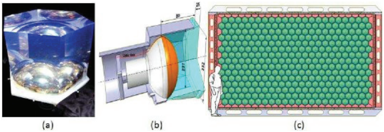
Single-Module: 5x4x1 m^3





- **track** (2000 wire Drift Cells in Geiger Mode)
- **calorimeter wall** (550 PVT +PMTs)
- **γ veto**
- 25 Gauss B

Calorimeter: PVT (plastic scintillator) + PMT (~550/module)

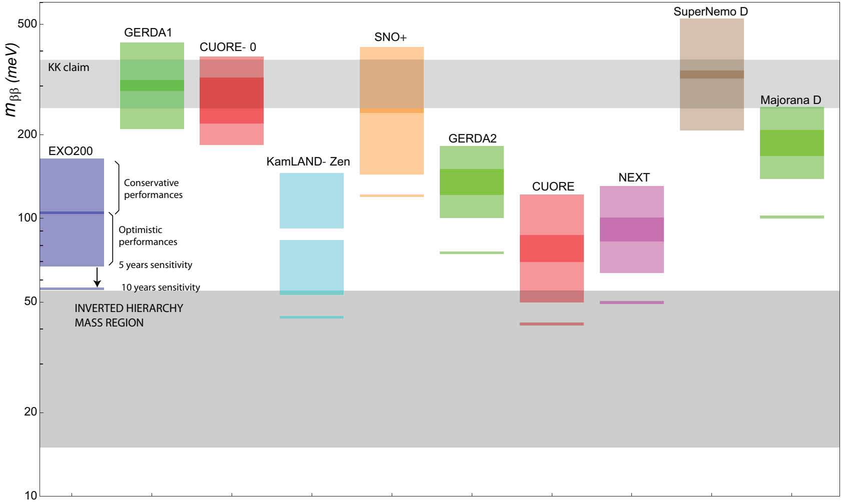


Parameters of approved and funded experiments

Experiment	$M_{\beta\beta}$ ($kg_{\beta\beta}$)	ε	ΔE (keV)	$c \times 10^3$ (counts/(keV $\cdot$ $kg_{\beta\beta}$ $\cdot$ year))	Bgr/ROI (cts/yr)
EXO-200	141	0.34	100	0.78–5	11–71
GERDA-1	15.2	0.95	4.2	12–70	0.77–4.5
GERDA-2	30.4	0.84	2	1.2–7	0.07–0.43
CUORE-0	10.9	0.83	5	180–390	9.8–21.3
CUORE	206	0.83	5	36–130	37.1–134
KamLAND-Zen	357	0.61	250	0.22–1.8	19.6–161
MAJORANA D.	17.2	0.85	2	1.2–12	0.04–0.41
SNO+	44	0.50	220	9–70	87–680
NEXT	89.2	0.33	18	0.2–1	0.32–1.6
SuperNEMO D.	7	0.28	130	0.6–6	0.55–5.5

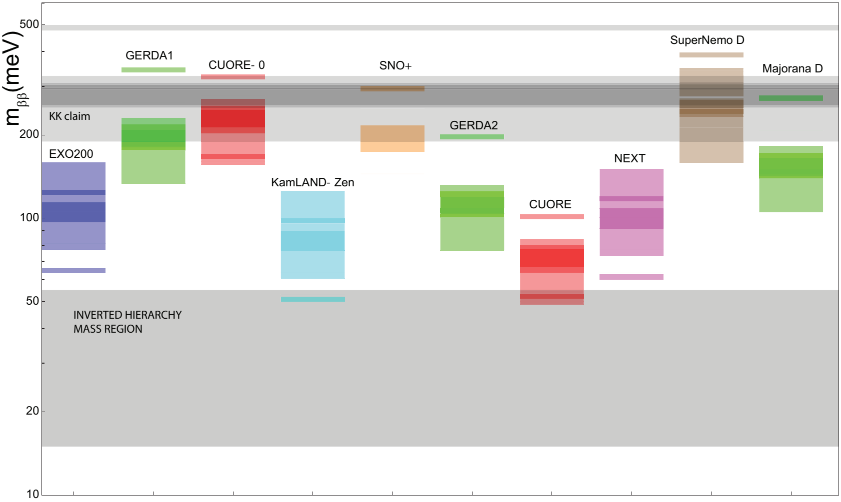
Note the conservative and optimistic assumptions about background rates

90% CL Sensitivity Plots: performance uncertainties



5 years exposure (10 years in the most optimistic scenario also shown), PMR intervals for the NMEs.Feldman-Cousins statistics; signal region of 1 FWHM and the corresponding efficiency.

