Neutrinoless Double Beta Decay: present and future

- Double Beta Decay (DBD) and neutrino properties
- Experimental approaches and sensitivities
- Present status of DBD experiments
- Future perspectives
- Future projects
- Conclusions

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Neutrino 2002 Munich

Double Beta Decay

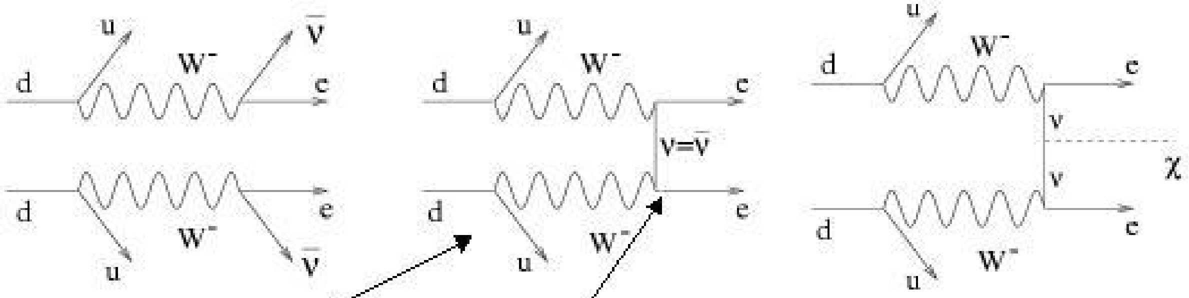
Three main decay modes

a) DBD2ν: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$

b) DBD0ν : $(A,Z) \rightarrow (A,Z+2) + 2e^-$

c) DBDχ: $(A,Z) \rightarrow (A,Z+2) + 2e^- + n\chi$

SM allowed

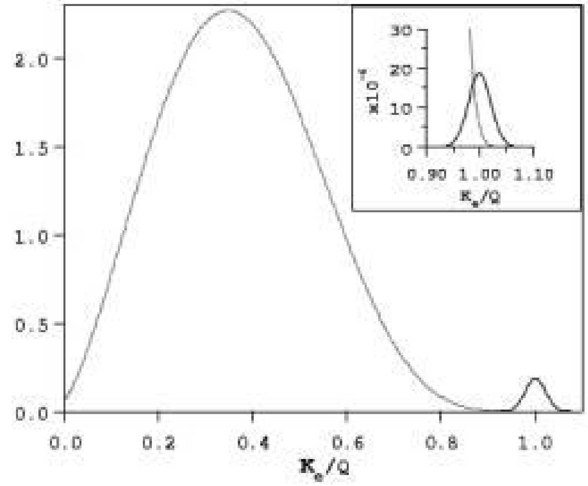


New neutrino properties:

$\nu = (\nu)^c$

$m_\nu \neq 0$

Helicity matching



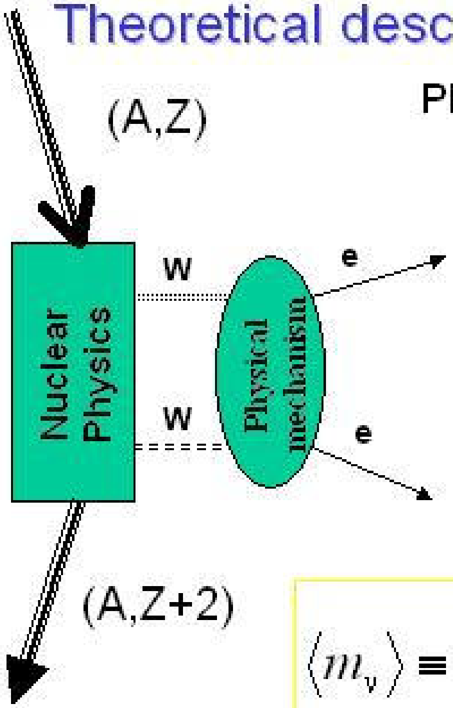
2 electrons sum energy spectra:

Main experimental signature ...

(single electron E and angular distributions)

DBD & Neutrino Properties

Theoretical description ...



Phase space: high Q

Nuclear matrix element:
Relevant uncertainty source (h)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \sum_k G_k(Q,Z) M_k^2 \, \omega_k^2$$

Physical mechanism

$$\boxed{G(Q,Z) M^2 \langle m_\nu \rangle^2}$$

Neutrino mass

±1 if CP conserved

$$\boxed{\langle m_\nu \rangle \equiv m_{ee} = \left|\sum_k U_{ek}^2 m_k\right| = \left|\sum_k \left|U_{ek}\right|^2 e^{i\alpha_{ek}} m_k\right|}$$

Pontecorvo-Maki-Nakagawa-Sakata **mixing matrix:** →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

DBD & Neutrino Properties (2)

Neutrino oscillation experiments have given convincent evidences that **neutrinos are massive and mixed**

Missing informations:

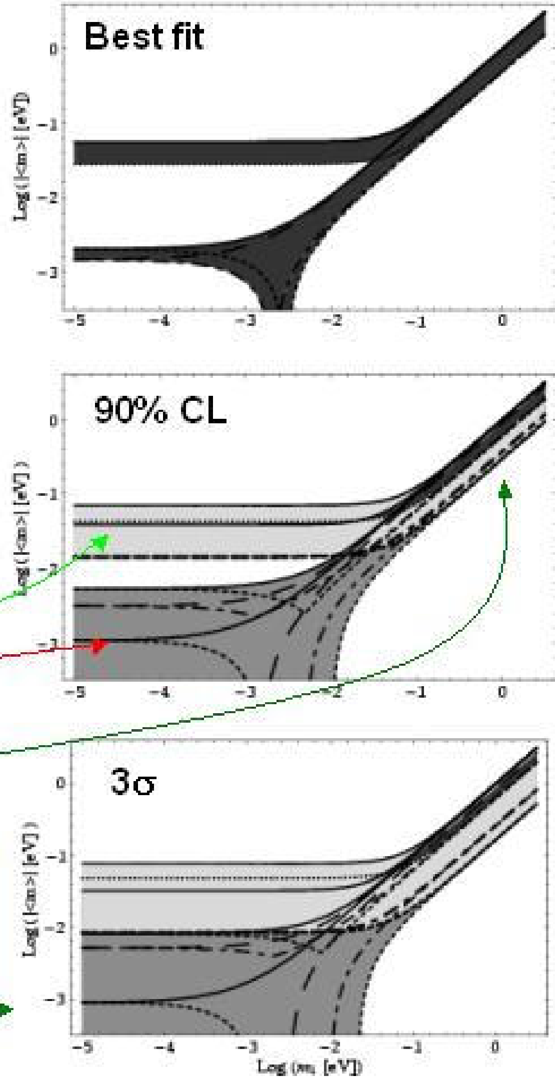
- neutrino absolute mass scale
- nature (Dirac/Majorana)
- CP (Majorana) phases
- exotic processes

β-endpoint

$0\nu2\beta$

$0\nu2\beta$ is a powerful tool to identify neutrino mass hierarchy:

- inverse
- direct
- quasi-degenerate



Pascoli S Petcov ST hep-ph/0205022
implications from solar ν experiments (last SNO results included) in the framework of 3 Majorana ν mixing

Spread due to Nuclear matrix elements indeterminations

Not included

DBD Experimental sensitivity

Experimental evaluation of a decay lifetime:

$$\tau_{1/2} = \ln 2 \cdot N_N \cdot T / N_S$$

N_N = number of decaying nuclei under observation
N_S = number of observed decays
T = measure live time

$(\tau >> T)$

"Zero Bkg" (No counts): $N_s = k$

Sensitivity = Lifetime corresponding to the minimum detectable number of events above background at a given C.L.

Background fluctuations:

$N_s = (N)^{1/2}$

1 FWHM

$$S = \ln 2 \cdot N_A \cdot n \cdot a \cdot \varepsilon \cdot \sqrt{T / (R \cdot W)}$$

N_A = Avogadro Number
R = Background level ($keV^{-1}\ y^{-1}$)
n = Mole number
a = Isotopic abundance
e = Detection efficiency
W = Energy resolution (FWHM)
T = Live time

Background $\propto$ detector mass

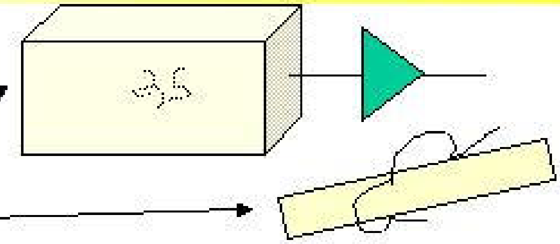
$$S = \ln 2 \cdot N_A \cdot a / A \cdot \varepsilon \sqrt{m \cdot T / (R' \cdot W)}$$

Linear dependence!

$0\nu2\beta$ Experimental Situation

2 main experimental approaches:

- Active Source
- Passive Source



Best $0\nu2\beta$ results involve active source experiments

Experiment	Isotope	$T_{1/2}^{0\nu}$ (y)	$<m_\nu>$ (eV)
You Ke et al. 1998	^{48}Ca	$> 9.5 \times 10^{21}$ (76%)	< 8.3
Klapdor-Kleingrothaus 2001	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
Aalseth et al 2002		$> 1.57 \times 10^{25}$	< 0.33 - 1.35
Elliott et al. 1992	^{82}Se	$> 2.7 \times 10^{22}$ (68%)	< 5
Ejiri et al. 2001	^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
Danevich et al. 2000	^{116}Cd	$> 7 \times 10^{22}$	< 2.6
Bernatowicz et al. 1993	$^{130/128}$Te*	$(3.52 \pm 0.11) \times 10^{-4}$	< 1.1 – 1.5
Bernatowicz et al. 1993	^{128}Te*	$> 7.7 \times 10^{24}$	< 1.1 – 1.5
Mi DBD – ν 2002	^{130}Te	$> 2.1 \times 10^{23}$	< 0.85 – 2.1
Luescher et al. 1998	^{136}Xe	$> 4.4 \times 10^{23}$	< 1.8 – 5.2
Belli et al. 2001	^{136}Xe	$> 7 \times 10^{23}$	< 1.4 – 4.1
De Silva et al. 1997	^{150}Nd	$> 1.2 \times 10^{21}$	< 3
Danevich et al. 2001	^{160}Gd	$> 1.3 \times 10^{21}$	< 26

$2\nu2\beta$ Experimental situation

2nd order weak process

Severe test for nuclear matrix elements calculations

$$\left[T_{1/2}^{2\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{2\nu}(Q,Z)\left|M_{GT}^{2\nu}\right|^2$$

Phase Space Integral

Exactly Calculable

Weighted average of the most recent experiments

i) average asymmetryc bars

ii) add systematic errors in quadrature

Isotope	$T_{1/2}^{2\nu}$(y)	$M_{GT}^{2\nu}$ (MeV^{-1})
^{48}Ca	$(4.25 \pm 1.6) \times 10^{19}$	0.05
^{76}Ge	$(1.38 \pm 0.14) \times 10^{21}$	0.15
^{82}Se	$(8.9 \pm 1.0) \times 10^{19}$	0.10
^{96}Zr	$(1.43^{+3.4}_{-0.8}) \times 10^{19}$	0.12
^{100}Mo	$(8.2 \pm 0.6) \times 10^{18}$	0.22
^{100}Mo($0^{+'}$)	$(6.8 \pm 1.2) \times 10^{20}$	0.1
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	0.12
^{128}Te	$(7.2 \pm 0.3) \times 10^{24}$	0.025
^{130}Te	$(2.7 \pm 0.1) \times 10^{21}$	0.017
^{136}Xe	$> 8.1 \times 10^{20}$	<0.03
^{150}Nd	$(7.0^{+12.0}_{-1.0}) \times 10^{18}$	0.07
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$	0.05

Elliott and Vogel 2002

Nuclear structure effects
cause variations by a
factor ~10
on the matrix elements
i.e. a factor ~100
on the lifetime

Calculated values span a range of
3-4 orders of magnitude
around the experimental value

Tretyak and Zdesenko 2002

Heidelberg-Moscow

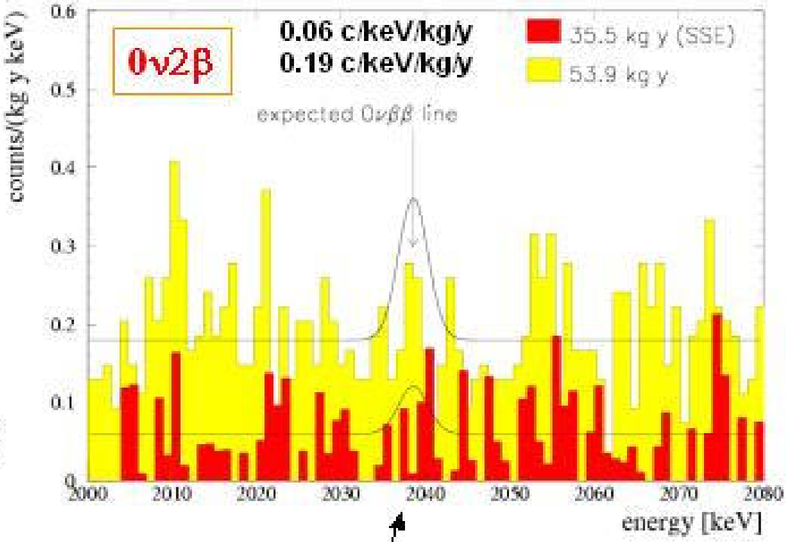
Klapdor-Kleingrothaus HV et al. Eur. Phys. J. 12 (2001) 147

