Crystal Based Double Beta Decay Experiments

A. Garfagnini

Padova University and INFN

July 23, 2011
Neutrinos

What we know

1. Masses:
   - $\Delta m_{12}^2$ and $|\Delta_{13}^2|$ are known;

2. Mixing matrix: $U_{ij}$ characterized by
   - three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
   - one Dirac CP phase: $\delta$
   - two Majorana phases: $\Phi_2, \Phi_3$

$\theta_{12}, \theta_{23}$ measured, new results on $\theta_{13}$

What we do NOT know (yet)

1. Absolute Mass Scale (offset);
2. Mass Hierarchy ($1 \Rightarrow 2 \Rightarrow 3$ or $3 \Rightarrow 1 \Rightarrow 2$)
3. Neutrino Nature (Majorana or Dirac particle);
4. phases ($\delta, \Phi_2, \Phi_3$).

Double Beta Decay experiments can address (3)
If $\nu$ is Majorana’s $\Rightarrow$ shed light on a combination of (1), (2), (4).
Neutrinos: Majorana versus Dirac particles

- How to test the neutrino mass nature?
- Experimental problem:

\[ P(\nu_L \rightarrow \nu_R) \sim \left( \frac{m_\nu}{E_\nu} \right)^2 \]

- is vanishing small, \( m_\nu \sim O(eV) \) or smaller . . . \( E_\nu \sim O(MeV) \) or bigger.

The only know technique is neutrinoless double beta decay.
Double Beta Decays ($2\nu$ and $0\nu$)

$2\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$
- 2nd order process, observed in many isotopes
- $T_{1/2} \sim 10^{19} - 10^{21}\text{y}$
- $\Delta L = 0$
  for $^{76}\text{Ge} : T_{1/2} \sim 1.5 \pm 0.1 \cdot 10^{21}\text{y}$

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + 2e^-$
- new physics
- $T_{1/2} > 10^{25}\text{y}$
- $\Delta L = 2$

Experimental signature

- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- grand-daughter isotope produced

\[
\frac{1}{\tau} = F(Q_{\beta\beta}, Z) \left| M_{\text{nucl}} \right|^2 < m_{ee} >^2
\]
Effective Neutrino Mass

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

F. Feruglio
A. Strumia
F. Vissani
Nucl. Phys. B 659

\[ < m_{ee} > = \left| \sum_i U_{ei}^2 m_i \right| \]

\( U_{ei} \) : neutrino mixing matrix (complex)

Negligible errors from oscillations; width of the curves due to CP phases.
### Best limits on $0\nu$ DBD

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Detector</th>
<th>Exposure (kg · y)</th>
<th>Technique</th>
<th>$\tau_{1/2}$ (y) - (90% C.L.)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>H&amp;M</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge</td>
<td>47.7</td>
<td>Ge diode</td>
<td>$&gt; 1.9 \cdot 10^{25}$ $^{2.23+0.44}_{0.31} \cdot 10^{25}$</td>
<td>1, 2</td>
</tr>
<tr>
<td>IGEX</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge</td>
<td>117 mol · y</td>
<td>Ge diode</td>
<td>$&gt; 1.6 \cdot 10^{25}$</td>
<td>3</td>
</tr>
<tr>
<td>NEMO 3</td>
<td>$^{82}\text{Se}$</td>
<td>Se</td>
<td>3.6</td>
<td>tracking</td>
<td>$&gt; 3.6 \cdot 10^{23}$</td>
<td>4</td>
</tr>
<tr>
<td>NEMO 3</td>
<td>$^{100}\text{Mo}$</td>
<td>Mo</td>
<td>26.7</td>
<td>tracking</td>
<td>$&gt; 1.1 \cdot 10^{24}$</td>
<td>4</td>
</tr>
<tr>
<td>CUORICINO</td>
<td>$^{130}\text{Te}$</td>
<td>TeO$ _2$</td>
<td>20</td>
<td>bolometric</td>
<td>$&gt; 2.8 \cdot 10^{24}$</td>
<td>5</td>
</tr>
<tr>
<td>DAMA</td>
<td>$^{136}\text{Xe}$</td>
<td>L Xe</td>
<td>4.5</td>
<td>Xe scint</td>
<td>$&gt; 1.2 \cdot 10^{24}$</td>
<td>6</td>
</tr>
<tr>
<td>Solotvina</td>
<td>$^{116}\text{Cd}$</td>
<td>CdWO$ _4$</td>
<td></td>
<td>Scintillator</td>
<td>$&gt; 1.7 \cdot 10^{23}$</td>
<td>7</td>
</tr>
</tbody>
</table>