90%CL Sensitivity for different: NME uncertainties



Computed for five different frameworks for NME calculations are considered, following Dueck:2011hu, and are drawn as overlapping rectangles. Optimistic experimental performances are assumed.

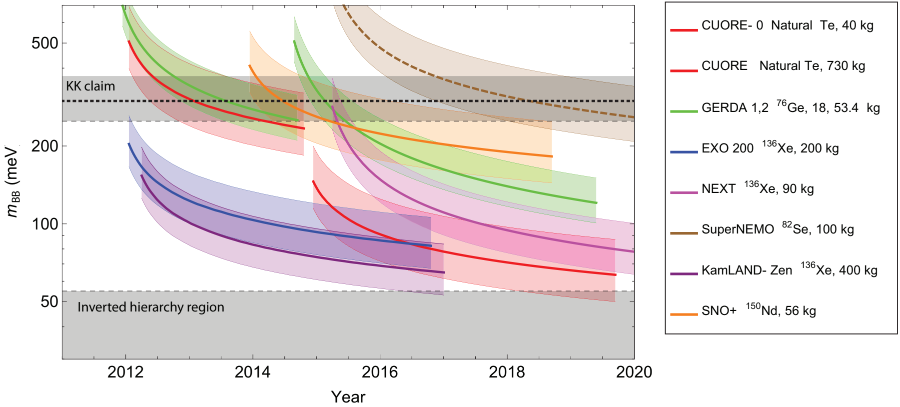
Sensitivity Table

Sensitivity of the experiments at 90% CL after a 5 years exposure, both in terms of half-life $T_{1/2}^{0\nu}$ and in terms of neutrino effective mass $m_{\beta\beta}$. These values are obtained from the optimistic background rate assumptions. The conversion from $T_{1/2}^{0\nu}$ to $m_{\beta\beta}$ assumes the central value of the PMR interval for the nuclear matrix elements.

Experiment	$T_{1/2}^{0\nu}$ (years)	$m_{\beta\beta}$ (meV)
CUORE-0	8.67×10^{24}	203
CUORE	8.86×10^{25}	63
GERDA-1	4.49×10^{25}	252
GERDA-2	1.37×10^{26}	121
EXO200	8.20×10^{25}	82
NEXT	9.13×10^{25}	78
KamLAND-Zen	1.32×10^{26}	65
SNO+	5.38×10^{24}	182
SuperNEMO Demonstrator	9.15×10^{25}	258
MAJORANA Demonstrator	7.19×10^{25}	258

Time Evolution

90%CL sensitivity along the time. Computed for the optimistic assumptions and the PMR values of NMEs.



Some Consideration

EXO-200 Published $\beta\beta 2\nu$data are for a fiducial of 63 out of the 175 kg of liquid xenon. The energy resolution was $\sigma_E/E = 4.5\%$ at 2615 keV for a 376 V/cm drift field and ionization signals only. An improvement of up to a factor of 2.5 could be achieved with higher (1–4 kV/cm) drift fields and combining ionization with scintillation information. As a worst-case background rate scenario, is taken what has already been achieved: 4×10^{-3} counts/(keV · kg · year), obtained without full lead shielding, radon exclusion tent, radon trap or full 3-dim reconstruction, and might therefore be improved in the future Goal rate is $c = 0.78 \times 10^{-3}$ counts/(keV · $kg_{\beta\beta}$ · year).
KamLAND-Zen $\beta\beta 2\nu$published data (after our review) has a background level 80 times bigger than their default value and 10 times worse our pessimistic assumptions. As shown before the collaboration foresee several purification cycles, it is uncertain which level of background they will achieve.
CUORE Main problem is timescale. The present foreseen date for data taking is late 2014. Background predictions/measurements are quite robust and published in arXiv:1108.4757.
GERDA Phase I achieved (after a while) the expected background rate before pulse shape analysis. No news so far about PSA performances. Gerda-II goal, 10 times smaller background than Gerda-I, relies mostly on improved PSA on new-concept crystals and scintillating light detection in LAr to veto comptons. It hasn't been demonstrated so far.
NEXT So far background rates haven't been measured.