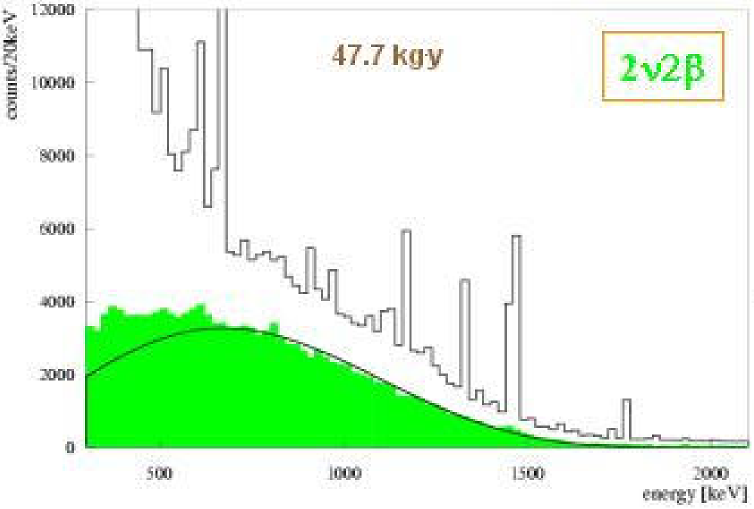
Max-Planck-Institut für Kernphysik
Russian Science Center Kurchatov Institute

since 1990

Gran Sasso underground laboratory

- **Five Ge diodes (overall mass 10.9 kg) isotopically enriched (86%) in ^{76}Ge**
- **Lead box and nitrogen flushing of the detectors**
- **Digital Pulse Shape Analysis (factor 5 reduction)**





$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ (90 % C.L.)

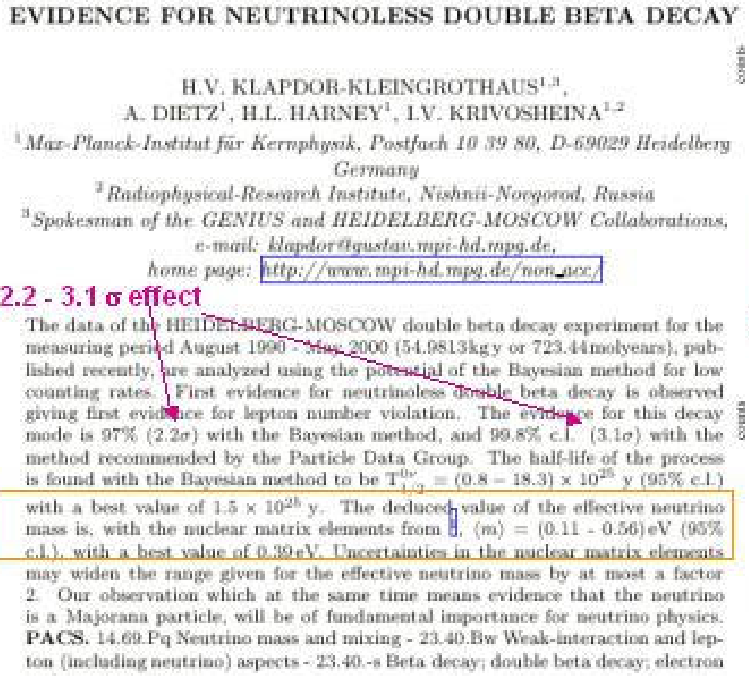
$\langle m_\nu \rangle < 0.35$ (0.3-1.24) eV

Accurate background model:

$T_{1/2}^{2\nu} > (1.55 \pm 0.01(\text{stat})\ ^{+0.19}_{-0.15}\ (\text{syst})) \times 10^{21}$

Evidence for 0ν2β: KDHK

Klapdor-Kleingrothaus HV et al. hep-ph/0201231
Klapdor-Kleingrothaus HV and Sarkar U. hep-ph/0201224



EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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home page: http://www.mpi-hd.mpg.de/non_acc/

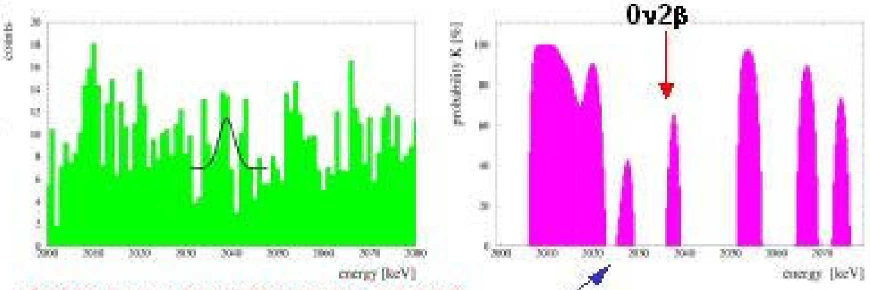
2.2 - 3.1 σ effect

The data of the HEIDELBERG-MOSCOW double beta decay experiment for the measuring period August 1990 - May 2000 (54.9813kg y or 723.44molyears), published recently, are analyzed using the potential of the Bayesian method for low counting rates. First evidence for neutrinoless double beta decay is observed giving first evidence for lepton number violation. The evidence for this decay mode is 97% (2.2σ) with the Bayesian method, and 99.8% c.l. (3.1σ) with the method recommended by the Particle Data Group. The half-life of the process is found with the Bayesian method to be $T^{0\nu}_{1/2} = (0.8 - 18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. The deduced value of the effective neutrino mass is, with the nuclear matrix elements from [], $\langle m \rangle = (0.11 - 0.56)$ eV (95% c.l.), with a best value of 0.39 eV. Uncertainties in the nuclear matrix elements may widen the range given for the effective neutrino mass by at most a factor 2. Our observation which at the same time means evidence that the neutrino is a Majorana particle, will be of fundamental importance for neutrino physics. **PACS.** 14.69.Pq Neutrino mass and mixing - 23.40.Bw Weak-interaction and lepton (including neutrino) aspects - 23.40.-s Beta decay; double beta decay; electron and muon capture.

Reanalysis of the 1990-2000 Heidelberg-Moscow data

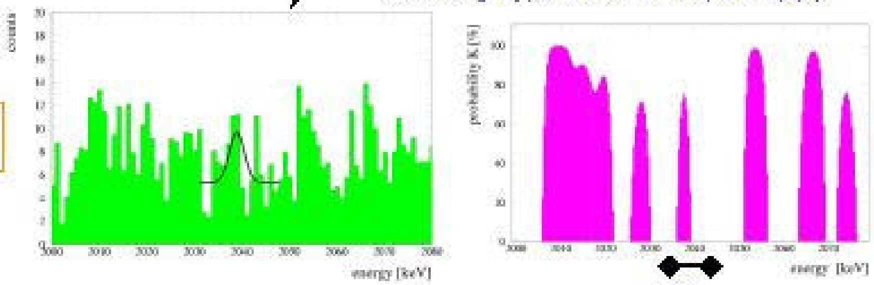
- Peak Detection Procedure
- Bayesian approach

Natural radioactivity lines recognized!
Select a small Energy interval around E_0

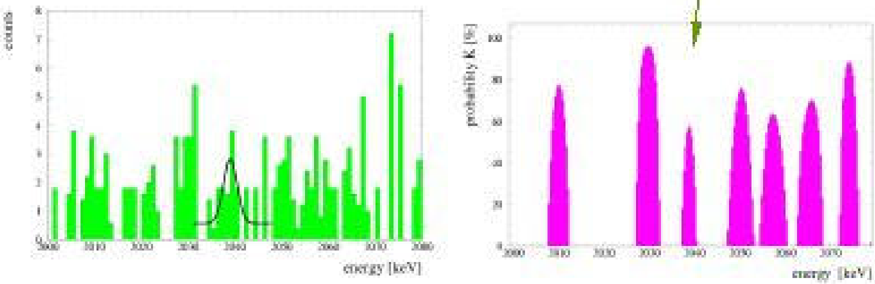


54.981 kg × y, 4 keV FWHM, det. 1,2,3,4,5

46.502 kg × y, 3.74 keV FWHM, det. 1,2,3,5



28.053 kg × y, 3.74 keV FWHM, det. 2,3,5: PSA

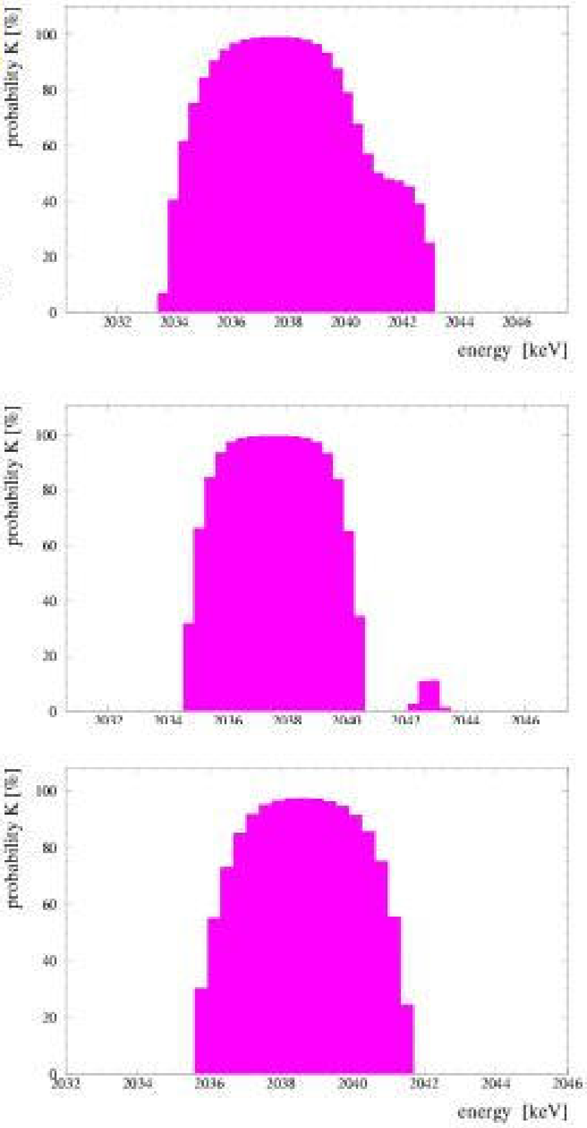


Evidence for 0ν2β: KDHK (2)

Key issue:
since 214Bi peaks have been identified in the large (2000-2080) interval, use a **narrower interval** (5σ)

Result:
a "clear" effect is apparent

Significance [$kg\,y$]	Detectors	$T^{0\nu}_{1/2}$ y	$\langle m \rangle$ eV	Conf. level
54.9813	1,2,3,4,5	$(0.80 - 35.07) \times 10^{25}$	(0.08 - 0.54)	95% *c.l.*
54.9813	1,2,3,4,5	$(1.04 - 3.46) \times 10^{25}$	(0.26 - 0.47)	68% *c.l.*
54.9813	1,2,3,4,5	1.61×10^{25}	0.38	Best Value
46.502	1,2,3,5	$(0.75 - 18.33) \times 10^{25}$	(0.11 - 0.56)	95% *c.l.*
46.502	1,2,3,5	$(0.98 - 3.05) \times 10^{25}$	(0.28 - 0.49)	68% *c.l.*
46.502	1,2,3,5	1.50×10^{25}	0.39	Best Value
28.053	2,3,5 SSE	$(0.88 - 22.38) \times 10^{25}$	(0.10 - 0.51)	90% *c.l.*
28.053	2,3,5 SSE	$(1.07 - 3.69) \times 10^{25}$	(0.25 - 0.47)	68% *c.l.*
28.053	2,3,5 SSE	1.61×10^{25}	0.38	Best Value



