Double-beta decay and the search for (elementary) Majorana particles

Giorgio Gratta

*Physics Dept. Stanford University*
For the first ~50 years since the neutrino was invented by Pauli, its properties could be fairly well described by quoting just 2 papers:

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California,
Los Alamos, New Mexico
(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The

⇒ Neutrinos really exist!

* Referred to in the text above.
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of \( \gamma \) rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with \( \text{Eu}^{152m} \), which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,\(^1\) \( 0^- \), we find that the neutrino is “left-handed,” i.e., \( \sigma \cdot \hat{p} = -1 \) (negative helicity).

→ Neutrinos are left handed particles
Helicity is the property that correlates the spin of a particle to its momentum. Because of special relativity the helicity of a particle is related to its mass.

The observer above sees a neutrino passing-by and reports its helicity (the scalar product between spin vector and momentum vector) as negative (left-handed).
Helicity is the property that correlates the spin of a particle to its momentum. Because of special relativity the helicity of a particle is related to its mass.

Now the observer is cruising in the same direction of the neutrinos, at higher speed. While overtaking the neutrino he will claim that its helicity is positive!
But if the neutrino has zero mass nothing can overtake it

\[ \Rightarrow \text{Neutrinos with fixed helicity have to be massless} \]

So the fixed helicity and the zero mass were encoded in the Standard Model of elementary particles for neutrinos
This changed in the last decade: the age of $\nu$ physics

**Discovery of $\nu$ flavor change**

- Solar neutrinos (MSW effect)
- Reactor neutrinos (vacuum oscillation)
- Atmospheric neutrinos (vacuum oscillation)
- K2K/Minos (vacuum oscillation)

We found that:

- $\nu$ masses are non-zero
- there are $2.981 \pm 0.008 \, \nu$ (Z lineshape)
- 3 $\nu$ flavors were active in Big Bang Nucleosynthesis
- The Sun emits neutrinos as expected
- Supernovae emit neutrinos
If $m_\nu \neq 0$ neutrinos show a different image depending on our vantage point:

- “Weak interaction eigenstate”
- “Mass eigenstate”

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
\]

this is the state of definite flavor: interactions couple to this state

\[
\begin{pmatrix}
\nu_{m1} \\
\nu_{m2} \\
\nu_{m3}
\end{pmatrix}
\]

this is the state of definite energy: propagation happens in this state
To see what propagates to the detector I have to project this flavor state onto the mass state using the matrix inverse of $U$.

A source produces –say– $\nu_e$ always via weak interactions.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_{m1} \\ \nu_{m2} \\ \nu_{m3} \end{pmatrix}$$
Now each of the $\nu_m$ will evolve in time as prescribed by the wave functions

\[
\begin{align*}
\nu_{m1}(t) &= e^{-i(E_1 t - p_1 L)} \nu_{m1} \\
\nu_{m2}(t) &= e^{-i(E_2 t - p_2 L)} \nu_{m2} \\
\nu_{m3}(t) &= e^{-i(E_3 t - p_3 L)} \nu_{m3}
\end{align*}
\]

but note that the periodic term contains the neutrino mass via $E_i = m_i c^2$

So at the end of their flight -at the detector- the mix of $\nu_{m1}$, $\nu_{m2}$, $\nu_{m3}$ will not necessarily be the one that makes “exactly” $\nu_e$!
The neutrinos are then detected via weak interactions and so we need to find again the composition in terms of $\nu_e$, $\nu_\mu$, $\nu_\tau$

Formally

$$\left| \nu_j \right> = \sum_{j'} \sum_l U_{lj} e^{-i(E_j t - p_j L)} U_{j' l}^* \left| \nu_{j'} \right>$$

So after some propagation one can "find" a neutrino of a flavor that was not originally present

This is a pure quantum-mechanical effect, there is no classical interpretation of it

It can ONLY happen if the mass is non-0
For 2 flavors this simplifies:

\[ U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \]

Only one mixing parameter \( \theta \)

\[ P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \sin^2 \frac{1.3\Delta m^2 L}{E} \]

Neutrino oscillations are basically an interferometric technique to measure tiny mass differences. This is the reason for such an exquisite sensitivity!

