Neutrinoless Double Beta Decay

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Lecture # 2

TASI-06, Boulder, June 13
i) Overview of the experimental status of the search for $\beta\beta$ decay.
ββ History

- ββ(2ν) rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? Background
  \[ \tau_{1/2}(U, \text{Th}) \sim 10^{10} \text{ years} \]
  \[ \tau_{1/2}(\beta\beta(2\nu)) \sim 10^{20} \text{ years} \]

- But next we want to look for a process with:
  \[ \tau_{1/2}(\beta\beta(0\nu)) \sim 10^{25-27} \text{ years} \]
Separating the two modes: Finite resolution and unequal rates. Ultimately we would like to observe the $0\nu\beta\beta$ transition with a rate that is $>10^6$ smaller than the $2\nu\beta\beta$ one.

With 2% resolution:

\[
\frac{dN}{d(K_e/Q)}
\]

from S. Elliott
## Candidate Nuclei for Double Beta Decay

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Q (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca $\rightarrow ^{48}$Ti</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}$Ge $\rightarrow ^{76}$Se</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se $\rightarrow ^{82}$Kr</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}$Zr $\rightarrow ^{96}$Mo</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo $\rightarrow ^{100}$Ru</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd $\rightarrow ^{110}$Cd</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}$Cd $\rightarrow ^{116}$Sn</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}$Sn $\rightarrow ^{124}$Te</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}$Te $\rightarrow ^{130}$Xe</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe $\rightarrow ^{136}$Ba</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd $\rightarrow ^{150}$Sm</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Table 1: Summary of experimentally measured 2νββ half-lives and matrix elements (136Xe is an important exception where a limit is quoted).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}^{2ν}$ (y)</th>
<th>References</th>
<th>$M_{GT}^{2ν}$ (MeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>$(4.2 \pm 1.2) \times 10^{19}$</td>
<td>BAL96,BRU00</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$(1.3 \pm 0.1) \times 10^{21}$</td>
<td>KLA01a,AVI91,AAL96</td>
<td>0.15</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$(9.2 \pm 1.0) \times 10^{19}$</td>
<td>ELL92,ARN98</td>
<td>0.10</td>
</tr>
<tr>
<td>$^{96}$Zr$^+$</td>
<td>$(1.4^{+3.5}_{-0.5}) \times 10^{19}$</td>
<td>ARN99,KAW93,Wieser01</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$(8.0 \pm 0.6) \times 10^{18}$</td>
<td>DAS95,EJI91a,EJI91c, DES97,ALS97,ASH01</td>
<td>0.22</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$(3.2 \pm 0.3) \times 10^{19}$</td>
<td>ARN96,DAN00,EJI95</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{128}$Te$^{(1)}$</td>
<td>$(7.2 \pm 0.3) \times 10^{24}$</td>
<td>BER93,CRU93</td>
<td>0.025</td>
</tr>
<tr>
<td>$^{130}$Te$^{(2)}$</td>
<td>$(2.7 \pm 0.1) \times 10^{21}$</td>
<td>BER93</td>
<td>0.017</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&gt; 8.1 \times 10^{20}$ (90% CL)</td>
<td>GAV00</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>$^{150}$Nd$^+$</td>
<td>$7.0^{+11.8}_{-0.3} \times 10^{18}$</td>
<td>DES97,ART95</td>
<td>0.07</td>
</tr>
<tr>
<td>$^{238}$U$^{(3)}$</td>
<td>$(2.0 \pm 0.6) \times 10^{21}$</td>
<td>TUR91</td>
<td>0.05</td>
</tr>
</tbody>
</table>

$^{(1)}$deduced from the geochemically determined half-life ratio $^{128}$Te/$^{130}$Te
$^{(2)}$geochemical result includes all decay modes; other geochemical determinations only marginally agree
$^{(3)}$radiochemical result, again for all decay modes

$$1/T_{1/2} = G(E,Z) \left( M_{GT}^{2ν} \right)^2$$

$$M_{GT}^{2ν} = \sum_m \frac{\langle f | \vec{\sigma} \tau^+ | m \rangle \cdot \langle m | \vec{\sigma} \tau^+ | i \rangle}{E_m - (M_i + M_f)/2}$$
Nuclear matrix elements for the $2\nu$ decay deduced from measured halflives.
Note the pronounced shell dependence.