4. A. S. Barabash, nucl-ex/1002.2862
New and future experiments with crystals

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Nucleus</th>
<th>Mass</th>
<th>Technology</th>
<th>Location</th>
<th>Time line</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE 0</td>
<td>$^{130}$Te</td>
<td>10 kg</td>
<td>$^{130}$TeO$_2$</td>
<td>LNGS</td>
<td>end 2011</td>
</tr>
<tr>
<td>CUORE</td>
<td></td>
<td>200 kg</td>
<td>bolometric</td>
<td></td>
<td>2014</td>
</tr>
<tr>
<td>GERDA I</td>
<td>$^{76}$Ge</td>
<td>18 kg</td>
<td>HPGe</td>
<td>LNGS</td>
<td>2011 - 2012</td>
</tr>
<tr>
<td>GERDA II</td>
<td></td>
<td>35 kg</td>
<td></td>
<td></td>
<td>end 2012</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>20 kg</td>
<td>HPGe</td>
<td>SUSL</td>
<td>2012 - 2014</td>
</tr>
<tr>
<td>COBRA</td>
<td>$^{116}$Cd, $^{130}$Te</td>
<td>40 kg</td>
<td>CdZnTe</td>
<td>LNGS</td>
<td></td>
</tr>
</tbody>
</table>

Other experimental R & D efforts that cannot be discussed in details:
- Lucifer: phonons and scintillations
- AMoRe: scintillations and semiconductor detectors
CUORICINO

- total exposure: 19.75 kg \cdot y
- average energy resolution at $Q_{\beta\beta}$: $\sigma_E = 7.5$ keV
- background index: $b = 0.169 \pm 0.006$ cts / (keV \cdot kg \cdot y)

$t_{1/2} > 2.8 \cdot 10^{24}$ y $\rightarrow m_e e < 0.3 - 0.7$ eV  
Barea, Iachello PRC 79 (2009) 044301
The CUORE experiment

- 20 times more massive than CUORICINO
- heavily shielded
- high detection efficiency, 87% (source = detector)
- excellent energy resolution: 5 keV ROI
- high granularity bolometric detector:
- background suppression through anti-coincidence:
  - neutron background suppressed by $\sim 30$;
  - $\mu$ background suppressed by $\sim 20$ (Atstr. Part. Phys 33 (2010 169))
  - crystal surface background suppressed by $\sim 4$
Bolometers techniques

Concept:
- $\Delta T = E/C$
  ($C =$ thermal capacity);
- low $C$ and low $T$
  ($T \ll 1$ K)
- dielectrics, superconductors

The ultimate limit to $E$ resolution is the statistical fluctuation of internal energy $U$: $\langle \Delta U^2 \rangle = k_B T^2 C$

Thermal Detector Properties:
- good energy resolution
- wide choice of absorber materials
- true calorimeters
- slow $\tau = C/G \sim 1 - 10^3$ ms
CUORE status and plans

The operation of the first CUORE tower is a general test for

- all assembly procedures;
- background reduction facilities and collaboration skills (shifts, management)

and it’s a $0\nu$ DBD experiment itself!

---

CUORE 0 plans

- all components at LNGS
- refurbishment of the old CUORICINO facility and cryogenics almost complete
- the CUORE-0 tower will be assembled end of August and inserted into the cryostat
- pre-operation/commissioning: 3-4 months
- data taking start at end of 2011
The GERDA experiment

- designed for external $\gamma$, n, $\mu$ background $\sim 0.001$ cts/(keV·kg·y);
- water vessel: $\emptyset = 10$ m;
- LAr cryostat: $\emptyset = 4.2$ m;
- 64 m$^3$ of LAr;
- 580 m$^3$ of water;
- up to five Ge diodes arranged in strings, 16 strings in total;

Water:
- moderator for neutrons;
- Čerenkov medium for $\mu$ veto;
- cheaper, safer and more effective than LN2 (LAr).

▲ 3800 m w.e. rock above ▲
Background reduction in GERDA

- **External bck:** $\gamma$ (Th, U), n, $\mu$
- **Shielding is possible**

  - bare Ge diodes
  - water: $\gamma$ & n shield, Čerenkov for $\mu$ veto
  - stainless steel cryostat with Cu shield, Rn tight
  - also active shield!

- **Intrinsic bck:**
  - cosmogenic $^{60}$Co (5.3 y), $^{68}$Ge (270 d),
  - radioactive surface contamination

- **Discriminate Single & MultiSite Events:**
  - SSE : $\beta\beta$, DEP;
  - MSE : Compton

- **anti-coincidence of detectors**
- **pulse shape analysis (PSA)**
GERDA commissioning phase

- A string with three $^{nat}$Ge detectors has been operated in GERDA (June 2010 - May 2011)
- AIM: study of background conditions;
- Resolution: 3.6 keV at 2.6 MeV ($^{228}$Th)

But:
- High $^{42}$Ar concentration in LAr (4× higher than expected)
- Measured bck level at ROI: 0.06 counts/(keV · kg · y)
  - No PSA applied.

