The Unbearable Lightness of Neutrinos

Laura Baudis
University of Zurich

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Mysterious Messengers from Outer Space

• February 23, 7:35 universal time, 1987: a hoard of billions upon billions of extragalactic messengers sweep through the Earth

• Only a few of them were stopped. In fact, 11 left a signal in a large, multi-ton water detector deep in the Kamioka mine in Japan

• Three hours later, the light from a Supernova explosion in a nearby galaxy reached the Earth; it was the closest Supernova since the invention of the telescope
What had happened?

- A star, 20 times the mass of our Sun, had exploded about 168’000 years ago

  (this Supernova explosion took place in the Large Magellanic Cloud, one of the 11 dwarf galaxies that orbit the Milky Way)

- The messengers to reach the Earth first were particles called **neutrinos**, they **had witnessed the death of the star as they zoomed out of the collapsing core**

- It took the photons a few extra hours to reach the surface of the exploding star
Neutrinos?

- Particles in the Standard Model of particle physics
- It deals with the composition of matter on its smallest scales, with symmetries and interactions between the matter constituents

Forces: particles called bosons mediate the interactions

Atoms Nuclei Protons, Neutrons

Gravity Magnetic

Weak Strong
Neutrinos?

- Neutrinos are electrically neutral and interact only via the weak force.

We know 3 families of quarks and leptons: these are fermions, spin 1/2.

Forces between fermions are mediated by gauge bosons, with spin 1.
First, some history....

- **Zürich, December 4, 1930**: Wolfgang Pauli, a 30 years old professor at the ETH, writes perhaps one of the most famous letters in modern physics: “Dear radioactive ladies and gentlemen...”

- The letter was addressed mainly to Lise Meitner, who had been working on radioactivity since 1907 and was attending a meeting in Tübingen (Pauli could not attend, because “a ball which takes place in Zürich the night of the sixth to sevenths of December makes my presence here indispensable”)

- Pauli was suggesting “a desperate way out” of some paradox that had arisen in the nascent field of nuclear physics

- He was proposing “a terrible thing” - a new subatomic particle, the **neutrino**, a particle “which can not be detected”

- In 1930, only the electron, the proton and the photon were known, and Pauli’s idea was quite radical!
And the Paradox was... the Energy Crisis

- It had been observed (by hard working experimental physicists), that **some nuclei are not stable, but decay under the emission of “beta rays” (electrons)**
- The energy of the emitted electrons could be measured - **the spectrum was continuous**
- This seemed to violate a well respected law in physics: the conservation of energy!

\[ mc^2 = E \]: the mass difference of the two nuclei is converted into the energy of the electron
Only One Reasonable Way Out...

- A new particle: the neutrino. It would share the energy with the electron, but would not be observed because of its incredible weak interaction with matter.

Niels Bohr, 1934: “I must confess that I don’t really feel fully convinced of the physical existence of the neutrino.”

Arthur Eddington, 1939: “I am not much impressed by the neutrino theory.... Dare I say that physicists will not have sufficient ingenuity to make neutrinos?”

Thus, while the idea was considered by most as a very useful hypothesis, few believed it is a real particle, until...
Neutrinos Galore

- Some 30 years later (1956), when Clyde Cowan and Fred Reines started the “Project Poltergeist” and finally detected (anti)neutrinos at the Savannah River Reactor in South Carolina.

Detector: 400 l water + CdCl₂ seen by 90 photodetectors

Detection via delayed (a few µs) coincidence reaction:

prompt: \( e^+ + e^- \rightarrow \gamma + \gamma \)
delayed: \( n + \text{Cd} \rightarrow \gamma' s \)

And this was only the beginning of the big adventure...
Neutrino Sources

- Reactors
- Sun
- Supernovae (collapsing stars)
- Extraterrestrial neutrinos
- Earth atmosphere (from cosmic rays)
- Earth crust (from natural radioactivity)
- Big Bang (Today ~ 330 $\nu$/cm$^3$)
- Indirect evidence
- SN 1987A

and people!
Neutrinos dominate our Universe

- The world around us (people, trees, stones, buildings, polenta, the Earth...) is made of electrons, protons and neutrons

- Is the whole Universe made of electrons, protons and neutrons?