$$\frac{1}{T_{1/2}} = G(E,Z) \left(M_{GT}^{2\nu}\right)^2$$

easily calculable phase space factor
$^{76}$Ge half-life limits
historical perspective
factor $\sim 34$ every 10 years

Half-life limit (y)


Year

enriched Ge, 90% CL
natural Ge, 68% CL
Moore’s law in $0\nu\beta\beta$ decay (progress in the last ~50 years)

$$\langle m_{\beta\beta} \rangle < \frac{1}{[M_{0\nu}(G_{0\nu} T_{1/2})^{1/2}]},$$
and use the $T_{1/2}$ limits

from S. Elliott
The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum

Half-life limit: $1.9 \times 10^{25}$ years (H-M and IGEX)

Majorana neutrinos ruled out for masses greater than $\sim 0.35$-1.0 eV
$\beta\beta 0\nu$ discovery claim

HV. Klapdor-Kleingrothaus, et. al,
Halflife deduced: $1.50^{+7.55}_{-0.71} \times 10^{25}$ y at 95\%C.L.
Brief review of competing next generation proposals CUORE, EXO, GERDA, MAJORANA designed to explore the `degenerate' mass region $<m_{\beta\beta}> \geq 0.1$ eV with $\sim 100$ kg sources of decaying nuclei. All of these, if their background projections are confirmed, can be scaled to $\sim$ton size sources capable of exploring most of the `degenerate' neutrino mass region.
CUORE
Cryogenic Underground Observatory for Rare Events

- Heat sink: $T \approx 10 \text{ mK}$
- Energy absorber: $C \approx 2 \text{ nJ/K}$ (TeO$_2$ crystal)
- Thermometer: NTD Ge-thermistor $R \approx 100 \text{ M\Omega}$, $dR/dT \approx 100 \text{ k\Omega/\mu K}$

Temperature signal: $\Delta T = E/C \approx 0.1 \text{ mK}$ for $E = 1 \text{ MeV}$

Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1 \text{ mV}$ for $E = 1 \text{ MeV}$

Signal recovery time: $\tau = C/G \approx 0.5 \text{ s}$

Energy resolution (FWHM): $\approx 5 \text{ keV at 2500 keV}$
Array of 988 crystals:
19 towers of 52 crystals/tower.
\[ M = 0.78 \text{ ton of TeO}_2 \]

Search for $0\nu$ DBD of $^{130}\text{Te}$
$Q_{\beta\beta} = 2529 \text{ keV}$
Natural isotopic abundance [$^{130}\text{Te}$] = 34.08% 
Therefore, isotopic enrichment is unnecessary
What can CUORE do?

Running prototype CUORICINO:

5 year sensitivity

Pessimistic

\[ b = 0.01 \quad \Gamma = 5 \text{ keV} \]
\[ F^{0 \nu} = 2.1 \times 10^{26} \text{ y} \]
\[ m_{ee} < 20 - 103 \text{ meV} \]

Optimistic

\[ b = 0.001 \quad \Gamma = 5 \text{ keV} \]
\[ F^{0 \nu} = 6.5 \times 10^{26} \text{ y} \]
\[ m_{ee} < 10 - 55 \text{ meV} \]

exposure = 10.85 kg y

\[ \tau_{1/2}^{0 \nu} > 1.8 \times 10^{24} \text{ y} \text{ at 90\% C.L.} \]
A liquid xenon TPC as a $\beta\beta 0\nu$ detector
The crown jewels of EXO

200 kg of xenon enriched to 80% in $^{136}$Xe: the most isotope in possession by any $\beta\beta 0\nu$ collaboration.

11 times larger than previous experiments.
EXO-200: the first 200 kg 0νββ experiment

200 kg of Liquid Xenon to be contained in low background vessel, surrounded by 50 cm of ultra pure cryofluid inside a copper cryostat and shielded by 25 cm of lead.