This is a situation analogous to that of **beats** in acoustics, again a very sensitive technique that allows musicians to accurately tune their instruments.
The oscillatory nature of the rate of $\nu$s of one flavor and, hence, the fact that different flavors really turn into each other is directly shown by some of the experiments.

\[ \propto \text{Proper time } \tau \]

\[ L_0 = 180 \text{ km} \]
Our knowledge of the $\nu$ mass pattern

- $\sim 2$ eV
  - From Tritium endpoint (Mainz and Troitsk)
  - From $0\nu\beta\beta$ if $\nu$ is Majorana

- $\sim 0.3$ eV
  - From $0\nu\beta\beta$ if $\nu$ is Majorana

- $\sim 1$ eV
  - From Cosmology

- Time of flight from SN1987A (PDG 2002)

- $\sim 20$ eV

But, of course, the oscillation only measures the mass differences, so we still do not know how large neutrino masses really are!
Some help from Nuclear Physics

**Double-beta decay:**
*a second-order process only detectable if first order beta decay is energetically forbidden*

<table>
<thead>
<tr>
<th>Candidate nuclei with Q&gt;2 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candidate</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$</td>
</tr>
<tr>
<td>$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$</td>
</tr>
<tr>
<td>$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$</td>
</tr>
<tr>
<td>$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$</td>
</tr>
<tr>
<td>$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$</td>
</tr>
<tr>
<td>$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$</td>
</tr>
<tr>
<td>$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$</td>
</tr>
<tr>
<td>$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$</td>
</tr>
<tr>
<td>$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$</td>
</tr>
<tr>
<td>$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$</td>
</tr>
<tr>
<td>$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$</td>
</tr>
</tbody>
</table>
There are two varieties of $\beta\beta$ decay

2$\nu$ mode: a conventional but rare process in nuclear physics

The 2$\nu$ mode (that is not relevant for our discussion) was first analyzed by Maria Goeppert-Mayer who calculated lifetimes $>10^{20}$ years

$M.\text{Goeppert-Mayer}$,

*Phys. Rev. 48 (1935) 512*
There are two varieties of $\beta\beta$ decay

2ν mode: a conventional but rare process in nuclear physics

$\nu$ mode: a $\nu$ is emitted and reabsorbed by the same process.

$\bar{\nu}$ mode: a conventional but rare process in nuclear physics

Particle interaction rules require
1) helicity change
2) particle=antiparticle
The distinction between particles and antiparticles is clear for charged particles:

A positron (anti-electron) carries a positive charge and cannot be confused with an electron (that carries a negative charge)

Electrons (and all other spin $\frac{1}{2}$ particles we know) are described by Dirac’s equation that has for solutions 4-component wavefunctions:
But the distinction is much less obvious in the case of neutral particles such as neutrinos

In fact long time ago Ettore Majorana wrote the possible theory of neutral, spin $\frac{1}{2}$ particles where the particle/antiparticle nature is blurred

*E. Majorana, Nuovo Cimento 14 (1937) 171*

According to this theory neutrinos would be described by a Majorana equation with as solutions 2 component wavefunctions:
But the distinction is much less obvious in the case of neutral particles such as neutrinos

In fact long time ago Ettore Majorana wrote the possible theory of neutral, spin $\frac{1}{2}$ particles where the particle/antiparticle nature is blurred

\[ E.\text{Majorana, Nuovo Cimento} 14 (1937) 171 \]

According to this theory neutrinos would be described by a Majorana equation with as solutions 2 component wavefunctions:

\[ \begin{align*} \psi \end{align*} \]

Since neutrinos are the only neutral elementary particle this idea can only be tested with them...

Are neutrinos their own antiparticles?
There is a *theorem*: “0νββ decay always implies new physics”

There is no scenario in which observing 0νββ decay would not be a great discovery

→ Majorana neutrinos
→ Lepton number violation
→ Probe new mass mechanism up to the GUT scale
→ Probe key ingredient in generating cosmic baryon asymmetry
→ The process that creates net matter (w/o balancing it with antimatter)
How to find 0ν double beta decay

Need to find rare nuclear decays in a large quantity of material containing nuclei of species $N$
**The challenge (1): What is “species N”?**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca→$^{48}$Ti</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}$Ge→$^{76}$Se</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se→$^{82}$Kr</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}$Zr→$^{96}$Mo</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo→$^{100}$Ru</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd→$^{110}$Cd</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}$Cd→$^{116}$Sn</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}$Sn→$^{124}$Te</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}$Te→$^{130}$Xe</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe→$^{136}$Ba</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd→$^{150}$Sm</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Most suitable nuclei are not very common in Nature

Candidate Abund. $Q>2\text{MeV}$

- Need massive isotopic enrichment
- EXO-200 has 200kg of $^{136}$Xe enriched to 80% from the natural level of ~8.8%
The challenge (2):
How much is a “large quantity”?

To reach interesting ν mass scales need tons of separated isotopes!
The challenge (3): How rare is “rare”?

Need to be sensitive to half-lives of $\sim 10^{28}$ years, this is $10^{18}$ times the age of the Universe!!