Possible Evidence for 0ν2β: comments

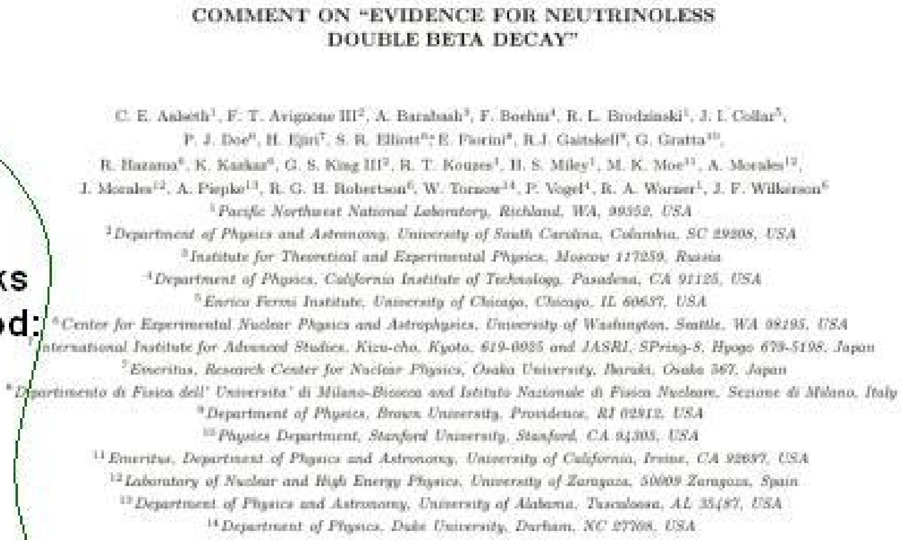
Aalseth CE et al. hep-ph/0202018

- Window size
- Relative heights of ^{214}Bi lines

  extrapolation from HM 2001 …
- No null hypothesys analysis
- No full spectrum presented
- No discussion of unidentified peaks
- No discussion of PSA effect on all peaks
- No analysis of robustness of the method:

  peak → found peak (with correct features)

  no peak → found no peak
- No analysis of results dependence on model and bkg assumptions



COMMENT ON "EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY"

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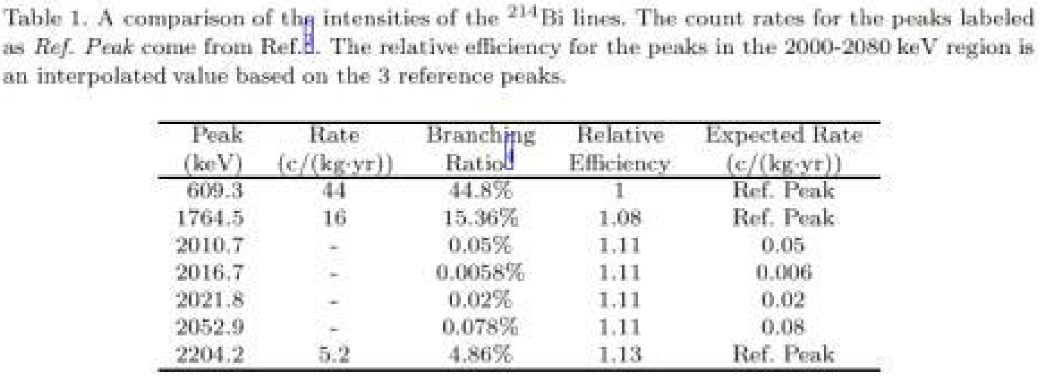
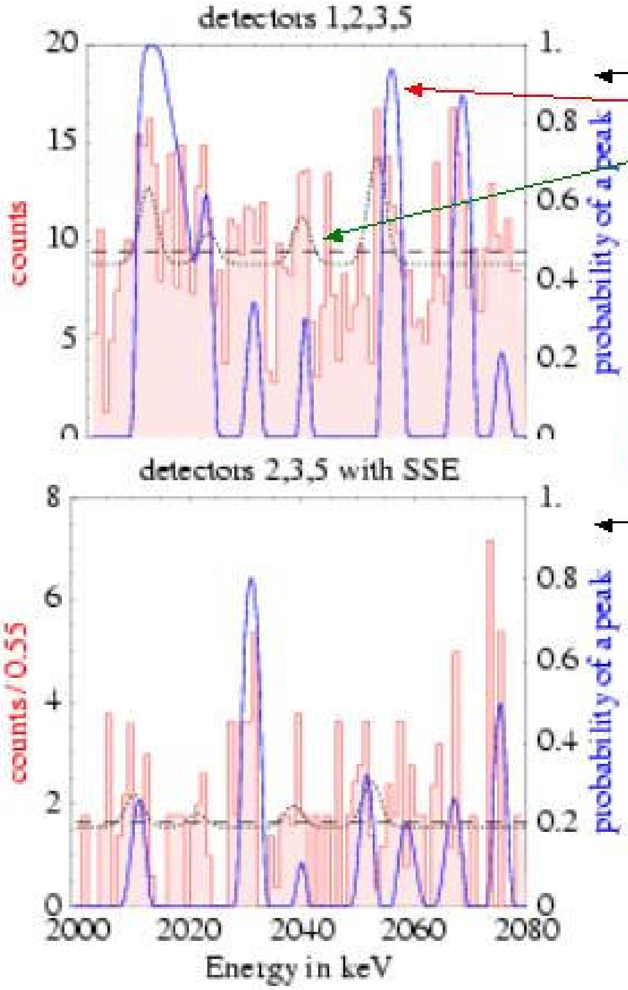


Table 1. A comparison of the intensities of the ^{214}Bi lines. The count rates for the peaks labeled as *Ref. Peak* come from Ref.[]. The relative efficiency for the peaks in the 2000-2080 keV region is an interpolated value based on the 3 reference peaks.

Peak (keV)	Rate (c/(kg·yr))	Branching Ratio[]	Relative Efficiency	Expected Rate (c/(kg·yr))
609.3	44	44.8%	1	Ref. Peak
1764.5	16	15.36%	1.08	Ref. Peak
2010.7	-	0.05%	1.11	0.05
2016.7	-	0.0058%	1.11	0.006
2021.8	-	0.02%	1.11	0.02
2052.9	-	0.078%	1.11	0.08
2204.2	5.2	4.86%	1.13	Ref. Peak

Possible Evidence for 0ν2β: comments

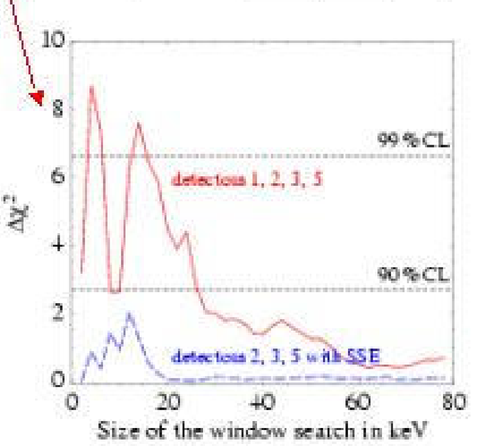
Feruglio F et al. hep-ph/0201291

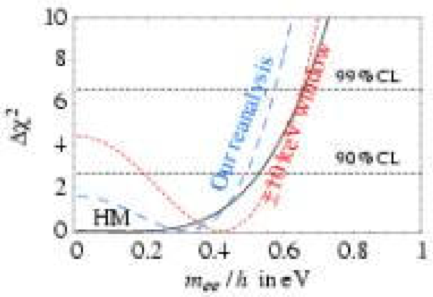


Reanalysis of H-M data sets # 2 and 3

- Peaks detection method: similar results
- **Global fit:** much less effect significance (1.5-0.7σ)
- **Fit with flat bkg**:
  - Dependence on the fit interval width
  - Bayes/Gauss approach: equivalent
- **Peaks identification** (^{214}Bi?): inconsistent

  criticised …
- PSA uniform suppression

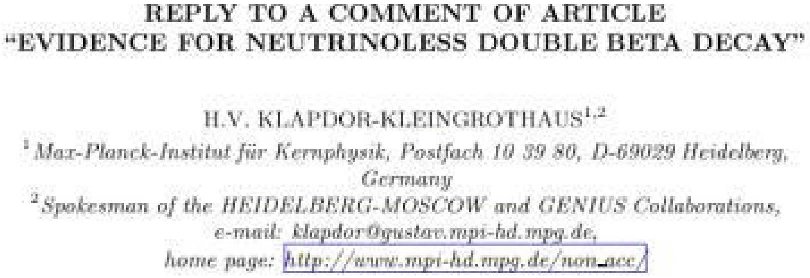




Possible Evidence for $0\nu2\beta$: comments

Klapdor-Kleingrothaus HV hep-ph/0205228

21-05-2002



REPLY TO A COMMENT OF ARTICLE
"EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY"

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Reply for each item in the "comment" defending original position of KDHK

More "soft" reply of H.L. Harney:

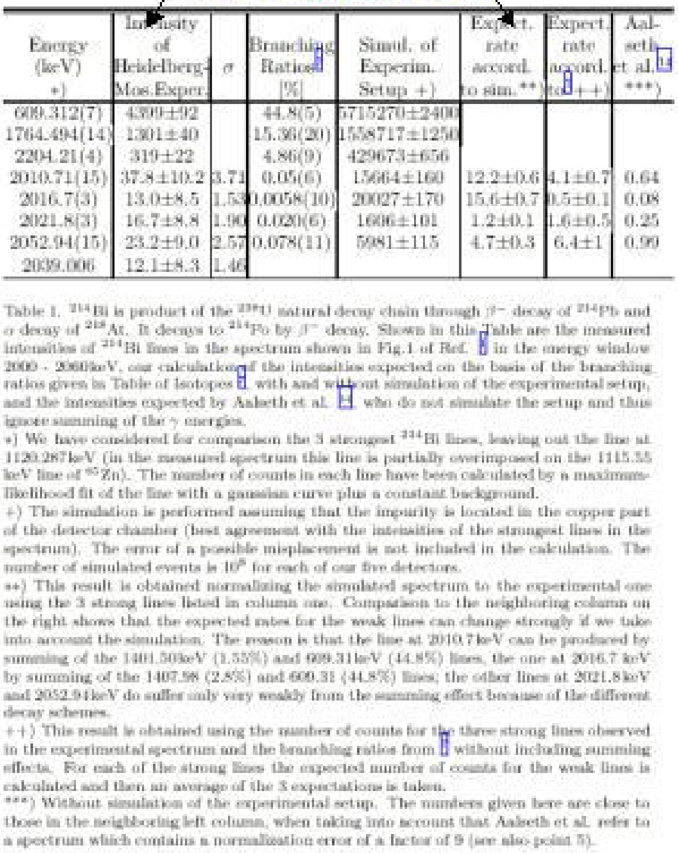
"part of the criticism is justified"

in particular:

"if the peaks at energies other than $Q_{\beta\beta}$ cannot be identified by way of the simulation the confidence on the possible structure at $Q_{\beta\beta}$ will be lower than given in KDHK"

New table (correct) of experimental and expected ^{214}Bi lines intensities

Still inconsistent!



Energy (keV) *)	Intensity of Heidelberg-Mos.Exper.	σ	Branching Ratios[illegible] [%]	Simul. of Experim. Setup +)	Expect. rate accord. to sim.**)	Expect. rate accord. to[illegible] ++)	Aalseth et al.[14] ***)
609.312(7)	4399±92		44.8(5)	5715270±2400			
1764.494(14)	1301±40		15.36(20)	1558717±1250			
2204.21(4)	319±22		4.86(9)	429673±656			
2010.71(15)	37.8±10.2	3.71	0.05(6)	15664±160	12.2±0.6	4.1±0.7	0.64
2016.7(3)	13.0±8.5	1.53	0.0058(10)	20027±170	15.6±0.7	0.5±0.1	0.08
2021.8(3)	16.7±8.8	1.90	0.020(6)	1606±101	1.2±0.1	1.6±0.5	0.25
2052.94(15)	23.2±9.0	2.57	0.078(11)	5981±115	4.7±0.3	6.4±1	0.99
2039.006	12.1±8.3	1.46					

Table 1. ^{214}Bi is product of the ^{238}U natural decay chain through β^- decay of ^{214}Pb and α decay of ^{218}At. It decays to ^{214}Po by β^- decay. Shown in this Table are the measured intensities of ^{214}Bi lines in the spectrum shown in Fig.1 of Ref. [illegible] in the energy window 2000 - 2060keV, our calculation of the intensities expected on the basis of the branching ratios given in Table of Isotopes [illegible], with and without simulation of the experimental setup, and the intensities expected by Aalseth et al. [illegible], who do not simulate the setup and thus ignore summing of the γ energies.

*) We have considered for comparison the 3 strongest ^{214}Bi lines, leaving out the line at 1120.287keV (in the measured spectrum this line is partially overimposed on the 1115.55 keV line of ^{65}Zn). The number of counts in each line have been calculated by a maximum-likelihood fit of the line with a gaussian curve plus a constant background.