Projected sensitivity of EXO-200: $T_{1/2} > 6.4 \times 10^{25}$ y in 2 years of running. Data taking to begin in 2007. TPC is being assembled and tested at Stanford right now.
The Germanium Detector Array for the search of neutrinoless decays of $^{76}\text{Ge}$ at LNGS (GERDA)

`Naked' $\text{Ge}$ detectors in a large LN/LAr container.
Phases and physics reach of GERDA

\[ \propto M \cdot T \]
\[ \propto (M \cdot T)^{1/2} \]

- **Phase-I**
  - HdM & IGEX
  - \( \sim 20 \text{ kg} \)
  - \( 3 \cdot 10^{25} \text{ (90 \% CL)} \)
  - \( <m_{ee}> < 0.09 – 0.29 \text{ eV} \)

- **Phase-II**
  - HdM & IGEX + new diodes
  - \( \sim 40 \text{ kg} \)
  - \( 2 \cdot 10^{26} \text{ (90 \% CL)} \)
  - KK

- **Exposure (kg y)**
- **2008**
- **2010**
New detectors for Phase II: Procurement of enriched Ge

1) procurement of 15 kg of natural Ge (‘test run’)
2) enrichment of 37.5 kg of Ge-76 completed!

Specially designed protective steel container reduces activation by cosmic rays by factor 20

\[ \text{natGe sample received March 7, 2005} \]
Majorana is scalable, allowing expansion to 1000 kg.

The 180 kg Experiment (M180)

- Reference Design
  - 171 segmented, n-type, 86% enriched $^{76}$Ge crystals.
  - 3 independent, ultra-clean, electroformed Cu cryostat modules.
  - Enclosed in a low-background passive shield and active veto.
  - Located deep underground (6000 mwe).

- Background Specification in the $0\nu\beta\beta$ peak ROI
  
  $1 \text{ count/t-yr}$

- Expected Sensitivity to $0\nu\beta\beta$
  (for 3 years, or 0.46 t-yr of $^{76}$Ge exposure)

  $T_{1/2} \geq 5.5 \times 10^{26} \text{ y (90\% CL)}$

  $<m_{\nu}> < 100 \text{ meV (90\% CL)}$ ([Rod05] RQRPA matrix elements)

  or a 10\% measurement assuming a 400 meV value.
The Majorana Modular Approach

- 57 crystal module
  - Conventional vacuum cryostat made with electroformed Cu.
  - Three-crystal stack are individually removable.

Diagram:
- Vacuum jacket
- Cold Plate
- Cold Finger
- 1.1 kg Crystal
- Thermal Shroud
- Bottom Closure
- Cap
- Tube (0.007" wall)
- Ge (62mm x 70 mm)
- Tray (Plastic, Si, etc)
- 1 of 19 crystal stacks
Majorana Sensitivity: Realistic runtime

<\textit{m}_\nu> of 100 meV [Rod05]
Nuclear matrix elements, continued

In order to relate decay rate to the effective mass \( <m_{\beta\beta}> \) we have to know the corresponding nuclear matrix elements. Any error in them is directly reflected as a like size error in \( <m_{\beta\beta}> \).

The operator, including the Fourier transform of the neutrino propagator, is \( \sum h(r_{ij})[\sigma_i \sigma_j - (g_V/g_A)^2]\tau_+ \tau_+ \) where the sum is over all nucleon pairs, and \( r_{ij} \) is the distance between the nucleons. \( h(r) \) is the `neutrino potential', the Fourier transform of the neutrino propagator \( h(r) \sim e^{-1.5E_{\nu}/r} \). Tests show that it is OK to treat this two-body operator in closure.

For evaluation of the matrix element it is important to consider:
1) How many single particle states near the Fermi level are included
2) How complicated configurations of the valence nucleons are included
There are two basic methods:
1) Nuclear shell model (SM) treats complicated configurations, but only few single-particle states (one shell or less).
2) Quasiparticle Random Phase Approximation (QRPA) can treat many single-particle states, but only simple particle-hole configurations.

Most existing calculations are QRPA, only very few are SM. The spread of calculated values is often used as a measure of uncertainty. Often, however, it merely reflects a spread in various assumptions and different choices of adjustable parameters in QRPA.
A provocative question: Do we know at all how large the matrix elements really are? Or, in other words, why there is so much variation among the published calculated matrix elements?

This suggests an uncertainty of as much as a factor of 5. Is it really so bad?
In contrast, Rodin et al, Nucl. Phys. A766, 107 (2006) suggest that the uncertainty is much less, perhaps only $\sim 30\%$ (within QRPA and its generalizations, naturally). So, who is right?

Slowly and smoothly decreasing (except $^{96}$Zr) with $A$
This moves the left outlier of Bahcall et al. right in the middle.

