The search for neutrino-less double beta decay ($0\nu\beta\beta$)

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Outline

• $0\nu\beta\beta$ decay and predictions from oscillation experiments
• Comparison of DBD isotopes
• Challenges & experimental approaches
• Overview experimental projects
• Outlook
$2\nu \beta \beta$ Decay

Observed in more than 10 isotopes
Life times $10^{18} – 10^{21}$ years
Mass parabolas

Ground states of even-even nuclei: $0^+$

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
$0\nu\beta\beta$ Decay

Not observed yet;
Life time limits $> 10^{24} - 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

$0\nu\beta\beta$ can be generated by:
• exchange of light Majorana neutrinos
• SUSY
• LR
• ..... 

Schechter & Valle:
if $0\nu\beta\beta$ observed $\Rightarrow \nu$ is Majorana particle!

S. Schöi
Phenomenology of $0\nu$- and $2\nu\beta\beta$ decay

$2\nu\beta\beta$: $(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e \quad \Delta L=0$

$T_{1/2}^{2\nu} = (10^{18} - 10^{21})$y

$0\nu\beta\beta$: $(A,Z) \to (A,Z+2) + 2e^- \quad \Delta L=2$

Experimental signatures:
- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- production of grand-daughter isotope
Decay rate and effective neutrino mass

Expected decay rate:

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \langle m_{ee} \rangle^2
\]

\(Q = E_{e1} + E_{e2} - 2m_e\)  
\(\langle m_{ee} \rangle = \sum_i U_{ei}^2 m_i\)  
\(U_{ei}\) (complex) neutrino mixing matrix

Phase space integral  
Nuclear matrix element  
Q-value of decay  
Effective neutrino mass

Assume leading term is exchange of light Majorana neutrinos

HK 9.7 P.Grabmayr
0νββ: physics implications

1) Dirac vs. Majorana particle: (i.e. its own anti-particle)?
   - $0νββ \Rightarrow$ Majorana nature
   - Majorana $\Rightarrow$ See-Saw mechanism
     \[ m_ν = \frac{m_D^2}{M_R} \ll m_D \]
     \[ m_3 \sim \left( \Delta m_{atm}^2 \right)^{1/2}, \quad m_D \sim m_t \Rightarrow M_R \sim 10^{15} \text{GeV} \]
   - Majorana $\Rightarrow$ CP violation in $M_R \rightarrow$ higgs + lepton
     $\Rightarrow$ Leptogenesis $\Rightarrow$ B asymmetry

2) Absolute mass scale:
   - Hierarchy: degenerate, inverted or normal
   - (effective) neutrino mass

S. Schöner, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Predictions from oscillation experiments

\[ \langle m_{ee} \rangle = \left| \sum_i U^2_{ei} m_i \right| \]

F. Feruglio, A. Strumia, F. Vissani, NPB 659

Negligible errors from oscillations; width due to CP phases

90% CL

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Predictions from oscillation experiments

KDKC claim:
[0.17-0.45] eV
(PRD79)

Goal of next generation experiments:
~10 meV

90% CL
Negligible errors from oscillations; width due to CP phases

F. Feruglio,
A. Strumia,
F. Vissani,
NPB 659
Comparison of DBD isotopes:
Recent calculations of nuclear matrix elements

QRPA calculations from other groups give similar results

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Comparison of DBD isotopes:
Recent calculations of nuclear matrix elements

But shell model and QRPA calculations still disagree up to a factor 2 for lighter nuclei

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Comparison of DBD isotopes:
Recent calculations of nuclear matrix elements

New IBM-2 calculations agree (coincide?) with QRPA values! Score 2:1?
IBM-2 includes deformations for $^{150}$Nd

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Comparison of DBD isotopes:
Recent calculations of nuclear matrix elements

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \langle m_{ee}\rangle^2
\]

Is $M$ decreasing with $A^{-2/3}$ (IBM-2, QRPA) or constant with $A$ (SM)?

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Comparison of isotopes: 
Is there a super-DBD-isotope?