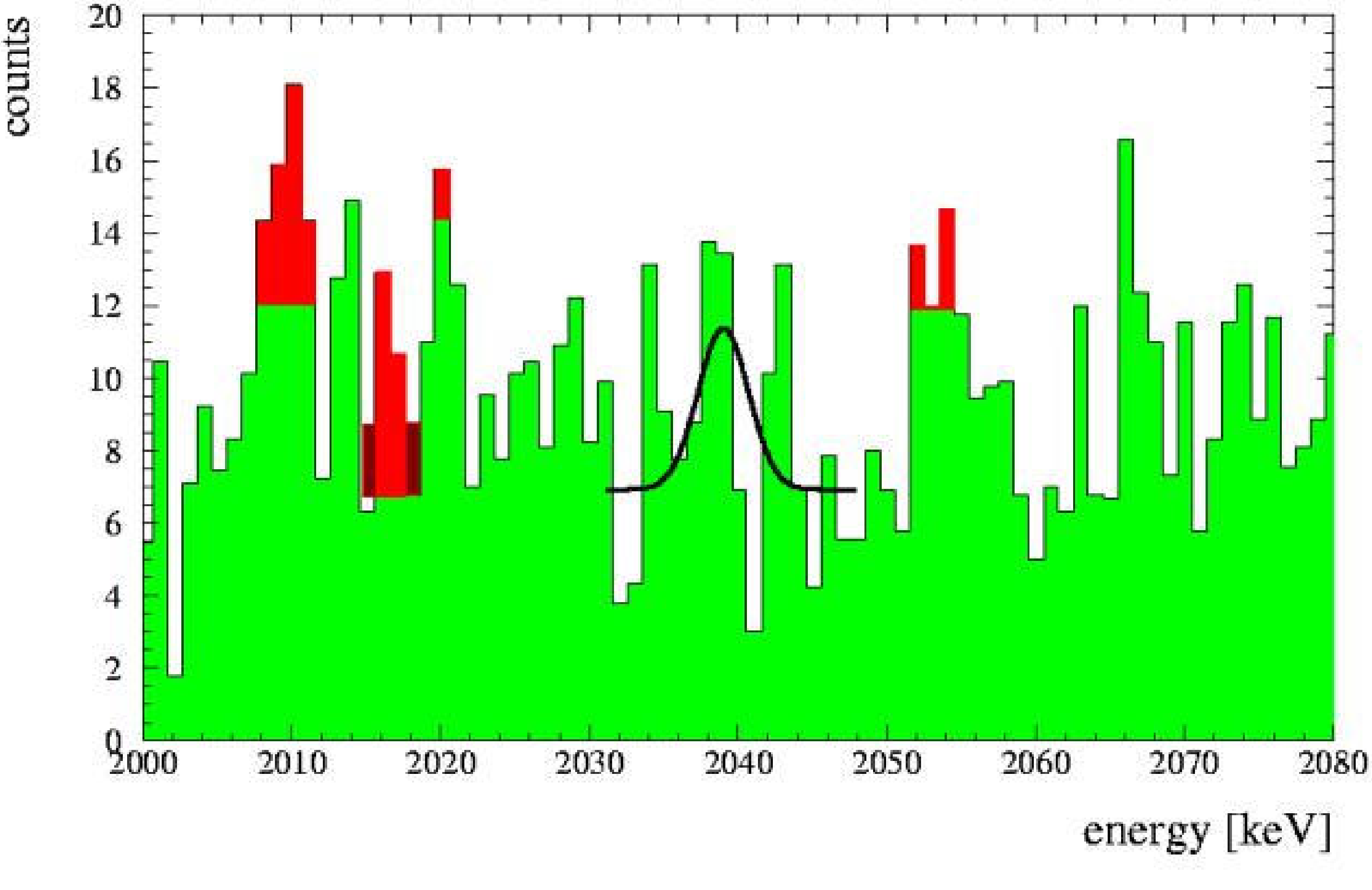
+) The simulation is performed assuming that the impurity is located in the copper part of the detector chamber (best agreement with the intensities of the strongest lines in the spectrum). The error of a possible misplacement is not included in the calculation. The number of simulated events is 10^8 for each of our five detectors.

**) This result is obtained normalizing the simulated spectrum to the experimental one using the 3 strong lines listed in column one. Comparison to the neighboring column on the right shows that the expected rates for the weak lines can change strongly if we take into account the simulation. The reason is that the line at 2010.7keV can be produced by summing of the 1401.50keV (1.55%) and 609.31keV (44.8%) lines, the one at 2016.7 keV by summing of the 1407.98 (2.8%) and 609.31 (44.8%) lines; the other lines at 2021.8keV and 2052.94keV do suffer only very weakly from the summing effect because of the different decay schemes.

++) This result is obtained using the number of counts for the three strong lines observed in the experimental spectrum and the branching ratios from [illegible] without including summing effects. For each of the strong lines the expected number of counts for the weak lines is calculated and then an average of the 3 expectations is taken.

***) Without simulation of the experimental setup. The numbers given here are close to those in the neighboring left column, when taking into account that Aalseth et al. refer to a spectrum which contains a normalization error of a factor of 9 (see also point 5).

Possible Evidence for 0ν2β: comments



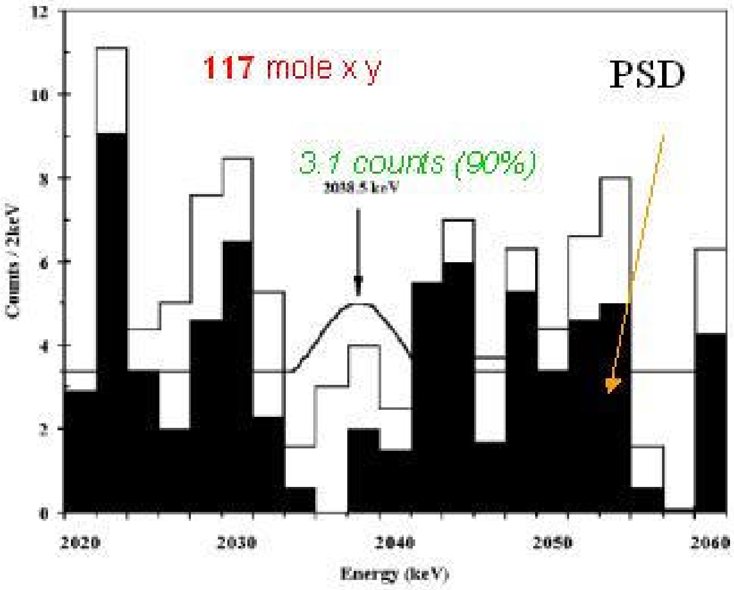
IGEX

hep-ex:0202026

Pacific Northwest National Laboratory (PNNL)
University of South Carolina (USC)
Institute for Theor and Exp Physics (ITEP, Rusia)
Institute for Nuclear Research (INR, Rusia)
Yerevan Physical Institute (Armenia)
University of Zaragoza (UZ)

$T_{1/2}(0\nu,0^+\rightarrow 0^+) > 1.57 \times 10^{25}$ y (90%)

$\langle m_\nu \rangle < 0.33\text{-}1.35$ eV



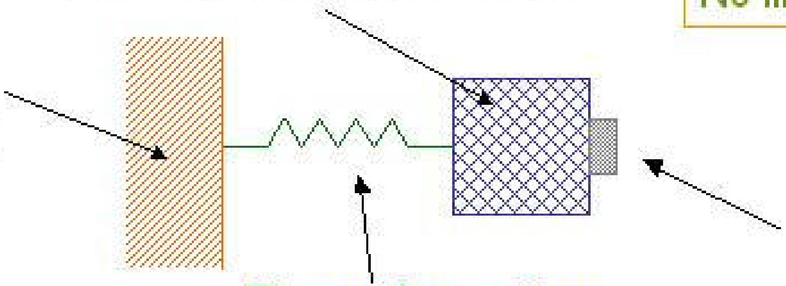
1994-2000
Canfranc underground laboratory
(Laboratory 3 at 2450 m.w.e.)

Three (2kg) Ge diodes (86% ^{76}Ge)

FWHM: 4 keV
Effective PSD (SSE): ~ 45% of total statistics

Heavy low activity shield:
- 40 cm of lead
- PVC box flushed with nitrogen
- 2mm of cadmium
- 20 cm of polyethilene
- active veto (plastic scintillators)

Low T Detector concepts



Te dominates in mass the compound
Excellent mechanical
and thermal properties

Energy absorber
TeO_2 crystal
$C \cong 2$ nJ/K $\cong 1$ MeV / 0.1 mK

Calorimetric approach
Good energy resolution
No limit to material choice

Heat sink
$T \cong 10$ mK

Thermometer
NTD Ge-thermistor
$R \cong 100$ MΩ
$dR/dT \cong 100$ kΩ/μK

Thermal coupling
$G \cong 4$ nW / K = 4 pW / mK

- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for $E = 1$ MeV
- Bias: $I \cong 0.1$ nA ⇒ Joule power $\cong 1$ pW ⇒ Temperature rise $\cong 0.25$ mK
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s
- Noise over signal bandwidth (a few Hz): $V_{rms} = 0.2\ \mu V$

In real life signal about
a factor 2 - 3 smaller

Energy resolution (FWHM): $\cong 1$ keV

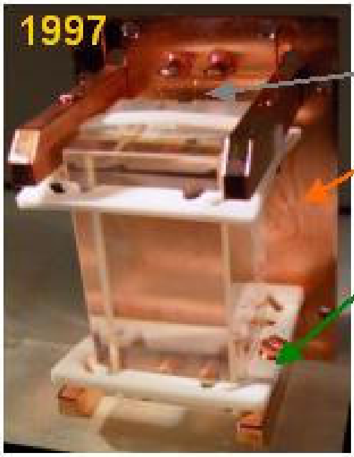
Structure & Evolution of the detectors

Common points:

Thermistor: NTD Ge chip glued with epoxy

Heat sink: Cu plates, frames and bars

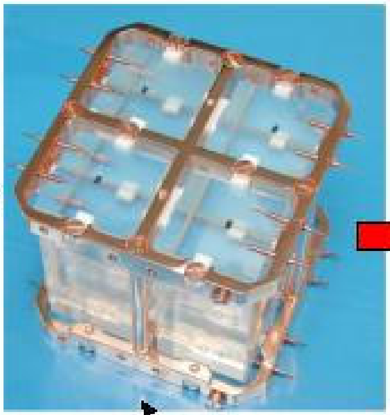
Holding method and thermal contact: Teflon elements

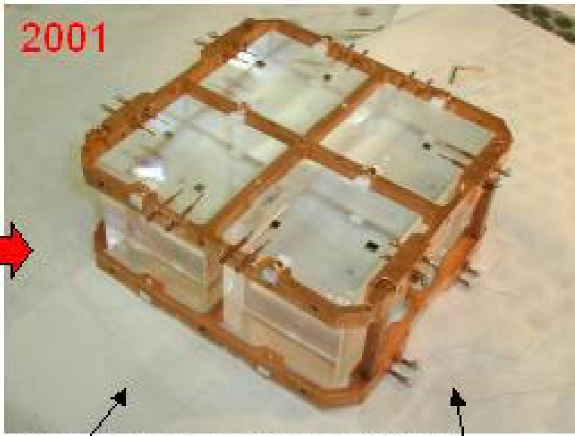


Mi DBD - I

- Crystal mass: 340 g
- Elementary module: 1 detector
- Large amount of Teflon
- Crystal surfaces: lapped in China with ^{238}U-contaminated power

- Crystal mass: 340 g - 760 g
- Elementary module: 4 detectors
- Small amount of Teflon
- Crystal surfaces: lapped by us with radio-pure power



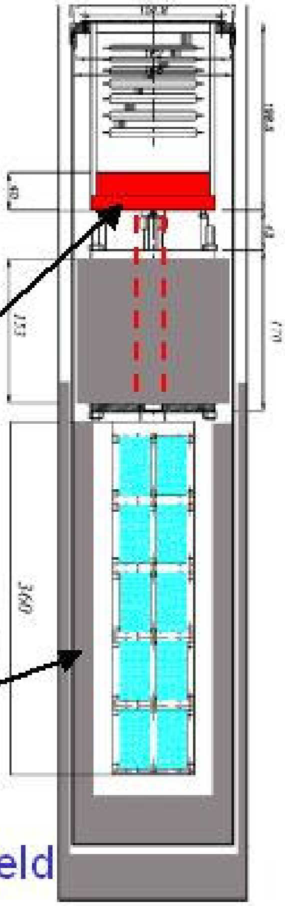


Mi DBD – II CUORICINO CUORE

The Mi DBD - II: experimental set-up

(a general test for the CUORICINO set-up)

5 modules, 4 detector each, are arranged in a tower-like compact structure (6.8 kg)