New string with three $^{76}$Ge enriched detectors recently deployed
GERDA Phase II detector R&D

- 37.5 kg of $^{enr}$Ge ($86\% 76$Ge) have been procured and are stored underground;
- new Broad Energy Germanium (BEGe) detectors will be used.

$\beta\beta$ decay: $\beta$ range in Ge $\sim$ few mm

Backgrounds:
- $^{228}$Th and $^{226}$Ra from nearby materials
- $^{60}$Co and $^{68}$Ge produced by cosmic-rays
  $\rightarrow$ $\gamma$-ray emitters: range in Ge $\sim$ few cm
- $^{42}$K $e^\pm$, U/Th decay chains $\alpha$s
  $\rightarrow$ surface events: peculiar pulses

A. Garfagnini (Padova Univ, and INFN)
The Majorana experiment

- Actively pursuing the development of R&D aimed at a 1 tonne scale $^{76}$Ge $0\nu\beta\beta$-decay experiment.

- Build a prototype module (Majorana demonstrator) to
  1. demonstrate background is low enough;
  2. verify the proposed technology and scrutinize the KK claim;

- the Majorana and GERDA collaborations work in close contact with the ultimate goal to prepare for a tonne-scale experiment

- Open exchange of knowledge and technologies (e.g. MaGe Monte Carlo)
  → select the best technologies tested in GERDA and Majorana)
The Majorana demonstrator

- Build a small experiment with 40 kg Ge point-contact detectors (enriched in $^{76}\text{Ge}$);
- located at 4850’ level in the Sanford Lab (Homstake);
- operate them in low background cryostat and shielding
  1. ultra-clean, electroformed Cu
  2. naturally scalable
  3. compact low background passive Cu and Pb shield with an active muon veto.
Majorana demonstrator status

Three phases

1. prototype cryostat (3 strings, $^{nat}\text{Ge}$) Fall 2012
2. cryostat 1 (3 strings $^{enr}\text{Ge}$, 4 strings $^{nat}\text{Ge}$) Summer 2013
3. cryostat 2 (up to 7 strings $^{enr}\text{Ge}$) Summer 2014
COBRA

- Search for double beta decay with room temperature semiconductor detectors
- Plan to use a large amount of CdZnTe pixel diodes

Background at 2810 keV
\sim 5 \text{ cts/(keV \cdot kg \cdot y)}
Pixelization of the diode is a unique and important feature for particle identification: allows to reduce background.

**Monte Carlo:** 200 µm pixel size

**Data:** 50 µm pixel size
Conclusions

- Observation of $0\nu\beta\beta$ decay is the only known way to determine the neutrino nature (Dirac vs Majorana)
- One claim exists on $^{76}$Ge, but independent measurement with different isotopes are needed to verify the hypothesis
- New generation experiments are starting to take data (CUORE 0, GERDA and Majorana Demonstrator). Results expected in one-two years
- A new phase is coming (CUORE, GERDA II and Majorana) in the next years (2012-2013) and will complete the current experimental program exploiting the full potentialities of present known technologies
  
  But ...

- O(1 ton) scale experiments are required to disentangle neutrino mass hierarchies
- new promising technologies (low backgound crystals, and combined readout techniques) are being developed and will provide very important complementary measurements
- Check the MEDEX 2011 conference talks for details on the various DBD experiments and the promising R&D activities (http://medex11.utef.cvut.cz/)
Best limits / values on $^{76}$Ge

- Use Ge as source of $0\nu\beta\beta$ and detector (high signal efficiency).

**KKDC - part of HD-Moscow Collab.**

- 5 enriched $^{76}$Ge diodes (71.7 kg·y)
- bck index, $B \sim 0.11$ cts/(keV·kg·y)
- $T_{1/2}^{0\nu} = (0.69 - 4.18) \cdot 10^{25}$ y

**IGEX Collab.**

- $^{76}$Ge enriched diodes (8.87 kg·y)
- bck index, $B \sim 0.2$ cts/(keV·kg·y)
- $T_{1/2}^{0\nu} > 1.57 \cdot 10^{25}$ y (90% CL)

Confirmation needed with same isotope. Key: reduce background by O(100) for better sensitivity.
$T_{1/2} \propto \sqrt{M \cdot T / (b \cdot \Delta E)}$

$M =$ Detector mass, $T =$ exposure, $b =$ background index, $
\Delta E =$ energy resolution.