  NO

- These are RARITIES; for every one of them, the Universe contains a billion of neutrinos!

- Moreover, our Universe is made of matter, and not of anti-matter

- To understand the Universe, we must understand neutrinos!
Neutrinos from the Big Bang

- As with photons of the **3 Kelvin Cosmic Microwave Background Radiation** (measured very precisely with the WMAP and now with the Planck Satellite)...

- **the Universe is filled with a sea of neutrinos**, that decoupled from the rest of the particles about 10 seconds after the Big Bang

Every cubic meter of space contains about **300 million neutrinos**

Could they make up the DARK MATTER in the Universe?

**NO**

Their mass is much too small!
Neutrinos - too light for the dark matter

- Dark energy 68.3% (cosmological constant)
- Neutrinos ~ 0.1–2%
- Dark matter 26.8%
- Normal matter ~4.9% (only ca. 10% shines)

Neutrinos are too light, but...
Neutrino, the Sun and Us

- Regardless, neutrinos are vital for our life!
- **No neutrinos would mean:**
  - no energy to keep us warm
  - no atoms more complicated than hydrogen
  - no carbon, no oxygen, no water
  - no Earth, no moon, no us

NO neutrinos would be very bad news indeed

The Universe would be a boring place
Solar Neutrinos

- Our Sun is a gigantic fusion reactor, it shines by converting protons into helium nuclei.
- These reactions are governed by the weak force, hence the Sun shines for a very long time.

\[
4 \text{ Protons} \rightarrow \text{He-nucleus} + 2 \text{ Positrons} + 2 \text{ Neutrinos}
\]

- The neutrino flux on Earth is 65 billion solar neutrinos pro cm\(^2\) and second!

Almost all of these neutrinos are zipping through the Earth and through us, and do NOTHING AT ALL.

The probability that a particular solar neutrinos will interact as it zips through one of you is \(1/10^{20}\).

Nonetheless...

\(T_{\text{core}} = 15'000'000\) Kelvin

\(\text{Photosphere}\)

\(\text{Sunspot}\)

\(\text{Nuclear Burning}\)
Gigantic Detectors for Solar Neutrinos

- We see the Sun in neutrinos!
- In fact, solar neutrinos are now routinely detected in gigantic experiments operated in deep underground laboratories around the world.
- From such observations, we learn about the Sun interior.
- And about the elusive particles themselves!

The Chlorine experiment in the US
The SNO experiment in Canada
The BOREXINO experiment in Italy
Physics Nobel Prize in 2002 for Neutrino-Astronomy

Ray Davis Jr. (1914–2006)
Masatoshi Koshiba (*1926)

“for pioneering work in astrophysics, in particular for the detection of cosmic neutrinos”
What do we know about neutrinos?

They come in three flavours: \( \nu_e \) electron, \( \nu_\mu \) muon, \( \nu_\tau \) tau.

The 3 neutrino flavours participate in charged current (CC) weak interactions together with the corresponding charged lepton.

These are of (V-A) type: neutrinos are LH, anti-neutrinos are RH.

In the Standard Model, the flavour lepton numbers are conserved, and neutrinos are exactly massless.
What do we know about neutrinos?

- However, when neutrinos propagate over macroscopic distances, they oscillate between flavours:
  - This is a well studied effect in quantum mechanics
  - It means that flavour is not conserved over macroscopic distances, for instance:

\[
P(\nu_e \rightarrow \nu_e) < 1
\]
\[
P(\nu_\mu \rightarrow \nu_\mu) < 1
\]
\[
P(\nu_\tau \rightarrow \nu_\tau) < 1
\]
What do we know about neutrinos?