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q, Z) \left| M_{0\nu} \right|^2 \left\langle m_{ee} \right\rangle^2$$

Expected $0\nu\beta\beta$ rates per mass vary within a factor $\sim 4$!
QRPA
(Simkovic et al. PRC 77, 2008)

for $\langle m \rangle = 50$ meV:
9.1 cts/(ton year)

IBM2
(Barea and Iachello, PRC 79, 2009)

~3
13.2 cts/(ton year)

SM
(Caurier et al., PRL 100, 2008)

~4
2.2 cts/(ton year)

jahrstagung HK, Bonn 16.3.2010
Experimental sensitivity

Without bkgd: \( \langle m \rangle \leq \frac{\text{const}}{(MT)^{1/2}} \)

With bkgd: \( \langle m \rangle \leq \text{const} \left( \frac{b \Delta E}{MT} \right)^{1/4} \)

⇒ Maximize number of nuclei under observation
⇒ Minimize background (radioactivity, cosmics) in energy window at \( Q_{\beta\beta} \) (“background free”)

⇒ 1 ton of isotopes AND \( b \cdot \Delta E < 10^{-3} / \text{kg y} \) for 10 meV scale
Two ways to measure $0
\nu\beta\beta$ decay

Source = Detector

Solid (~1mm) – gas (~50 cm)

Source ≠ Detector

Energy measurement

Track measurement
 optional: meas. sign with magnetic field

Calorimetry & tracking

~10 - 1000 mm

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
State-of-the-art: limits & claim

71.7 kg year - Bgd 0.11 / (kg y keV)
28.75 ± 6.87 events (bgd:~60)
Claim:4.2σ evidence for 0νββ
(0.69–4.18) x10^{25} y (3σ)
Best fit: 1.19 x10^{25} y (NIMA 522/PLB 586)
PSA analysis (Mod. Phys. Lett. A21):
(2.33 + 0.44 − 0.31)x10^{25} y (6σ)
Tuebingen/Bari group (PRD79):
\( m_{ee} / \text{eV} = 0.28 \ [0.17-0.45] \ 90\% \text{CL} \)

Significance and \( T_{1/2} \) depend on bgd description:
  using realistic background model
⇒ peak significance: 1.3σ,
⇒ \( T_{1/2} = 2.2 \times 10^{25} \text{ y} \)
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⇒ Claim must be scrutinized with

76Ge AND other isotopes

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
### Overview of Experiments

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$^{130}$Te: Cuoricino @ LNGS

Measurement of $\Delta T = E/C$

- 41 kg TeO$_2$
- nat. abundance of $^{130}$Te: 34%
- active mass: 11 kg of $^{130}$Te
- New $Q_{\beta\beta}$:
  $2527.518 \pm 0.013$ keV (F. Avignone et al 2008)
  $2527.01 \pm 0.32$ keV (R. Norman et al 2008)
- $\Delta E$: -3 keV

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Cuoricino data taking completed,....

- Cuoricino data taking successfully completed in 2008
- Full statistics statistics: 18 kg x year of $^{130}\text{Te}$
- Background at $0\nu\beta\beta$: $0.18 \pm 0.02 \text{ cts/(keV kg y)}$
- Degraded $\alpha$'s (60%) ext. $^{208}\text{Tl}$ $\gamma$'s (40%)
- Limit on $^{130}\text{Te}$ $0\nu\beta\beta$ decay: $T_{1/2} > 2.94 \times 10^{24} \text{ y (90\% C.L.)}$ $m_{\text{ee}} < 0.2 - 0.98 \text{ eV}$

(M. Sisti, Taup 09)

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
...CUORE construction started..

The COURE building in hall A of LNGS

988 TeO₂ 5x5x5 cm³ crystals => 741 kg TeO₂ => 204 kg $^{130}$Te

Cryostat order placed

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
…. and LUCIFER is funded!

Suppression of surface alphas by simultaneous read-out of heat & light

Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
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NEMO 3 @ LSM: The ‘2νββ factory’...

Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 60 mg/cm²

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
....and its sources

$^{100}\text{Mo} \ 6.914 \text{ kg}$
$Q_{\beta\beta} = 3034 \text{ keV}$

$^{82}\text{Se} \ 0.932 \text{ kg}$
$Q_{\beta\beta} = 2995 \text{ keV}$

$^{116}\text{Cd} \ 405 \text{ g}$
$Q_{\beta\beta} = 2805 \text{ keV}$

$^{96}\text{Zr} \ 9.4 \text{ g}$
$Q_{\beta\beta} = 3350 \text{ keV}$

$^{150}\text{Nd} \ 37.0 \text{ g}$
$Q_{\beta\beta} = 3367 \text{ keV}$

$^{48}\text{Ca} \ 7.0 \text{ g}$
$Q_{\beta\beta} = 4272 \text{ keV}$

$^{130}\text{Te} \ 454 \text{ g}$
$Q_{\beta\beta} = 2529 \text{ keV}$

$^{\text{nat}}\text{Te} \ 491 \text{ g}$

$^{62}\text{Cu} \ 621 \text{ g}$

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Results from NEMO3’s strongest source: $^{100}$Mo