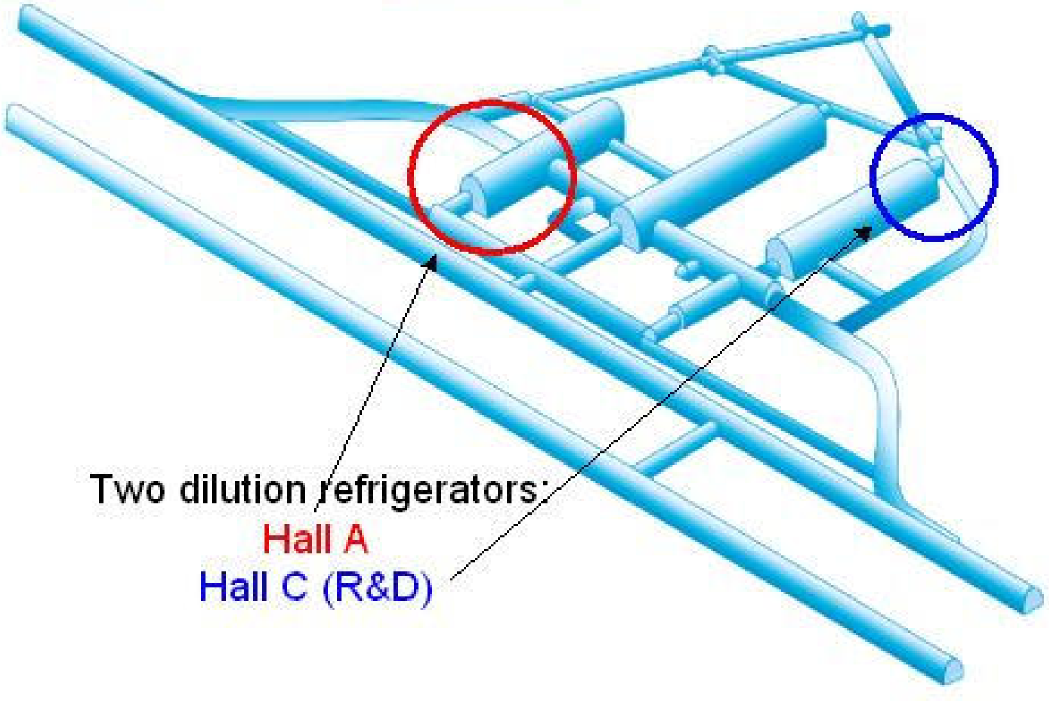
The tower is mounted inside a dilution refrigerator

Coldest point and cold finger

The tower is surrounded by an inner lead shield, (Roman lead) and all the refrigerator by a 20 cm thick outer lead shield

Mi DBD – II @ LNGS

Laboratori Nazionali
del Gran Sasso



Two dilution refrigerators:
Hall A
Hall C (R&D)

Mi DBD II: results

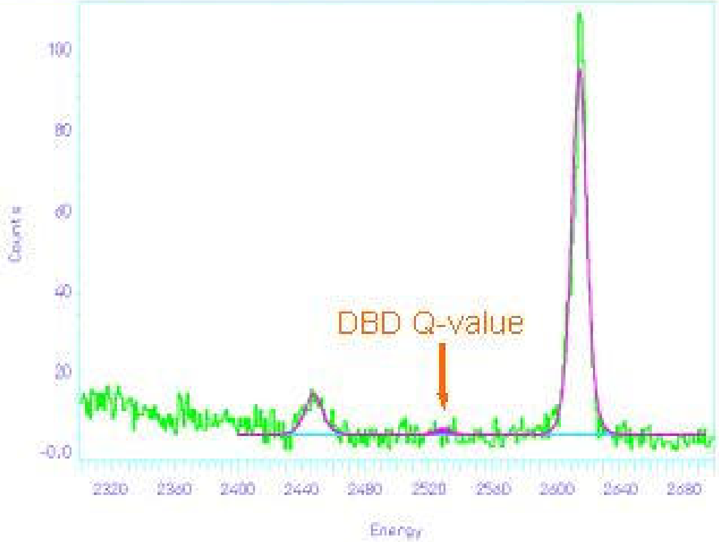
$0\nu2\beta$

Total statistic:

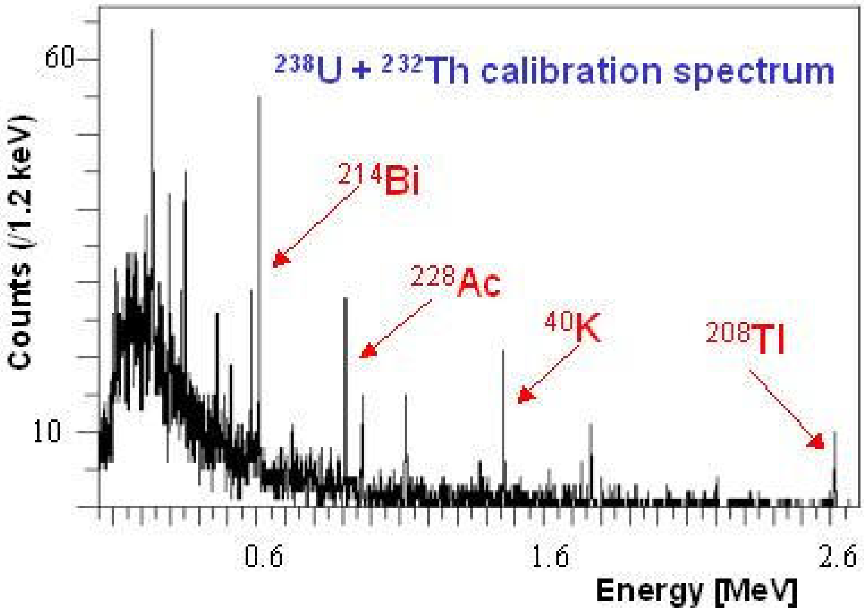
single 340 g detector +
4 × array +
20 × array (I and II) +
enriched crystal =
4.3 kg y

$\tau_{1/2} > 2.08 \times 10^{23}$ y @ 90% c.l.
(M.L. assuming flat BKG + ^{208}Tl and ^{214}Bi peaks)

$<m\nu> < 0.9 – 2.1$ eV



similar to 340 g crystal
thanks to improved detector design



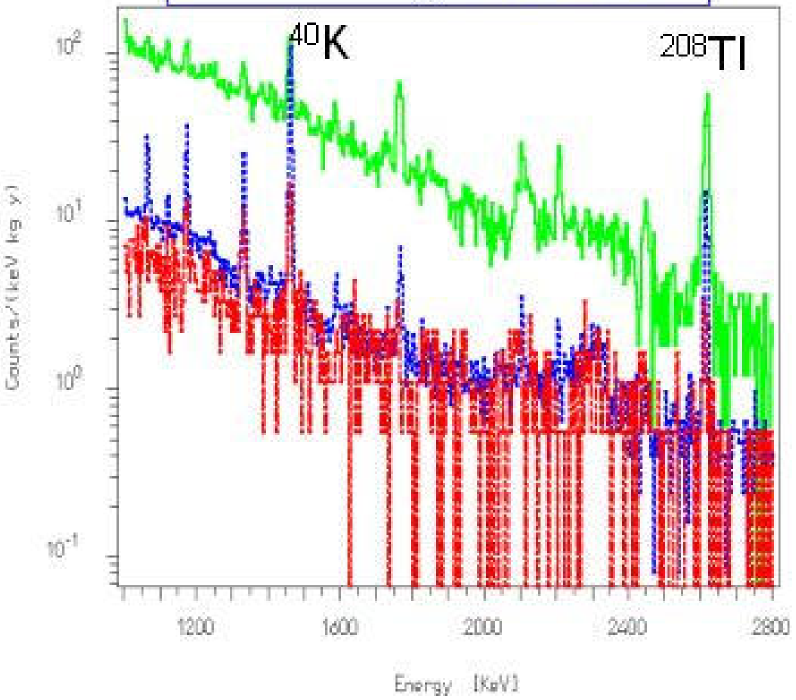
Performance of CUORICINO-type detectors (5×5×5 cm³ - 760 g):

- **Detector base T: ~ 7 mK**
- **Detector operation T: ~ 9 mK**
- **Detector response: ~ 250 mV/ MeV**
- **FWHM resolution: ~ 3.9 keV @ 2.6 MeV**

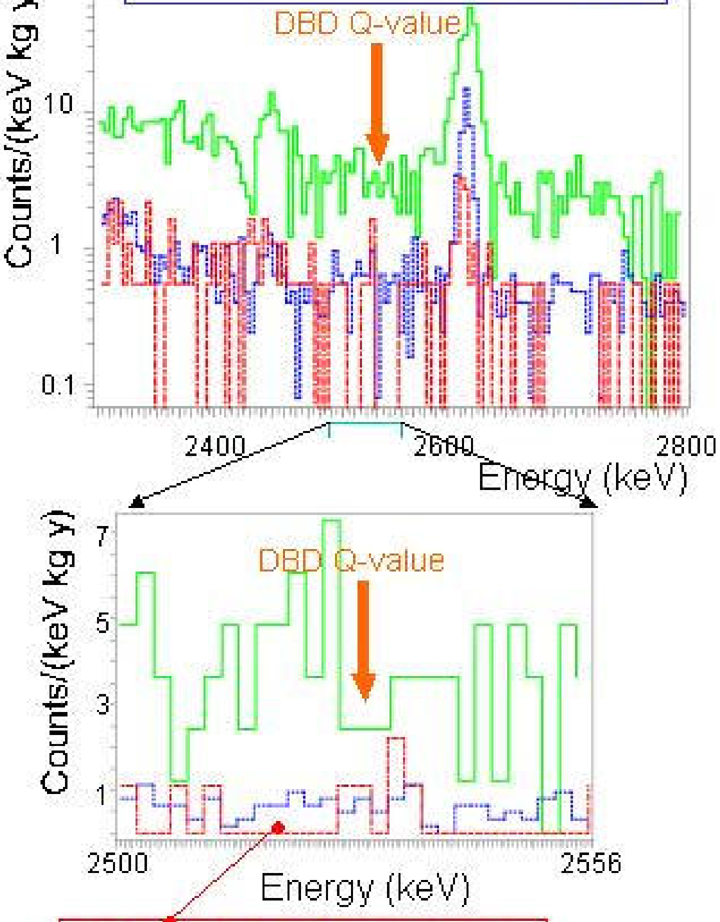
Mi DBD: background

- Mi single 340 g detector
- Mi DBD I
- Mi DBD II

BKG in the range 1.0 - 2.8 MeV



BKG in the range 2.3 - 2.8 MeV



0.33 ± 0.11 c/kev/kg/y

Mi DBD Background Model

Experiment/Montecarlo comparison:

- reliability
- quantitative contributions from different sources

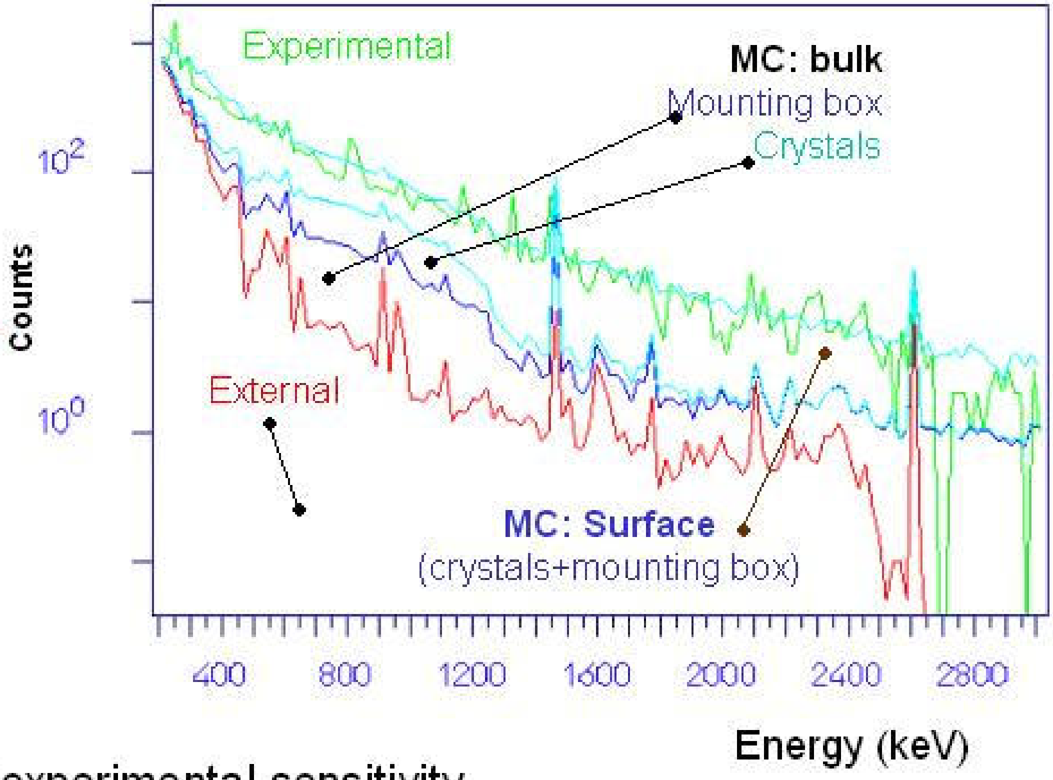
GEANT4

Mi DBD I

Mi DBD II

Cuoricino

Cuore



Reliable estimate of experimental sensitivity

Sensitivity limits

2^{nd} generation experiments common features:
- Large amount of source material (isotopic enrichment)
- Background reduction (R&D required)
- Intermediate scale steps (0.1-0.5 eV sensitivity on $<m_\nu>$)
- Ultimate goal: $<m_\nu>$ ~ 20-50 meV