- A compelling explanation of all the available data comes from the assumption that:
  - neutrino states with different flavours $\nu_\alpha$ mix with neutrino states with different masses $\nu_i$
- The mixing is introduced “a la CKM” in the left-handed fields of the CC interaction Lagrangian:

$$
\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i
$$

- $U_{\alpha i}$ unitary neutrino mixing matrix (PMNS matrix)
- $\nu_\alpha, \nu_i$ quantum fields

- $P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha \beta} - 4 \sum_{j>i} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2 \frac{\Delta m^2_{ij} x}{4E}$

- $P$: flavor transition probability in the case of CP invariance ($U = U^*$)
Neutrino mixing

For 3 neutrino flavours, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix can also be parameterized:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}\]

Data from atmospheric neutrinos and accelerators
\[\theta_{23} \approx 45 \text{ deg}\]

Data from reactors and accelerators
\[\theta_{13} \approx 9 \text{ deg}\]

Data from solar and reactor neutrinos
\[\theta_{12} \approx 34 \text{ deg}\]

In general, we have 3 mixing angles, 1 CP violating phase, 3 different \(\Delta m^2\) (only 2 being independent)

\[\Rightarrow \text{no information about the absolute neutrino mass scale}\]

\[\Delta m_{sol}^2 \sim 7.5 \times 10^{-5} \text{ eV}^2 \quad \Delta m_{atm}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2\]
One Open Question: The Mass of Neutrinos

- What is the absolute value of the neutrino mass?
- From experiments that measure the endpoint of the Tritium beta-decay to $^3\text{He}$:
  - the neutrino mass $< 2.1$ eV
  - BUT HOW SMALL?

The KATRIN experiment on its long journey to Karlsruhe

$$\left(\sum_{i=1}^{3} m_i \left| U_{ei} \right|^2\right)^{1/2} [\text{eV}]$$

Bound from MAINZ and TROITSK

Sensitivity of KATRIN

- $\Delta m_{23}^2 < 0$
- $\Delta m_{23}^2 > 0$

99% CL (1 dof)
One Open Question: The Mass of Neutrinos

- Neutrinos: much lighter than other known particles

⇒ Why is their mass so small?
⇒ What is their absolute mass scale?

\[ m^2 = 0 \]

\[ m^2_{\text{lightest}} = ? \]

\[ \sum_i m_i < 230 - 600 \text{ meV} \]
The Double Beta decay

- An ultra-rare nuclear decay, with a half-life > 10 billion times larger than the age of the Universe

- The decay with emission of 2 neutrinos was observed in more than 10 different nuclei: \(^{48}\text{Ca}, \, ^{76}\text{Ge}, \, ^{82}\text{Se}, \, ^{96}\text{Zr}, \, ^{100}\text{Mo}, \, ^{116}\text{Cd}, \, ^{128}\text{Te}, \, ^{130}\text{Te}, \, ^{136}\text{Xe}, \, ^{150}\text{Nd}, \, ^{238}\text{U}\)

\[
\text{Nucleus (A,Z)} \rightarrow \text{Nucleus (A,Z+2)} + 2\nu_e + 2\nu_e
\]
Neutrinoless double beta decay

- **More interesting:** the decay mode without emission of neutrinos ("forbidden" in the Standard Model of particle physics, since the lepton number is violated: $\Delta L = 2$)

\[
\begin{align*}
2n &\rightarrow 2p + 2e^- \\
2p &\rightarrow 2n + 2e^+
\end{align*}
\]

Energy [keV]

expected: sharp "peak" at the Q-value of the decay

\[
Q = E_{e_1} + E_{e_2} - 2m_e
\]
Neutrinoless double beta decay

- A virtual neutrino is exchanged:

\[
\begin{array}{c}
u \\
d \\
d \\
W^- \\
\nu_M \\
\nu_R \\
d \\
d \\
u
\end{array} \rightarrow 
\begin{array}{c}
u \\
d \\
d \\
e^- \\
e^- \\
e^- \\
u \\
d \\
u
\end{array}
\]

\[\Rightarrow\] the neutron decays under emission of a right handed ‘anti-neutrino’ \[|\nu_R\rangle^C\]
\[\Rightarrow\] the \[|\nu_R\rangle^C\] has to be absorbed at the second vertex as left handed ‘neutrino’ \[|\nu_L\rangle\]

\[\Rightarrow\] neutrinos and anti-neutrinos must be identical: Majorana particles

\[\Rightarrow\] for the helicity to change, we must have \(m_\nu > 0\)
Neutrinoless double beta decay