Benes, Faessler, Simkovic, to be submitted, June 2006

- Pairing fixed to exp. pairing gaps (constant pairing considered)
- BCS overlap factor taken into account
- uncertainties of 2νββ-decay half-lives not considered
Lipkin-Nogami BCS ground state

Closed shell nuclei: $^{48}\text{Ca}$, $^{116}\text{Sn}$, $^{136}\text{Xe}$, deformed $^{150}\text{Nd}$
Results of Suhonen et al. are larger (about 2x) than those of Rodin, but again only mildly varying from one nucleus to the next.
Where are the differences of these two examples coming from?
The bulk of the differences is understood, but there is no consensus which approach is correct (or at least more correct).
The main effect (by a factor of ~2) comes from taking into account (for Rodin et al.) and not taking into account (Civitarese and Suhonen) the short-range nucleon repulsion $O \rightarrow fOf$. Another effect comes (by ~30%) from including (or not) the induced pseudoscalar coupling.
Why the effect of short range correlation is so large could be understood (as well as other things) if one separates the contribution of `Cooper pairs' (pairs with $0^+$) and of the `broken pairs' or `higher seniority states'.

The $0^+$ pairs are highly correlated, the s.r.c. affects them by $\sim 30\%$. At the same time, their contribution is not affected by n-p force characterized by the coupling constant $g_{pp} \sim 1$.

The `broken pairs' are less affected by s.r.c., but strongly depend on $g_{pp}$. They have a tendency to cancel the contribution of $0^+$ pairs.

The sum of these two contributions is much smaller than either of them, depends sensitively on $g_{pp}$ and is strongly reduced by s.r.c.
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Comparison of $M^{0\nu}$ of Rodin et al. (RQRPA) and Nowacki et al. (SM, private comm., preliminary 2004) and older published (Caurier et al. 1996)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>RQRPA</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2.3-2.4</td>
<td>1.6</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>1.9-2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>0.3-0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>1.1-1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>1.2-1.4</td>
<td>1.9</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>1.3</td>
<td>2.0 (1.0)</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>0.6-1.0</td>
<td>1.6 (0.6)</td>
</tr>
</tbody>
</table>

Except for $^{100}\text{Mo}$ the agreement between these very different calculations is reasonably good.

Note that the SM calculations include the reduction caused by the s.r.c. and induced currents.
$0\nu\beta\beta$ half-lives for $<m_{\beta\beta}> = 50$ meV based on the matrix elements of Rodin et al.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>$(2.1 - 2.6) \times 10^{27}$ y</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>$(6.0 - 8.7) \times 10^{26}$ y</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>$(1.1 - 1.7) \times 10^{27}$ y</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>$(0.7 - 1.7) \times 10^{27}$ y</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>$(1.5 - 5.6) \times 10^{27}$ y (no $2\nu$ observed yet)</td>
</tr>
</tbody>
</table>

Note: Calculated matrix elements decrease with increasing $A$, but the phase-space factors usually increase, particularly the Coulomb factor, hence relatively little variation of $T_{1/2}$ with $A$.

Note: The sensitivity to $<m_{\beta\beta}>$ scales as $1/(T_{1/2})^{1/2}$. 50 meV is near the top of the `inverted hierarchy' mass region, its bottom is $\sim 20$ meV so sensitivity to $\sim 10^{28}$ years would be needed.
from observational cosmology, $M = m_1 + m_2 + m_3$

- blue shading: normal hierarchy, $\Delta m^2_{31} > 0$
- red shading: inverted hierarchy, $\Delta m^2_{31} < 0$

shading: best fit parameters, lines 95% CL errors.

Thanks to A. Piepke
Neutrino mass and magnetic moment are intimately related. In the orthodox SM with massless neutrinos magnetic moments vanish. However, in the minimally extended SM containing gauge-singlet right-handed neutrinos, one finds that $\mu_\nu$ is nonvanishing, but unobservably small: $\mu_\nu \approx 3 \times 10^{-19} \mu_B[m_\nu/1\text{ eV}]$ [1].

$$\mu_\nu = \frac{3eG_F}{(2^{1/2} \pi^2 8)} m_\nu$$
Typically, magnetic moment could be observed in $\nu$-e scattering. A nonvanishing $\mu_\nu$ will be recognizable only if the corresponding electromagnetic cross section is comparable in magnitude with the well-understood weak interaction cross section. The magnitude of $\mu_\nu$ which can be probed in this way is then given by

$$\frac{|\mu_\nu^{\text{exp}}|}{\mu_B} \approx \frac{G_F m_e}{\sqrt{2}\pi\alpha} \sqrt{m_e T} \sim 10^{-10} \sqrt{\frac{T}{m_e}}.$$  \hspace{1cm} (1)$$