Matrix elements calculations:
- QRPA
- NSM
- OEM

For each method: strength/weakness

… customary … but not really justified…

Spread on calculated $0\nu2\beta$ matrix elements

$\equiv$ uncertainty on their calculation

^{48}Ca	12.7	35.3	-	-	-	10.0
^{76}Ge	6.8	70.8	56.0	9.3	12.8	14.4
^{82}Se	2.3	9.6	22.4	2.4	3.2	6.0
^{100}Mo	-	-	4.0	5.1	1.2	15.6
^{116}Cd	-	-	-	1.9	3.1	18.8
^{130}Te	0.6	23.2	2.8	2.0	3.6	3.4
^{136}Xe	-	48.4	13.2	8.8	21.2	7.2
^{150}Nd^{a})	-	-	-	0.1	0.2	-
^{160}Gd^{a})	-	-	-	3.4	-	-

Backgrounds:
- Natural activity
- Cosmogenic and Induced activities
- Artificial produced activity
- $2\nu2\beta$

Comparable efforts are required

Future projects

Experiment	Author	Isotope	Detector description	$T^{5y}_{1/2}$(y)	$\langle m_\nu \rangle^*$
COBRA	Zuber 2001	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	0.71
CUORICINO	Arnaboldi et al 2001	^{130}Te	40 kg of TeO_2 bolometers	1.5×10^{25}	0.19
NEMO3	Sarazin et al 2000	^{100}Mo	10 kg of bb(0n) isotopes (7 kg Mo) with tracking	4×10^{24}	0.56
CUORE	Arnaboldi et al. 2001	^{130}Te	760 kg of TeO_2 bolometers	7×10^{26}	0.027
EXO	Danevich et al 2000	^{136}Xe	1 t enriched Xe TPC	8×10^{26}	0.052
GEM	Zdesenko et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen + water shield	7×10^{27}	0.018
GENIUS	Klapdor-Kleingrothaus et al 2001	^{76}Ge	1 t enriched Ge diodes in liquid nitrogen	1×10^{28}	0.015
MAJORANA	Aalseth et al 2002	^{76}Ge	0.5 t enriched Ge segmented diodes	4×10^{27}	0.025
DCBA	Ishihara et al 2000	^{150}Nd	20 kg enriched Nd layers with tracking	2×10^{25}	0.035
CAMEO	Bellini et al 2001	^{116}Cd	1 t $CdWO_4$ crystals in liquid scintillator	$> 10^{26}$	0.069
CANDLES	Kishimoto et al	^{48}Ca	several tons of CaF_2 crystal in liquid scintillator	1×10^{26}	
GSO	Danevich 2001	^{160}Gd	2 t Gd_2SiO_5:Ce cristal scintillator in liquid scintillator	2×10^{26}	0.065
MOON	Ejiri et al 2000	^{100}Mo	34 t natural Mo sheets between plastic scintillator	1×10^{27}	0.036
Xe	Caccianiga et al 2001	^{136}Xe	1.56 t of enriched Xe in liquid scintillator	5×10^{26}	0.066
XMASS	Moriyama et al 2001	^{136}Xe	10 t of liquid Xe	3×10^{26}	0.086

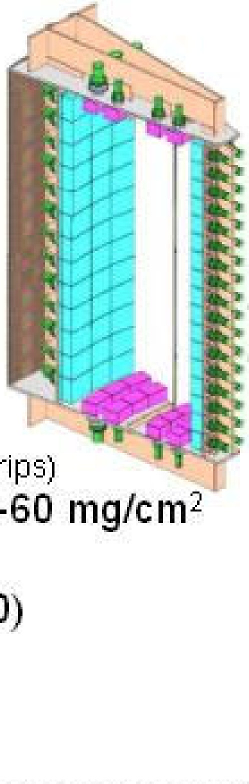
* Staudt, Muto, Klapdor-Kleingrothaus Europh. Lett 13 (1990) 31

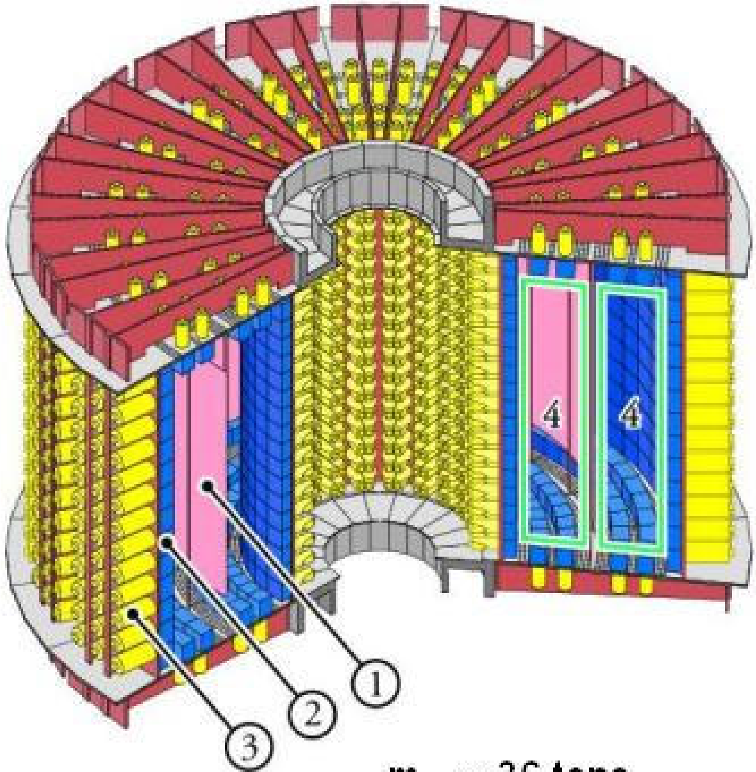
Neutrinoless Experiment with MOlibdenum III
or Neutrino Ettore Majorana Observatory

Large Collaboration: 13 groups from Europe, USA and Japan

Passive source - Spectroscopic approach

$0\nu2\beta$ sensitivity:
$T \sim 10^{24}$ y
$<m\nu> \sim 0.1$ eV





Detector structure: 20 sectors

1 Source:
up to 10 kg of $\beta\beta$ isotopes
(metal film or powder glued to mylar strips)
cylindrical surface: 20 m^2 x 40-60 mg/cm^2

2 Tracking volume:
open octagonal drift cells (6180)
operated in Geiger mode
(σ_r=0.5 mm, σ_Z=1 cm)

3 Calorimeter:
1940 plastic scintillators coupled to low activity PMs:
FWHM(1 MeV) ~ 11-14.5 %

$m_{tot} \sim 36$ tons
Low activity materials

Magnetic Field (30 G) + Iron Shield (20 cm) + Neutron Shield (30 cm H_2O)

NEMO 3

D.Lalanne&CS.Sutton contr. pap. ν 2002

Now Operating in the Frejus Underground Laboratory: 4800 m.w.e.

Identification of e^-, e^+, γ, n and delayed-α

- *ββ* events
- source radiopurity → after enrichment and chemical processing
- BKG rejection

by e-γ, e-γ-α coincidences analysis

Enriched sources placed in NEMO3

Isotope	Mass (g)	I.A.	Intended studies	$<m^{5y}{}_{\nu}>$ (eV)
^{100}Mo	6914	97%	ββ(0ν)	0.2-0.7
^{82}Se	932	97%	ββ(0ν)	0.6-1.2
^{116}Cd	405	93%	ββ(2ν)	
^{130}Te	454	89%	ββ(2ν)	
^{150}Nd	36.6	91%	ββ(2ν)	
^{96}Zr	9.4	57%	ββ(2ν)	
^{48}Ca	7.0	73%	ββ(2ν)	
^{nat}Te	207		Ext. γ bkg	
Cu	621		Ext. γ bkg	

March 2002: start without shielding
Summer 2002: start with full shielding

The CUORE set-up

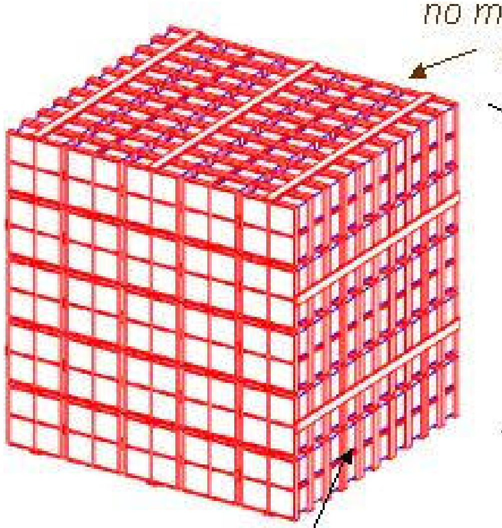
Cryogenic Underground Observatory for Rare Events

LBL – U. Como – U. Firenze – Legnaro (LNL)
LNGS – U. Milano – USC – U. Zaragoza

CUORE = closely packed array of 1000 detectors
25 towers - 10 modules/tower - 4 detector/module

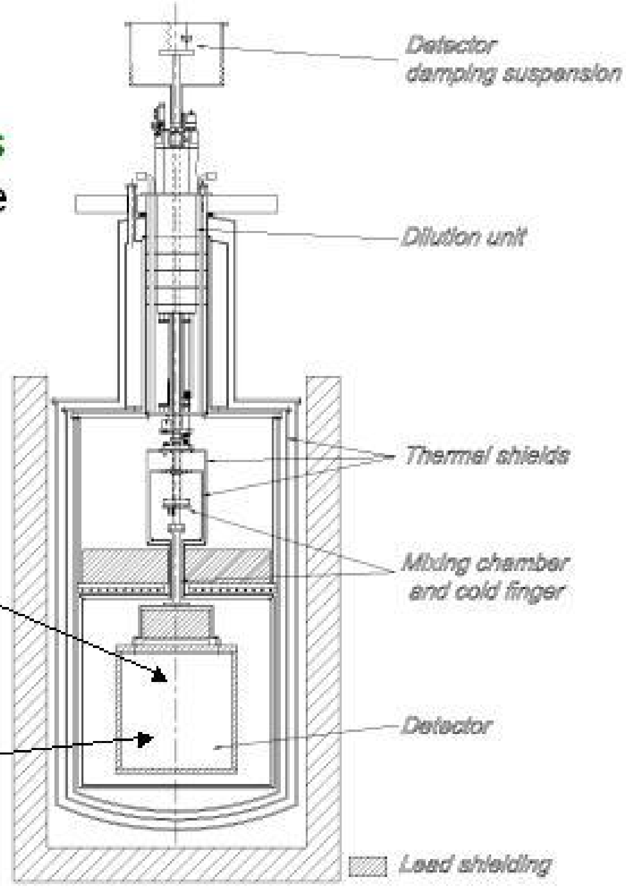
→ Cubic structure, ideal for active shielding

no more inert Cu plates facing crystals



M = 760 kg

Each tower is a CUORICINO-like detector



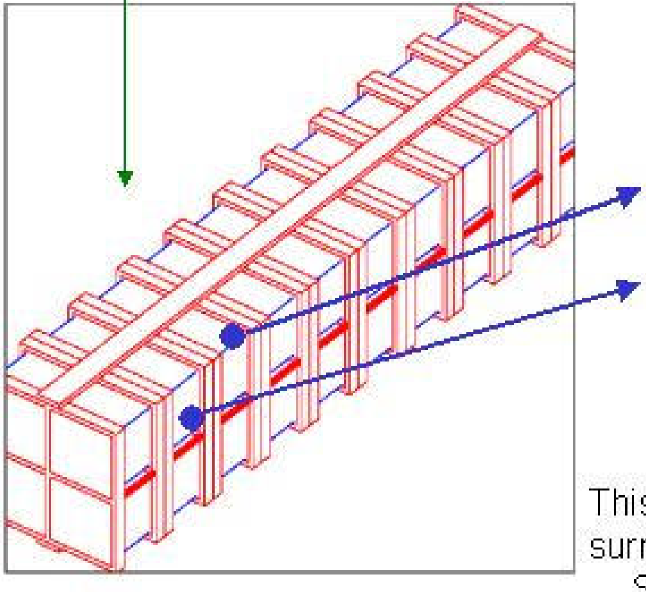
Special dilution refrigerator

The CUORICINO set-up

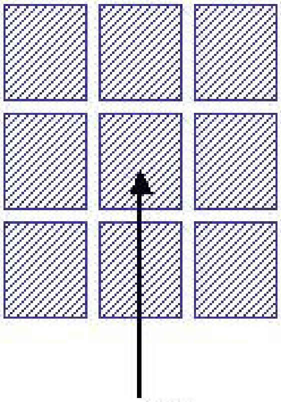
CUORICINO = tower of 13 modules, 4 detector (760 g) each