• The decay rate is:

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

• with the **effective Majorana neutrino mass**: 

\[ |m_{\beta\beta}| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(\alpha_1 - \alpha_2)} + m_3|U_{e3}|^2 e^{i(-\alpha_1 - 2\delta)} \]

- a mixture of \(m_1, m_2, m_3\), proportional to the \(U_{ei}^2\), \(c_{ij} = \cos\theta_{ij}\), \(s_{ij} = \sin\theta_{ij}\), \(\alpha_1, \alpha_2 =\) Majorana phases

• \(U_{ei}\) = matrix elements of the PMNS-Matrix, \(m_i\) = eigenvalues of the neutrino mass matrix

Flavor eigenstates \( |\nu_e\rangle = \sum_i U_{ei} |\nu_i\rangle \)  Eigenstates of the mass operator
Effective neutrino mass as a function of the smallest neutrino mass for the neutrino mass scenarios: “normal” and “inverted” hierarchy, and “degenerate” hierarchy.

Current sensitivities:

- $T_{1/2} \sim 10^{27}$ yr for the normal hierarchy
- $T_{1/2} \sim 10^{29}$ yr for the inverted hierarchy

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**Effective Majorana neutrino mass**

- The effective Majorana neutrino mass plot shows the relationship between the effective mass and the minimum neutrino mass for different mass scenarios.

**Diagram:**

- The plot illustrates the effective Majorana neutrino mass as a function of the minimum neutrino mass for normal and inverted hierarchies.

- The diagram includes labels for different mass splittings and their implications for the mass hierarchy.

**Parameters:**

- $\Delta m^2_{31} < 0$ for degenerate mass scenario
- $\Delta m^2_{31} > 0$ for non-degenerate mass scenario

**Notation:**

- $\theta_{12} = 33.58$, $\delta m^2_{sol} = 75.8$ meV$^2$
- $\theta_{13} = 8.33$, $\delta m^2_{atm} = 2350$ meV$^2$

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**Graphical Elements:**

- The graph has a logarithmic scale on the y-axis and a linear scale on the x-axis.
- The graph is divided into regions for normal and inverted mass hierarchies.
- The current sensitivities are indicated with arrows pointing towards the graph.

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**Table:**

<table>
<thead>
<tr>
<th>Current Sensitivity</th>
<th>Count Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-1000 counts/(y  t)</td>
<td>Normal</td>
</tr>
<tr>
<td>0.5 - 5 counts/(y  t)</td>
<td>Inverted</td>
</tr>
<tr>
<td>0.1-1 counts/(y 100 t)</td>
<td>Degenerate</td>
</tr>
</tbody>
</table>
Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}^{0\nu}$

$$T_{1/2}^{0\nu} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T_{1/2}^{0\nu}}}$$

Minimal requirements:
- large detector masses
- enriched materials
- ultra-low background noise
- excellent energy resolution

Additional tools to distinguish signal from background:
- angular distribution
- decay to excited states (gamma-rays)
- identification of daughter nucleus
Experiments: Main Approaches

Source ≠ Detector

- Source as thin foil
- Electrons detected with: scintillator, TPC, drift chamber, semiconductor detectors
- Event topology
- Low energy resolution and detection efficiency

Source = Detector (calorimeters)

- The sum of the energy of the two electrons is measured
- Signature: peak at the Q-value of the decay
- Scintillators, semiconductors, bolometers
- High resolution + detection efficiency
- No event topology

Source = Detector = Tracker

- Source is the (high-pressure) gas of a TPC
- Charge and light detected with electron multipliers and/or photosensors
- Good energy and position resolution, high efficiency
- Event topology very helpful in reducing the background and in identifying the potential signal
Double Beta Isotopes and Techniques

Phase space factor $G \sim Q^5$

Figure from A. Giuliani

End-point of $^{222}$Rn-induced radioactivity

End-point of natural $\gamma$ radioactivity
Double Beta Isotopes and Techniques

Gamma and beta background, also degraded alphas

Figure from A. Giuliani

Nonetheless, best current sensitivities!