Considering realistic values of $T$, it would be difficult to reach sensitivities below $\sim 10^{-11} \mu_B$. The limits derived

$$\sigma_{\text{elm}} = \pi \alpha^2 \mu^2 / m_e^2 \left(1 - T/E_\nu\right)/T$$

characteristic $T$ dependence
Limits on $\mu_\nu$ can also be derived from bounds on unobserved energy loss in astrophysical objects. For sufficiently large $\mu_\nu$, the rate for plasmon decay into $\nu \bar{\nu}$ pairs would conflict with such bounds. Since plasmons can also decay weakly into $\nu \bar{\nu}$ pairs, the sensitivity of this probe is again limited by size of the weak rate, leading to [4]

\[
\frac{|\mu_\nu^{\text{astro}}|}{\mu_B} \approx \frac{G_F m_e}{\sqrt{2} \pi \alpha} (\hbar \omega_P),
\]

where $\omega_P$ is the plasma frequency. Since $(\hbar \omega_P)^2 \ll m_e T$, this bound is stronger than the limit in Eq. (1). Given the
The interest in $\mu_\nu$ and its relation to $m_\nu$ dates from ~1990 when it was suggested that there is an anticorrelation between the neutrino flux observed in the Cl (Davis) experiment, and the solar activity (number of sunspots that follows a 11 year cycle).

A possible explanation of this was proposed by Voloshin, Vysotskij and Okun, with $\mu_\nu \sim 10^{-11} \mu_B$ and its precession in solar magnetic field. Even though the effect does not exist, the possibility of a large $\mu_\nu$ and small mass was widely discussed.

I like to describe a model independent constraint on the $\mu_\nu$ that depends on the magnitude of $m_\nu$ and moreover depends on the charge conjugation properties of neutrinos, i.e. makes it possible, at least in principle, to decide between Dirac and Majorana nature of neutrinos.
m_{\nu} \sim \Lambda^2/2m_e \mu_{\nu}/\mu_B \sim \mu_{\nu}/10^{-18} \mu_B [\Lambda(\text{TeV})]^2 \text{eV}

It is difficult to reconcile small $m_{\nu}$ with large $\mu_{\nu}$. 
To overcome this difficulty Voloshin (88) proposed existence of a \( SU(2)_\nu \) symmetry in which \( \nu_L \) and \((\nu_R)^c\) form a doublet. Under this symmetry \( m_\nu \) is forbidden but \( \mu_\nu \) is allowed.

For Dirac neutrinos such symmetry is broken by weak interactions, but for Majorana neutrinos it is broken only by the Yukawa couplings.

Note that Majorana neutrinos can have only transition in flavor magnetic moments.

Also note, that in flavor basis the mass term for Majorana neutrinos is symmetric but the magnetic moments are antisymmetric.

In the following I show that the existence of nonvanishing \( \mu_\nu \) leads through loop effects to an addition to the neutrino mass \( \delta m_\nu \) that, naturally cannot exceed the magnitude of \( m_\nu \).

(See Bell et al, PRL95, 151802, Davidson et al. Phys.Lett. B626, 151, and Bell et al., in preparation)
Consider first the Dirac case:

Assuming that $\mu_\nu$ is generated by some physics beyond the SM at a scale $\Lambda$, its leading contribution to the neutrino mass, $\delta m_\nu$, scales with $\Lambda$ as

where $\delta m_\nu$ is the contribution to a generic entry in the $3 \times 3$ neutrino mass matrix arising from radiative corrections at one-loop order. The dependence on $\Lambda^2$ arises from the quadratic divergence appearing in the renormalization of the dimension four neutrino mass operator. Although the

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
The usual graph for $\mu_\nu$ can be expressed in a gauge invariant form:

\[
\mu = C_W + C_B
\]

One can now close the loop and obtain a quadratically divergent contribution to the Dirac mass:

\[
m_\nu \sim \frac{\alpha}{16\pi} \frac{\Lambda^2}{m_e} \frac{\mu_\nu}{\mu_B}
\]
When $\Lambda$ is not substantially larger than $\nu$, the contribution to $\delta m_\nu$ from higher dimension operators can be important.