Data until the end of 2008

V. Tretyak (Medex’09), also F. Mauger (Taup09)

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
## From NEMO3 to SuperNEMO

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<tr>
<td>$T_{1/2} &gt; 1.4 \times 10^{24}$ y, $&lt;m&gt; &lt; 390 - 810$ meV</td>
<td>$T_{1/2} &gt; 1 - 1.5 \times 10^{26}$ y, $&lt;m&gt; &lt; 43 - 145$ meV *</td>
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<tr>
<td>7 kg</td>
<td>100 – 200 kg</td>
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<tr>
<td>8 % FWHM @ 3 MeV</td>
<td>4 % FWHM @ 3 MeV</td>
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<tr>
<td>18 %</td>
<td>30 %</td>
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<td>$^{208}$TI $&lt; 20$ μBq / kg</td>
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</tr>
<tr>
<td>$^{214}$Bi $&lt; 300$ μBq / kg</td>
<td>$^{214}$Bi $&lt; 10$ μBq / kg</td>
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**Notes:**

Baseline: $^{82}$Se
Alternatives: $^{150}$Nd, $^{48}$Ca

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
SuperNEMO at the new LSM

- 5 - 7 kg of $\beta\beta$ isotope per module
- 20 - 22 modules for the full detector for 100 – 150 kg of isotope in total
- modules surrounded by water shielding
- Location: LSM (France)
- demonstrator operational 2011

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
### Running & recently completed experiments

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*: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%

2010
Two new $^{76}$Ge Projects:

**GERDA**

- ‘Bare’ $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / H$_2$O
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

**Majorana**

- Array(s) of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)

**Physics goals:** degenerate mass range
**Technology:** study of bgds. and exp. techniques

**LoI**
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana
Novel Ge-detectors with advanced $0\nu\beta\beta$-signal recognition & background suppression

- **$0\nu\beta\beta$:** point-like events
- **Bgd:** multi-site or partial energy deposition outside crystal

n-type detectors with 18-fold segmented electrodes

HK 9.2 A.Vauth
T 110.6 S.Hemmer

R&D: LAr scintillation read out

HK 9.6 D.Budjáš
HK 9.9 M.Agostini
T 109.6 H.A.Khozani
T 113.8 M.Heisel,
Unloading of vacuum cryostat
(6 March 08)

Produced from selected low-background austenitic steel
Construction of water tank

∅ 10 m
H = 9.5 m
V = 650 m³

Designed for external $\gamma, n, \mu$ background
~$10^{-4}$ cts/(keV kg y)
construction of clean room
Water tank and cryostat prior muon veto installations

WT and cryostat with muon veto installed

“Pill box”
Glove-box for Ge-detector handling and mounting into commissioning lock under N$_2$ atmosphere installed in clean room
• Liquid argon filled in Dec.’09
• Successful commissioning of cryogenic system
• Water tank partially filled
• Installation c-lock in March
• Ready for commissioning run with natGe detector string in April ’10
• Subsequently, start Phase I physics data taking
Phases and physics reach

- $2 \times 10^{27}$ (90 % CL) *
- $2 \times 10^{26}$ (90 % CL) *
- $3 \times 10^{25}$ (90 % CL)*

*: no event in ROI

required for ‘background free’ exp. with $\Delta E \sim 3.3$ keV (FWHM):

$O(10^{-3}) \quad O(10^{-4})$ counts/(kg·y·keV)

**Background requirement for GERDA/Majorana:**

⇒ Background reduction by factor $10^2 - 10^3$ required w.r. to precursor exps.
⇒ Degenerate mass scale $O(10^2 \text{ kg·y})$ ⇒ Inverted mass scale $O(10^3 \text{ kg·y})$
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*: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%
EXO-200: a liquid $^{136}$Xe TPC
(without $^{136}$Ba grand-daughter tagging)

~110 kg $^{136}$Xe active mass

46 -170 events on top of bgd for KK claim

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
EXO-200 goes underground…

…and commissioning will start early 2010
Gaseous $^{136}$Xe TPC R&D

**Advantage:** Gas Xe has the potential of providing event topology information along with very good energy resolution

**Challenge:** low density provides limited self shielding

**EXO-gas** with Ba-tagging

Initial concept: in-situ tagging
New concept: Ba++ extraction

(D. Sinclair, Taup 2009)