$^{76}\text{Ge}$: HPGe diodes (GERDA, MAJORANA)

$^{130}\text{Te}$: bolometers, TeO$_2$ crystals (CUORE) and Te dissolved in large liquid scintillator (SNO+)

$^{136}\text{Xe}$: xenon TPCs (EXO, NEXT) and Xe dissolved in large LS (KamLAND-Zen)
Double Beta Isotopes and Techniques

No gamma background, but degraded alphas

Figure from A. Giuliani

Figure 11: Design of the Majorana experiment with the strings of germanium detectors placed at the center of the shield.

4.2. MAJORANA
The Majorana experiment [8] is based on the use of Ge semi-detectors to look for neutrinoless double beta decay of $^{76}\text{Ge}$. The main advantage is the very good energy resolution and the efficiency of these detectors. Compared to the GERDA experiment, the Majorana collaboration strategy is to keep the conventional method to run Ge semi-conductor diodes by improving the radiopurity of the materials used in the detector, the passive shielding and the pulse shape discrimination. The Ge diodes will be installed in the cryostats as strings of 4 detectors. The copper used will be electroformed in underground conditions to avoid activation of cosmogenics. The compact shielding will be optimised with an active muon veto. The detector will be located at Sanford Laboratory (USA). The objective is to reach a background of $3 \, \text{cts ct.keV}^{-1}\text{.ton}^{-1}\text{.y}^{-1}$ in the region of interest and to reach a sensitivity of $\sim 0.1 \text{ eV}$ in 2.5 years of data taking.

This project has three phases. The first one is a cryostat prototype with 2 strings of $^{nat}\text{Ge}$ and will finish end of 2012. The second phase will be to install in a first cryostat 3 strings of $^{enr}\text{Ge}$ and 4 strings of $^{nat}\text{Ge}$ in fall 2013. The last one will be the installation of 7 string of $^{enr}\text{Ge}$ in a second cryostat. This phase is scheduled for fall 2014.

4.3. LUCIFER
The Lucifer experiment [9] is based on bolometers of $^{82}\text{Se}$ (12). With $^{82}\text{Se}$ bolometers, it is possible to measure both heat and scintillation light. By comparison, in CUORE bolometric experiment, only the heat of is measured in the $\text{TeO}_2$ bolometers. This double signature allows to reduce the background by discriminating surface events from $\alpha$ decay from double beta decay bulk events. The energy resolution is $\sim 10 \text{ keV}$ (FWHM). The detector have a mass of $\sim 500 \text{ g}$ and it is planned to use in a first phase between 36 and 44 crystals. The expected background is $3-6 \, \text{ct.keV}^{-1}\text{.kg}^{-1}\text{.y}^{-1}$ in the Region Of Interest (around 2995 keV). The Lucifer experiment will be installed in the cryostat of the Cuoricino experiment when the test of CUORE-0 will be finished in 2015.

A production of 15 kg of enriched $^{82}\text{Se}$ will be done in 2013. In parallel, the crystal growth will be performed. The detector could be assembled for end of 2015. An R&D is also in progress with bolometers of $^{\text{ZnMoO}_4}$ in which the scintillation light yield is higher than for Se based bolometers.

4.4. SNO
The SNO$^+$ detector [10] consists in a large volume of liquid scintillator in a very low background environment. It is dedicated to the study of solar neutrinos but it can be also used to look for neutrinoless double beta decay of $^{150}\text{Nd}$ by dissolving $^{nat}\text{Nd}$ or $^{enr}\text{Nd}$ in the liquid scintillator. The possibility to add up to 0.3 % of Nd keeping good properties for the scintillator allows to measure a large amount of Nd. In a first phase, around 2014, it is planned to add $\sim 800 \, \text{kg}$ $^{nat}\text{Nd}$ corresponding to 44 kg of $^{150}\text{Nd}$. The expected sensitivity on the effective neutrino mass is around 100 meV for 4 years of data taking.