→ detect $\sim$ few nuclear decays/year in tons of material

Each decay liberates energies of order few MeV

Backgrounds are a huge issue

- *Most standard materials are MANY orders of magnitude too radioactive to be part of the detector!!*
- *Need to locate experiments underground, to suppress the effects of cosmic radiation*
How low background is low background in this field?

In terms of the radiopurity of some of the innermost detector components...

<table>
<thead>
<tr>
<th>Materials</th>
<th>Approximate U or Th concentration (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average rock from the Earth’s Crust</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Average rock from the Earth’s Mantle</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Copper used in EXO-200</td>
<td>$&lt;2\cdot10^{-13}$</td>
</tr>
<tr>
<td>3M HFE-7000 (1-methoxyheptfluoropropane)</td>
<td>$&lt;1.5\cdot10^{-14}$</td>
</tr>
</tbody>
</table>

In terms of the radiopurity of the count-rate of the full detector...

<table>
<thead>
<tr>
<th>Object</th>
<th>Activity (Bq)</th>
<th>Specific Activity (Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 150g banana (from $^{40}$K)</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>The 6000kg nEXO detector (from all isotopes in the neighborhood of the ββ-decay Q-value)</td>
<td>$1.6\cdot10^{-8}$</td>
<td>$3\cdot10^{-12}$</td>
</tr>
</tbody>
</table>
Underground science

Muon intensity ($m^{-2} yr^{-1}$)

Depth, meters of standard rock

Depth (mwe)

6 orders of magnitude reduction in cosmic ray flux

sea level: $10^8$
Example:

EXO-200

A ultra-low background TPC filled with $^{136}$Xe in liquid phase (165K)

Read out ionization and scintillation light
EXO-200 LXe TPC field cage & readout planes

- Acrylic supports
- Central HV plane (photo-etched phosphor bronze)
- Flex cables on back of APD plane
- ~40cm
Low background cryostat containing the detector in a shielding bath of cold fluid... getting ready for “first light”
This and the failure to discover the neutrino-less double-beta decay lead to current results

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Experiment</th>
<th>Exposure (kg yr)</th>
<th>$T^{0\nu\beta\beta}_{1/2}$ 90% CL limit ($10^{25}$yr)</th>
<th>$T^{0\nu\beta\beta}_{1/2}$ average sensitivity ($10^{25}$yr)</th>
<th>$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (Age of the Universe, 13.8 Gyr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}$Ge</td>
<td>Gerda</td>
<td>47.6</td>
<td>&gt;8.0</td>
<td>5.8</td>
<td>$4.4\times10^{15}$</td>
<td>Agostini et al., Nature 544 (2017) 5</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>EXO-200</td>
<td>100</td>
<td>&gt;1.8</td>
<td>3.8</td>
<td>$2.7\times10^{15}$</td>
<td>Albert et al. arXiv:1707.08707 (2017)</td>
</tr>
<tr>
<td></td>
<td>KamLAND-ZEN</td>
<td>504*</td>
<td>&gt;11 (run 2)</td>
<td>4.9</td>
<td>$3.5\times10^{15}$</td>
<td>Gando et al., arXiv:1605.02889 (2016)</td>
</tr>
</tbody>
</table>

* All Xe. Fiducial Xe is more like ~150 kg yr
Moving towards the tonne scale: the 5000kg $^{enr}$Xe nEXO detector

13m

Water Cherenkov veto/shield

14m

Charge readout strips (anode)

SiPM `staves’ plastering barrel behind field-shaping rings

In LXe electronics (charge and SiPMs)

Cathode

Summer 2018

G. Gratta
Need ~4m² of VUV-sensitive SiPMs

Installed behind the field shaping rings for better coverage
At least one type of 1cm$^2$ VUV devices now match our desired properties, with a bias requirement $\sim$30V (as opposed to the 1500V of EXO-200 APDs)
Charge will be collected on arrays of strips fabricated onto low background dielectric wafers (baseline is silica)

- Self-supporting/no tension
- Built-on electronics (on back)
- Far fewer cables
- Ultimately more reliable, lower noise, lower activity
Test of prototypes in LXe ongoing


Max metallization cover with min capacitance:

80 fF at crossings
0.86 pF between adjacent strips
Conclusions

• Neutrinoless double-beta decay is great discovery physics. Like LHC or other frontier endeavors it has the potential of changing our view of the Nature
• This is also an area where the most advanced techniques are needed to produce the science
• Even more so than in other fields, detectors require a very subtle balance of electronics, sensors, material science, mechanics, analytics, cryogenics and more. In many cases, moving a single screw will degrade the performance