**NEXT** high pressure TPC (without Ba-tagging) in Canfranc

T 110.4 M. Ball

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
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SNO+

- $300M of heavy water removed and returned to Atomic Energy of Canada Limited (every last drop)
- SNO detector to be filled with liquid scintillator
  - 50-100 times more light than Cherenkov
- linear alkylbenzene (LAB)
  - compatible with acrylic, undiluted
  - high light yield, long attenuation length
  - safe: high flash point, low toxicity
  - cheaper than other scintillators
- physics goals: pep and CNO solar neutrinos, geo neutrinos, reactor neutrino oscillations, supernova neutrinos, double beta decay with Nd

(C. Krauss, Taup 09)

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
0νββ Signal for $\langle m_\nu \rangle = 0.150$ eV

1000 events per year (assuming QRPA with spherical nucleus!)
with 1% natural Nd-loaded liquid scintillator in SNO++

- 0.1% natural Nd-loaded liquid scintillator in SNO+ $\Rightarrow$ 56 kg of $^{150}$Nd
- Future: use of enriched $^{150}$Nd?

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
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<td>26 kg</td>
<td>ionization</td>
<td>SUSL</td>
<td>2012</td>
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<tr>
<td>NEXT</td>
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<td>80 kg</td>
<td>gas TPC</td>
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*: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%
COBRA: CdZnTe Semiconductor Detectors

Focus on $^{116}\text{Cd}$, Q-value: 2809 keV

Energy measurement only

Underground setup at LNGS

Energy measurement and tracking

(K. Zuber, Taup 2009)

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
COBRA as solid-state TPC:

Pixelisation can be used for background reduction by particle identification

Monte Carlo: 200 $\mu$ m pixel size

Real data: 55 $\mu$ m pixel size

Samples of different particles

(K. Zuber TAUP09)
Summary & Outlook

0νββ experimental strategy during the next decade

Recent & current experiments:
- ~ 1 eV
- few 10 kg·year

Quasi-degenerate:
- ~ 100 meV
- 100 kg·year
- 4-6 expts

Inverted hierarchy:
- few 10 meV
- several ton·years
- at least 2 expts

Normal hierarchy:
- few meV
- ~ 100 ton·years

measure ≥8 DBD isotopes with different techniques;
Precision <m> & NME, leading term

observed

NOT observed

until present 2009 - 2014 2013 - 2020

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Outlook

ASPERA
European strategy

ASPERA recommendation for Neutrino Mass:
Depending on the outcome of the present generation of double beta decay experiments being prepared, we recommend the eventual construction and operation of one or two double beta decay experiments on the ton-scale, capable of exploring the inverted-mass region, with a European lead role or shared equally with non-European partners. A decision on the construction could be taken around 2013.

Similar financial efforts from North America & Japan required to realize ton scale experiments!

S. Schönert, MPIK - DPG Frühjahrstagung HK, Bonn 16.3.2010
Extra slides
Many thanks to all colleagues & friends for providing up to date material!

Apologies to those whose projects could not be covered in this talk!
<table>
<thead>
<tr>
<th>Name</th>
<th>Nucleus</th>
<th>Mass*</th>
<th>Method</th>
<th>Location</th>
<th>Time line</th>
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<tbody>
<tr>
<td><strong>Operational &amp; recently completed experiments</strong></td>
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<td>CUORICINO</td>
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$^{48}$Ca CANDLES.....

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer

- undoped CaF$_2$ (CaF$_2$(pure))
  - $^{48}$Ca ($Q_{\beta\beta}$=4.27 MeV)
  - Attenuation length > 10 m
  - Low radioactive impurities
- Low background detector
  - $4\pi$ active shield (LS)
  - Passive shield (Water, LS)
  - Pulse shape information
- Good energy resolution
  - large photo-coverage
  - Two phase LS system

(I. Ogawa, Taup 2009)

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....will illuminate Kamioka

Kamioka room D

San-chika

First PMT was installed at 24 June, 2009.

305 kg (96 x 10^3 cm^3 crystals) of natural-CaF_2
\Rightarrow 350 g of Ca-48
GERDA @ LNGS
Commissioning started in autumn 2009

Detector string
Glove box & lock
Clean room
Cryostat & \(\mu\)-veto
Heat exchanger & pipes