A neutrino magnetic moment coupling would be generated by gauge-invariant, dimension six operators that couple the matter fields to the SU(2)$_L$ and U(1)$_Y$ gauge fields $W^a_\mu$ and $B_\mu$, respectively.

\[ O^{(6)}_1 = g_1 \bar{\nu} \phi \sigma^{\mu\nu} \nu R B_{\mu\nu}, \]
\[ O^{(6)}_2 = g_2 \bar{\nu} \gamma^a \phi \sigma^{\mu\nu} \nu R W^a_{\mu\nu}, \]
\[ O^{(6)}_3 = \bar{\nu} \phi \nu (\phi^+ \phi), \]

Consider an effective

\[ \mathcal{L}_{\text{eff}} = \sum_{n,j} \frac{C^n_j(\mu)}{\Lambda^{n-4}} O^{(n)}_j(\mu) + \text{H.c.}, \]

After SSB

\[ \frac{\mu_\nu}{\mu_B} = -4\sqrt{2} \left( \frac{m_\nu}{\Lambda^2} \right) [C^6_1(\nu) + C^6_2(\nu)]. \]

Thus

\[ \delta m_\nu = -C^6_3(\nu) \frac{\nu^3}{2\sqrt{2} \Lambda^2}. \]

This leads to a similar bound on $\mu_\nu$ as from the dim-4 operator. Thus, the $\mu_\nu$ for a Dirac neutrino is essentially unobservable at present time.
Now consider the Majorana case:

$$\mu_\nu$$

The lowest order contribution to $\mu_\nu$ arises at dim-7.

After SSB
In the case that

and thus as in Dirac case

However for the case of arbitrary $C_{W}^{\dagger}$ we obtain constraints from either $O_{W}$ or $O_{B}$ by inserting of two Yukawa couplings to achieve the required symmetry.

The above is also valid if $C_{W}^{-}$ is replaced by $C_{B}$.

The most general bound on Majorana magnetic moment is

$$
\mu_{\alpha\beta} \leq 4 \times 10^{-9} \mu_{B} \left( \frac{[m_{\nu}]_{\alpha\beta}}{1 \text{ eV}} \right) \left( \frac{1 \text{ TeV}}{\Lambda} \right)^{2} \left| \frac{m_{\tau}}{m_{\alpha}^{2} - m_{\beta}^{2}} \right|
$$
Thus if a neutrino magnetic moment is observed near its present experimental limit we would conclude that neutrinos are Majorana, and that the corresponding new scale $\Lambda < 100$ TeV.

If we, further, could assume that all elements of the matrix $\mu_{\alpha\beta}$ are of similar magnitude, than a discovery of $\mu_\nu$ at, say $10^{-11}\mu_B$ would imply $\Lambda < 10$ TeV with a possible implication for the mechanism of $0\nu\beta\beta$ decay.

Hence search for $\mu_\nu$ is in some sense complementary to the search for $0\nu\beta\beta$ decay. But, unlike the $0\nu\beta\beta$ decay, we have just an upper bound, and not a clear map where to look.
The distinction between Dirac and Majorana does not require processes that violate lepton number, just amplitudes. For example the neutrino $\gamma$ decay:

![Diagram of neutrino decay](image)

**FIG. 1.** Processes which interfere for Majorana, but not for Dirac, neutrinos.

Angular distribution of photons in the lab system with respect to the neutrino beam direction is

$$dN = \frac{1}{2} (1 + a \cos \theta) d \cos \theta,$$

where $a = 0$ for Majorana and $a = -1$ for Dirac and left handed couplings.
Summary and/or Conclusions

Study of 0νββ decay entered a new era. No longer is the aim just to push blindly the sensitivity higher and the background lower, but to explore specific regions of the <m_{ββ}> values.

The `phased' program means that first we will explore the `degenerate' region (0.1-1 eV), with ~100 kg sources, and prepare for the `inverted hierarchy' (0.01-0.1eV) region with ~ ton sources that should follow later.

It is also important to keep in mind the questions that I discussed:

a) Relation of <m_{ββ}> and the absolute mass (rather clear already, becoming less uncertain with better oscillation results).

b) Mechanism of the decay (exploring LFV, models of LNV, running of LHC to explore the ~TeV mass particles).

c) Nuclear matrix elements (exploring better, and agreeing on, the reasons for the spread of calculated values, and deciding on the optimum way of performing the calculations, while pursuing vigorously also the application of the shell model).

d) Other processes sensitive to Majorana vs. Dirac (neutrino magnetic moments etc.)