4.5. Other R&D
There are also other R&D on scintillating crystals like the AMoRe project (Korea) which want to develop $\text{CaMoO}_4$ crystals with enriched $^{100}\text{Mo}$ and depleted $^{48}\text{Ca}$. The energy resolution is 5 % FWHM in the ROI and a half-life sensitivity of $6.0 \times 10^{24} \text{y}$ (90 % CL) is expected. The advantage of such crystals is also the possibility to use them as bolometers to improve the energy resolution (15 keV FWHM). In this case with 100 kg of
Double Beta Isotopes and Techniques

Almost background-free

Figure from A. Giuliani

But low isotopic abundance, difficult to enrich

Zr, Nd: Tracking calorimeters with thin foils (SuperNEMO)

CaF₂ scintillators (CANDLES)
Double beta detectors, world wide

Here only very recent results: GERDA, EXO, KamLAND-Zen
The GERDA experiment at Gran Sasso

- HPGe detectors, enriched to ~86% in $^{76}$Ge, directly submersed in LAr, which is shielded by ~ 10 m x 10 m of water
The GERDA experiment at LNGS

- LAr as cooling medium and shielding (U/Th in LAr < 7x10^-4 μBq/kg)
- a minimal amount of surrounding materials

• Phase I (Nov 2011 - May 2013)
  ➞ ~18 kg enriched 76Ge detectors
• Phase II (early 2014)
  ➞ additional 20 kg Ge detectors
Half life of the 2-neutrino decay mode

Measurement of the half-life of the two-neutrino double beta decay of $^{76}$Ge with the GERDA experiment

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}) \times 10^{21} \text{ yr}$$

<table>
<thead>
<tr>
<th>Item</th>
<th>Uncertainty on $T_{1/2}^{2\nu}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-identified background components</td>
<td>+5.3</td>
</tr>
<tr>
<td>Energy spectra from $^{42}$K, $^{40}$K and $^{214}$Bi</td>
<td>±2.1</td>
</tr>
<tr>
<td>Shape of the $2\nu\beta\beta$ decay spectrum</td>
<td>±1</td>
</tr>
<tr>
<td>Subtotal fit model</td>
<td>+5.8 -2.3</td>
</tr>
<tr>
<td>Precision of the Monte Carlo geometry model</td>
<td>±1</td>
</tr>
<tr>
<td>Accuracy of the Monte Carlo tracking</td>
<td>±2</td>
</tr>
<tr>
<td>Subtotal Monte Carlo</td>
<td>±2.2</td>
</tr>
<tr>
<td>Data acquisition and selection</td>
<td>±0.5</td>
</tr>
<tr>
<td>Grand total</td>
<td>+6.2 -3.3</td>
</tr>
</tbody>
</table>
The neutrinoless decay mode: no signal

GERDA lower limit from PL fit of the 3 data sets, with constant term for background (3 parameters for the 3 data sets) and Gaussian term for signal: best fit is \( N_{\text{signal}} = 0 \)

\[
T_{1/2}^{0\nu} > 2.1 \times 10^{25} \text{ yr (90\% C.L.)}
\]

- the limit on the half life corresponds to \( N_{\text{signal}} < 3.5 \) counts

- Observed and predicted number of background events in the energy region \( Q_{\beta\beta} \pm 5 \text{ keV} \)

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Predicted background</th>
</tr>
</thead>
<tbody>
<tr>
<td>No PSD</td>
<td>7</td>
<td>5.1</td>
</tr>
<tr>
<td>PSD</td>
<td>3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

- 5.9 \( \pm 1.4 \) events are expected for "claim", and 2.0\( \pm 0.3 \) signal events

**Claim of evidence for 0vbb-decay:**
signal: 28.8 \( \pm 6.9 \) events
BG level: 0.11 counts/(keV kg yr)
HVKK et al., PLB 586 (2004) 198-212
EXO-200 at WIPP (Carlsbad, USA)

- Liquid xenon TPC: 175 kg LXe, 80.6% enriched in $^{136}\text{Xe}$
- Charge and light readout (triplet wire channels and large area avalanche photodiodes)
- Drift field: 376 V/cm
Half life of the 2-neutrino decay mode