Other proposals

CANDLES CaF_2 scintillating crystals to search for $\beta\beta 0\nu$ in $^{48}\mathrm{Ca}$. The crystals would be immersed in liquid scintillator providing shielding and an active veto against external backgrounds. Among the $\beta\beta$ isotopes, $^{48}\mathrm{Ca}$ has the highest Q-value, 4.27 MeV. This places the signal well above the energy region of the natural radioactive processes. Unfortunately, the natural abundance of the isotope is only 0.187% and enrichment seems complicated. Therefore, many tons of crystals are needed for a competitive new-generation experiment.

COBRA Cadmium Zinc Telluride (CdZnTe) room-temperature semiconductor detectors for $\beta\beta 0\nu$ searches. Out of the several $\beta\beta$ candidate isotopes in CdZnTe, COBRA is focusing on $^{130}\mathrm{Te}$, because of its natural abundance, and $^{116}\mathrm{Cd}$, because of its high Q-value of 2.8 MeV. Activities are split in two main directions: (a) the identification of the main background components in a setup of 64 commercial 1-cm^3 CdZnTe diodes located at LNGS; and (b) the development of pixelized devices that would allow to reduce the background by particle identification.

DCBA The Drift Chamber Beta-ray Analyzer is a magnetized tracker (drift chambers) that can reconstruct the trajectories of charged particles emitted from a $\beta\beta$ source foil. The momentum and kinetic energy are derived from the track curvature in the magnetic field. A prototype, DCBA-T2, has shown energy resolution of about 150 keV (FWHM) at 1 MeV, and the main source of background ($^{214}\mathrm{Bi}$) has been identified. A new apparatus, DCBA-T3, with a more intense magnetic field is now under construction at KEK.

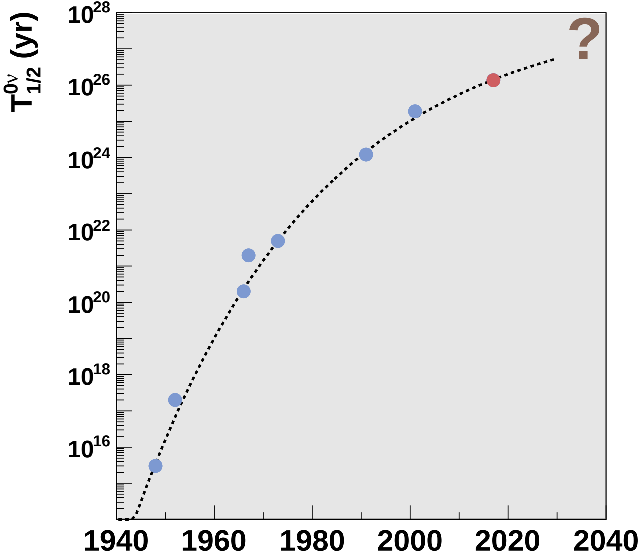
LUCIFER Join the bolometric technique proposed for the CUORE experiment with the bolometric light detection technique used in cryogenic dark matter experiments. Preliminary tests on several $\beta\beta0\nu$ detectors have clearly demonstrated the background rejection capabilities that arise from the simultaneous, independent, double readout (heat and scintillation). LUCIFER will consist of an array of ZnSe crystals operated at 20 mK. The proof of principle with about 10 kg of enriched Se is foreseen for 2014.

MOON A stack of multi-layer modules, each one consisting of a scintillator plate for measuring energy and time, two thin detector layers for position and particle identification, and a thin $\beta\beta$ source film interleaved between them. At present, NaI(TI) scintillators are considered as the candidates for the scintillator plates. Energy resolution around 3% FWHM at 3 MeV has been achieved during the R&D phase. For position-sensitive detectors, possible candidates are multi-wire proportional chambers (MWPCs) and Si-strip detectors.

XMASS A multi-purpose liquid xenon scintillator. Although optimized for dark matter searches, it will also investigate neutrinoless double beta decay and solar neutrinos. The detector, with about 800 kg of xenon, was installed in the Kamioka mine (Japan) in the fall of 2010. The excellent self-shielding capabilities of the liquid xenon will be used to define a virtually background-free inner volume.

Conclusions

Seventy years of direct $\beta\beta0\nu$ searches in perspective.



Conclusions

- The present generation of double beta decays experiments is an impressive worldwide efford.
- Experiments exploit past technologies pushed to their ultimate limits or solar neutrino experiments converted to double beta decays searches.
- Those experiments will improve by about a factor five the present sensitivity, nevertheless they will not enter in the inverted hierarchy mass region.
- To explore this region brute force appears to be useless. New bright ideas are needed to improve the sensitivity in this new mass scale.