M = 40 kg

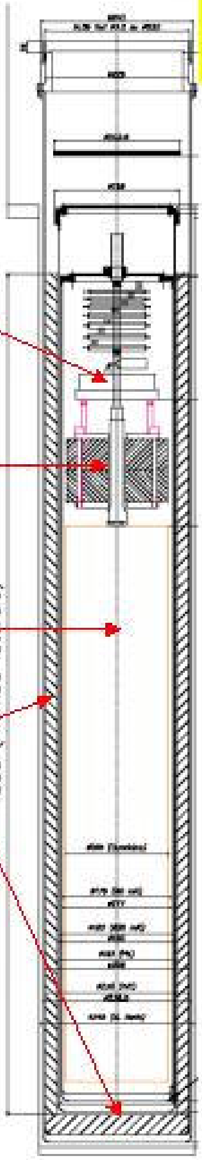
New configuration: 2 planes will consist of 340 g detectors arranged in a 3×3 matrix



Plane section



This detector will be completely surrounded by active materials.
Substantial improvement in BKG reduction



Coldest point

Cold finger

Tower

Lead shield

Same cryostat and similar structure as Mi DBD

EXO

Danilov M. et al. Phys. Lett. B480 (2000) 12

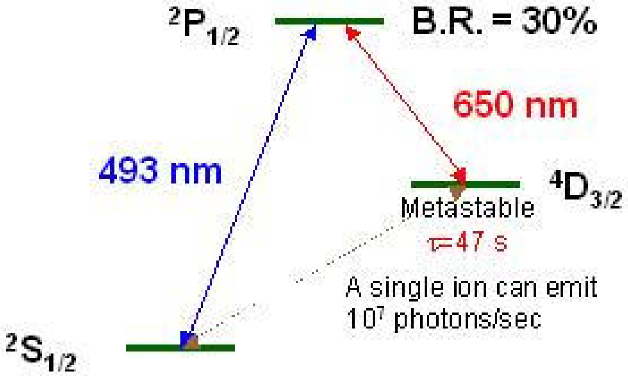
Large Xenon TPC
with single Ba^+-ion detection via laser tagging

Caltech
IBM Almaden
INFN Padova
ITEP Mosca
UC Irvine
Stanford University
U. of Alabama
U. of Neuchatel
U. of Torino
U. of Trieste
WIPP Carlsbad

- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$
- Double Laser Pulse
- Optical Spectroscopy

Strong background reduction

M.Moe PRC 44(1991)931



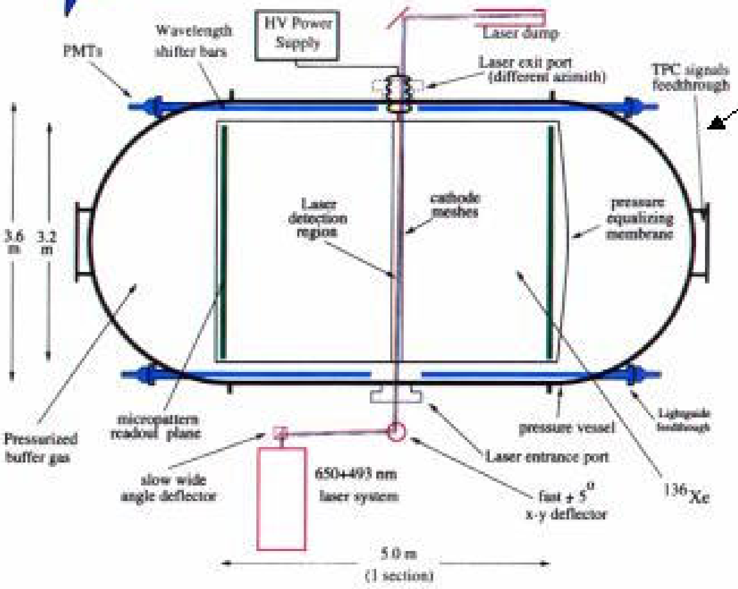
Ba^+ level structure

Xenon Properties:
- active source approach
- contonuous purification
- no activation
- versatility
- depleted Xe: bkg check
- easy isotopical enrichment

Requirements for high $0\nu2\beta$ sensitivity:
- Large mass (1-10 t)
- High Density Isotopically Enriched (90%) Xe TPC
- Good Energy Resolution (2%)
- Low Background Environment
- Ba^{++} Neutralization
- Long Ba lifetime in detector chamber

$T^{0\nu} > 8.3 \times 10^{26}$ y (90% C.L.) - $<m_\nu> < (0.05-0.14)$ eV in 5 y

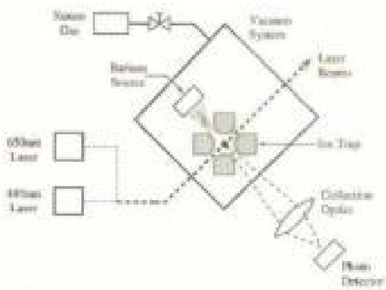
EXO (2)



Detector Configuration

Gas-Phase	
•Tracking: event topography	•High Pressure
•Additive gas for quenching and neutralization •In situ Spectroscopy •No Cryogenics	•Large Size
Liquid Phase	
•Small Size •No High Pressure •Ion analysys and quenching in vacuum	•Cryogenics •No tracking •No laser in liquid •Electrostatic Ion Extraction •Ba atom extraction for analysis

Single Ion Ba Spectroscopy:



- Ion trapping & measurement in vacuum
- Collisional broadening in Xe
- Ion lifetimes in Xe
- Distinguish ^{136}Ba from ^{137}Ba

Energy Resolution:

Ionization + Scintillation ⇒ 2%

100 kg PROTOTYPE goals

- Large Xe TPC engineering
- Energy resolution of large detector
- Background analysis

MAJORANA

Aalseth CE et al. hep-ex/0201021

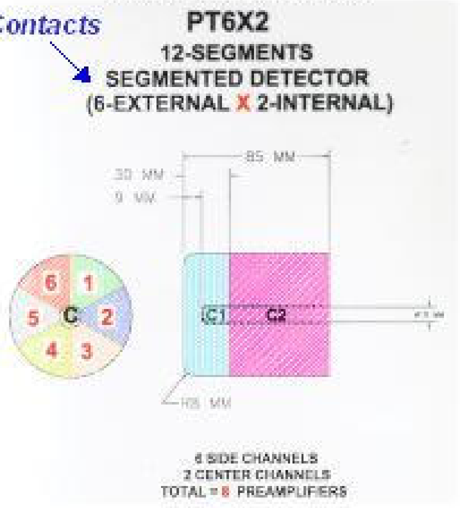
PNNL
South Carolina University
TUNL
ITEP
Dubna
NMSU
Washington University

GOAL: $\langle m_\nu \rangle \sim 0.02\text{-}0.07$ eV

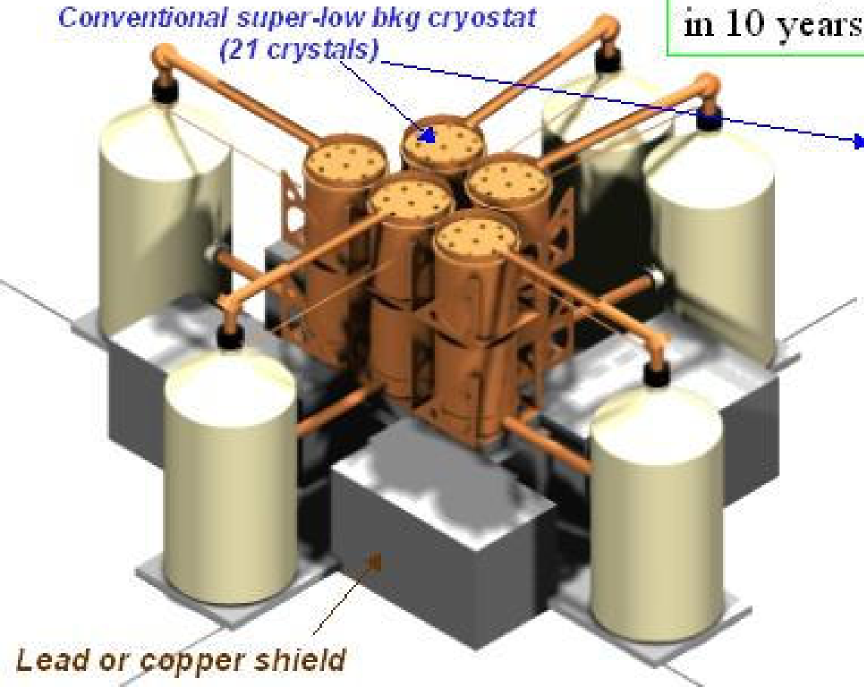
Main concern:

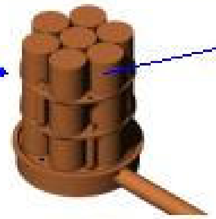
- cost and time for i.e. ^{76}Ge
- cosmogenic background
- material selection

Perkin-Elmer design



$T^{0\nu} > (0.4\text{-}2) \times 10^{28}$ y
in 10 years measurement





- **Deep underground location WIPP/Homestake**
- **~$20M enriched 85% ^{76}Ge**
- **210 2kg crystals, 12 segments**
- **Advanced signal processing**
- **~$20M Instrumentation**
- **Special materials (low bkg)**
- **10 year operation**

GENIUS

Klapdor-Kleingrothaus HV hep-ph/0103074

Very large mass extension of the active source Ge-diodes approach

GOAL:

- $\langle m_\nu \rangle$ sensitivity ~10-20 meV
- test all possible m_ν scenarios allowed by oscillation experiments

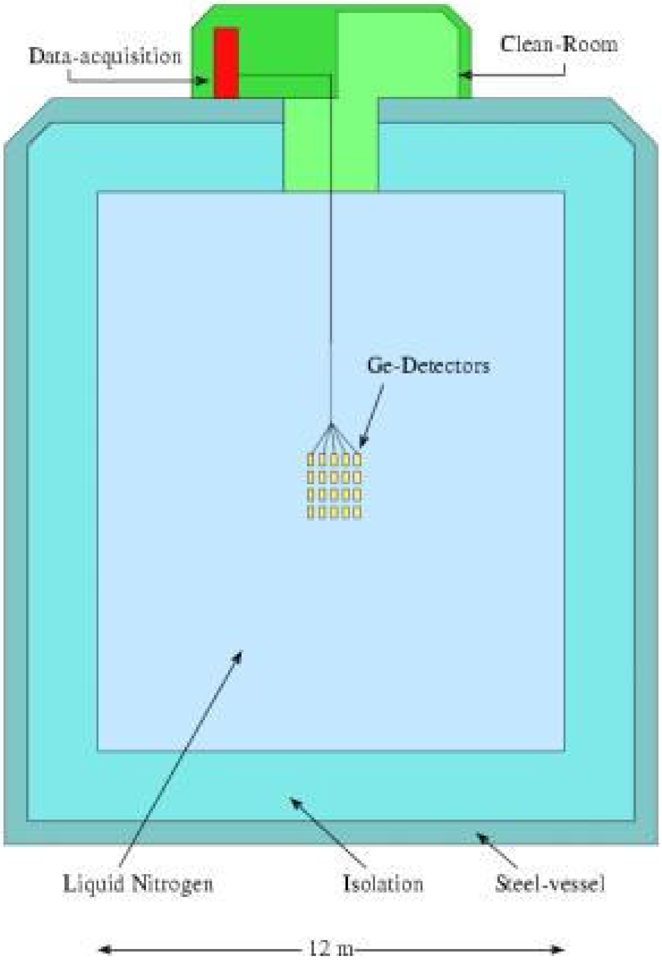
- Reduce Background
- Enlarge mass

SOLUTION:

large number (400) of naked i.e. (86%) diodes (total mass ~1 ton) → 10 tons suspended in a very large container of liquid nitrogen (clean shield)