- The first observation of this decay for $^{136}$Xe
- The $T_{1/2}$ corresponds to a matrix element of $M = 0.0218 \pm 0.0003$ MeV$^{-1}$, the smallest among the isotopes measured so far.

$$T^{2\nu\beta\beta}_{1/2} = 2.165 \pm 0.016 \text{(stat)} \pm 0.059 \text{(sys)} \cdot 10^{21} \text{ years}$$
The neutrinoless decay mode: no signal

- No 0-neutrino signal observed => lower limit on $T_{1/2}$

$$T^{0\nu\beta\beta}_{1/2} > 1.6 \times 10^{25} \text{ yr (90\% C.L.)}$$

Exposure: 32.5 kg yr, background: $\sim 1.5 \times 10^{-3} \text{ kg}^{-1}\text{yr}^{-1}\text{keV}^{-1}$

PRL 109, 2012
KamLAND-Zen

• Scintillator loaded with xenon

• 320 kg 90% enriched $^{136}$Xe so far (more than 600 kg in the Kamioka mine)

• Advantages: huge and clean (U: 3.5e-18 g/g, Th: 5.2e-17 g/g) running detector

• Xe + liquid scintillator can be purified, and is highly scalable

• No escape or invisible energy from gammas and beta: good background identification

• Disadvantage: relatively poor energy resolution

• no beta/gamma discrimination

• limited scintillator composition
KamLAND-Zen: installation

Installation in a class 10~100 clean room built at the top of KamLAND.

Balloon and corrugated tube deployment.

Balloon went through the black sheet.

Installation completed.

Mini-balloon inflated with dummy LS and then replaced with Xe-loaded LS. Density tuning finished and tubes to be extracted.
The 2-neutrino and 0-neutrino decay modes

- Resolution at 2.6 MeV: sigma ~ 4.1%; background dominated
- No evidence for a 0-neutrino signal

\[ T_{1/2}^{2\nu} = 2.38 \pm 0.02 \text{(stat)} \pm 0.14 \text{(syst)} \times 10^{21} \text{ yr} \]

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

PRL 110, 2013

PRC 85, 2012
The search continues...

- Ton-scale experiments are needed to explore the *inverted mass hierarchy* scale.
- Several technologies are moving towards this scale with ultra-low backgrounds.
- It remains to be seen which ones can be upgraded to 10-100 ton scale and explore the *normal hierarchy*.
Current and future double beta experiments
Summary

- Neutrinos are different!

- Strong evidence for non-zero neutrino masses and non-trivial mixing from oscillation experiments

- Nonetheless, many questions remain unanswered:
  - absolute mass scale and hierarchy?
  - Majorana- versus Dirac particles?
  - is there CP-violation in the neutrino-sector?
  - what is the origin of small neutrino masses?
  - what is the origin of the large neutrino mixing?

- The observation of the neutrinoless double beta decay could help in answering some of these questions
End
Matrix elements

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

Fig. 3. Values of the NME calculated with the methods in Tab. 2.

Bilenky, Giunti: arXiv:1203.5250v2

Matrix elements: vary by a factor of 2-3 for a given A
Phase space

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

$G^{0\nu}(Q, Z) \propto (Z, Q^5)$

<table>
<thead>
<tr>
<th>Transition</th>
<th>$G \ [10^{-14} \text{ yr}^{-1}]$</th>
<th>$Q \ [\text{keV}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
<td>6.35</td>
<td>4373.7</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
<td>0.63</td>
<td>2039.1</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
<td>2.70</td>
<td>2995.5</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
<td>4.36</td>
<td>3035</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
<td>4.62</td>
<td>2809</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
<td>4.09</td>
<td>2530.3</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
<td>4.31</td>
<td>2461.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
<td>19.2</td>
<td>3367.3</td>
</tr>
</tbody>
</table>
Neutrino masses

\[
\langle M_{\beta\beta} \rangle \text{[eV]}
\]

\[
\Sigma \text{[eV]}
\]

b-decay

cosmology

bb-decay