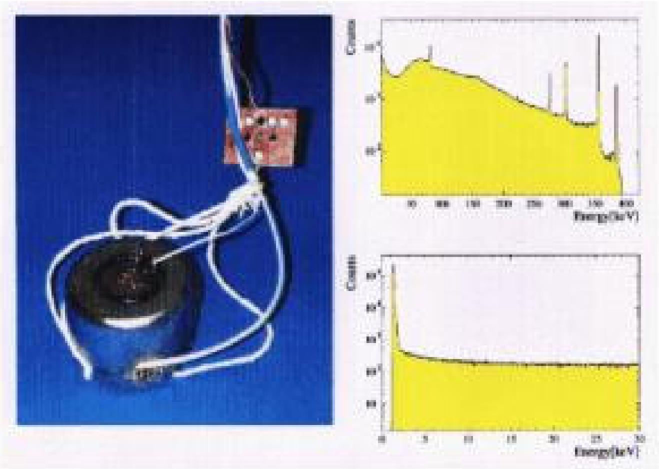
Gran Sasso or USA underground laboratory

DM & Solar Neutrinos



GENIUS (2)

- 3 small naked Ge detectors operated (for a short time) in LN @ LNGS
- Background analysis: very detailed Montecarlo calculations



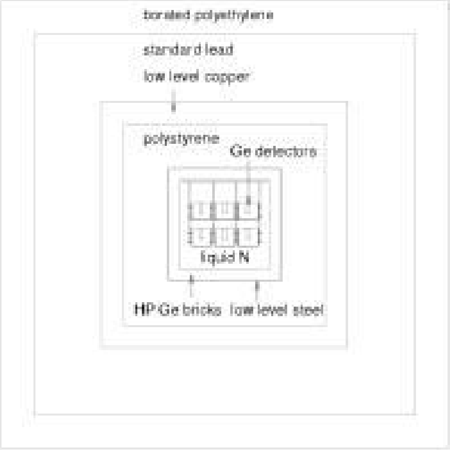
Main concern:

- **cost and time for i.e. ^{76}Ge**
- **liquid nitrogen vessel: dimensions & security**
- **cosmogenic background**

GENIUS-TF

Klapdor-Kleingrothaus HV hep-ph/0012022

Small 'naked HPGE in LN' setup



- 14 HP(natural)Ge diodes (m_T ~ 40 kg)
- small liquid nitrogen box
- standard (Cu+Pb) shield borated polyethylene

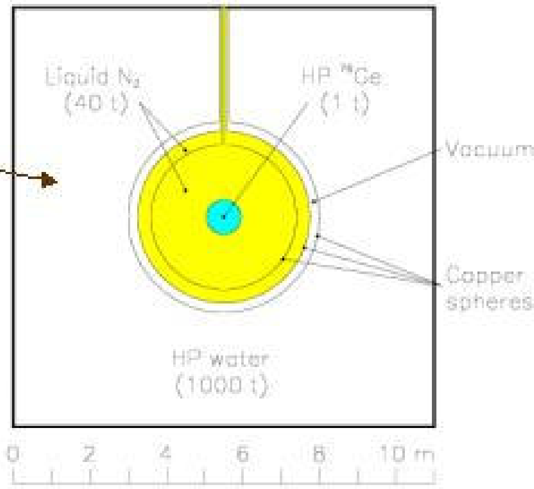
- Test long-term stability
- Cosmogenics deactivation
- Improve $0\nu2\beta$ sensitivity (<mn> ~ 0.1 eV)
- Improve DM search sensitivity (DAMA)

approved by the Scientific Committee of the Gran Sasso Laboratory

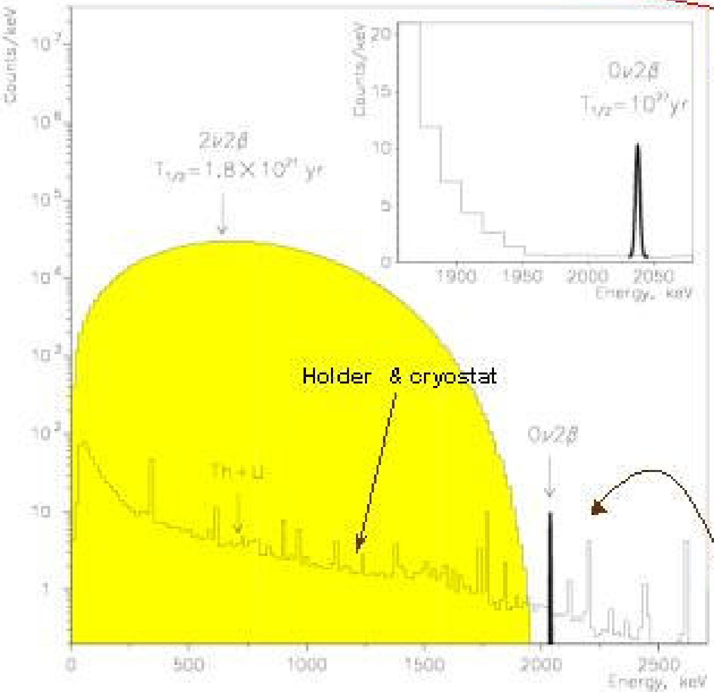
GEM

Zdesenko Y et al. nucl-ex/0106021

- 1 ton of naked HPGe diodes
  - phase-1: natural
  - phase-2: enriched (86%) in ^{76}Ge
- ultrapure liquid nitrogen (Ø 5m, 40 tons)
- copper vacuum cryostat
- high purity water (Ø 11 m, 1000 tons)



BOREXINO CTF?



Very detailed Montecarlo background estimate assuming the best up-to-date radioactive contamination levels (GENIUS, SNO and BOREXINO values)

⇒ bkg: 0.2 count/keV/ton/year

10 year measurement:

phase-1: $T^{0\nu} \geq 10^{27}$ y $<m_\nu> \leq 0.05$ eV

phase-2: $T^{0\nu} \geq 10^{28}$ y $<m_\nu> \leq 0.015\text{-}0.05$ eV

DCBA/COBRA

Drift Chamber Beta-ray Analyzer

Ishihara N et al , NIM A 443,101 (2000)

Passive source approach

^{150}Nd (Q=3.37 MeV)

OTO underground laboratory

Detector:

- Drift Chamber Module (464x524x680 mm^3)
- Solenoidal coil (720 Ø mm x 1.1 m)
- Cosmic-ray veto counter

Easy Large mass scaling

3D tracking in uniform **B**

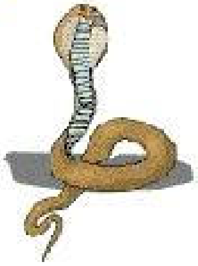
BKG reduction

Features:

- Particle identification
- Momentum measurement
- Energy meas. (140 keV FWHM @ 1MeV)
- Vertex detection (Δx ~3 mm)
- Detection efficiency (0.5-0.6)
- Versatility (natural/i.e. ^{150}Nd)
- 0ν-2ν separation

4 phases:

$\langle m_\nu \rangle \sim 6 - 0.05$ eV

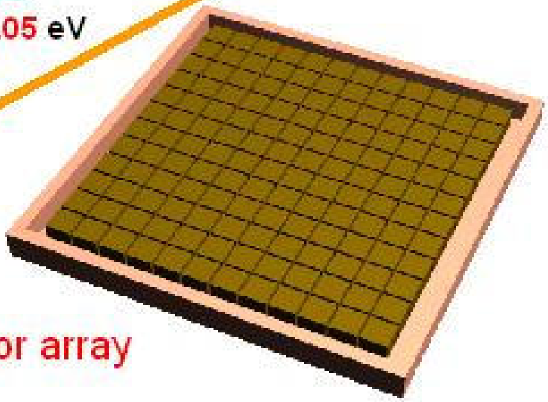


Use large amount of CdTe (CdZnTe) Semiconductor Detectors

Active source approach

- 10 kg CdTe
- 1600 1 cm^3 detectors
- En. resolution: 1% @ 662 keV
- 7 isotopes (especially ^{116}Cd and ^{130}Te)
- Mass limits for both below 1 eV in 5 y
- Study of double electron capture
- Upgrades possible (Tracking, Enrichment)

K. Zuber, Phys. Lett. B 519,1 (2001)



Detector array

MOON

Ejiri H. et al. Phys. Rev. Lett. 85 (2000) 2917

^{100}Mo → passive source for $0\nu2\beta$
→ target for solar neutrinos

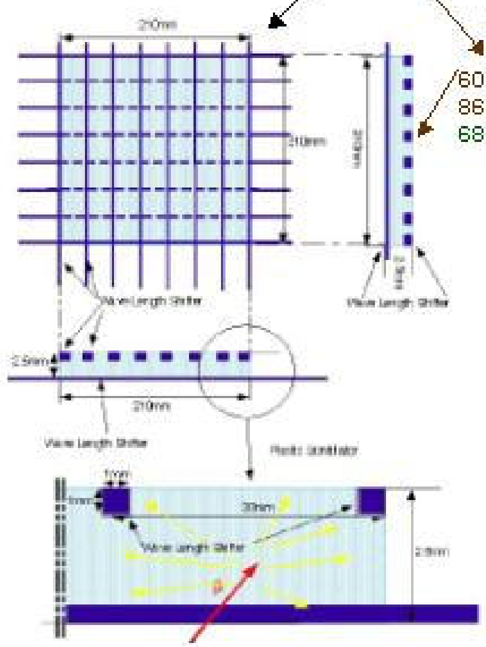
Electron energy and angular correlations

Supermodule of scintillator and Mo ensembles

1. 34 tons of natural Mo (~ 3.3 tons of ^{100}Mo: 6 x 6 x 5 m^3)

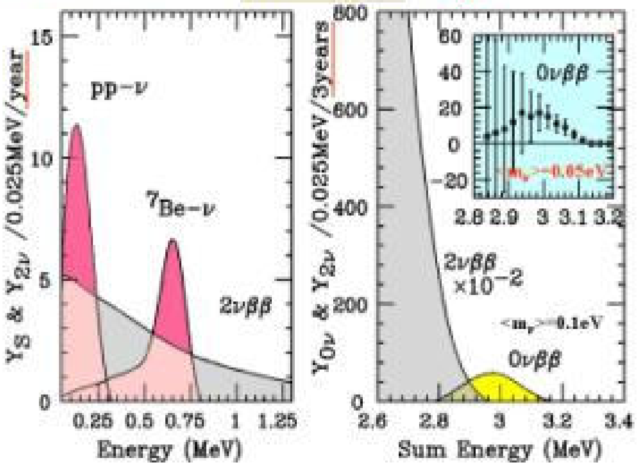
2. 1 ton of i.e. ^{100}Mo (2 x 2 x 2 m^3)

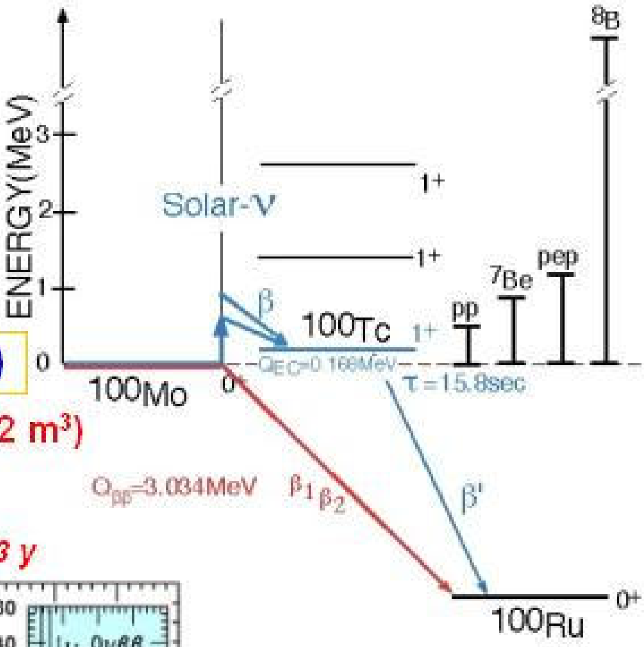
60.000 plastic scintillators
866.000 WLS fibers
68.000 16 anode PMTs



3.3 tons ^{100}Mo

3 y





Oto laboratory
Japan

Main concern:
- FWHM: 7%
- Mo radio-purity

Conclusions

- $0\nu2\beta$: a powerful telescope on otherwise unaccessible neutrino properties
- $0\nu2\beta$ @ $\langle m_\nu \rangle \sim 10$ meV ?
- Experimental goal: OBSERVE $0\nu2\beta$
- Larger, expensive and more challenging experiments
  - Background
  - Mass
  - Energy Resolution
  - Isotopic Enrichment
- Subproducts: Dark Matter, Solar n's, Radioactivity
- A wealth of proposal
  - International collaborations

Recent reviews:

Elliott SR and Vogel P Annu. Rev. Nucl. Part Sci. 52(2002), hep-ph/0202264
Tretyak VI and Zdesenko Y Atomic Data and Nuclear Data Tables 80 (2002) 83
Vergados JD Physics Reports 361 (2002) 1
Klapdor-Kleingrothaus HV, Pas H, Smirnov AY Phys. Rev. D 63:073005 (2001)
Ejiri H. Physics Reports 338 (2000) 265