Discovering intermediate mass sterile neutrinos through
\( \tau^- \rightarrow \pi^- \mu^- e^+ \nu \) (or \( \bar{\nu} \)) decay

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Neutrinos are the only neutral fermions in the standard model (SM).

Neutrinos produced in charged-current interactions are always accompanied by a charged lepton and are said to be of the flavor of the charged lepton: $W^+ \rightarrow \ell^+ \nu_\ell$, where $\ell \in \{e, \mu, \tau\}$.

Neutrinos were first inferred in $\beta$-decays: $n \rightarrow p e^- \bar{\nu}_e$.

In $\beta$-decay of $^{60}_{27}$Co: $^{60}_{27}$Co $\rightarrow$ $^{60}_{28}$Ni + $e^-$ + $\bar{\nu}_e$, C. S. Wu observed in 1957 that in presence of a magnetic field, the electrons are emitted in direction opposite to that of the magnetic field direction.

(Fig Ref: ‘The Oscillating Neutrino’, Los Alamos Science, Number 25, 1997.)
Introduction

Neutrinos have mass.

- In the SM, neutrinos are
  - massless ($m_\nu = 0$) and
  - only left-handed ($\nu_L$). No right-handed neutrinos ($\nu_R$) observed yet.

- Giving neutrinos mass in the SM is possible iff we introduce $\nu_R$, 
  \[ \mathcal{L}_{\text{SM}} \supset -m_\nu (\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R), \text{ where } m_\nu = \frac{Y_\nu \nu}{\sqrt{2}}, \]
  \[ Y_\nu = \text{Higgs-neutrino Yukawa coupling constant,} \]
  \[ \nu = \text{Higgs VEV}. \]

- Neutrino oscillation $\implies m_\nu \neq 0$.
- **Nobel Prize in Physics 2015**

“For the discovery of neutrino oscillations, which shows that neutrinos have mass”.

\[ Takaaki Kajita \quad Arthur B. McDonald \]
There are various suggestions as to how neutrinos can get mass.

**Dirac mass:**
- **Assumption:** $\nu_R$ exists.
- **Lagrangian:**

$$\mathcal{L}_{\text{mass}}^D = -m^D_\nu (\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R).$$

- **Disadvantage:** No reason for $m^D_\nu$ to be small.
- **Challenge:** Finding $\nu_R$.

**Majorana mass:**
- **Assumption:** Neutrino $\equiv$ anti-neutrino. (Majorana condition)
- **Lagrangian:**

$$\mathcal{L}_{\text{mass}}^M = \frac{1}{2} m^M_\nu \left( \bar{\nu}_L^C \nu_L + \bar{\nu}_L \nu_L^C \right).$$

- **Disadvantage:** $\mathcal{L}_{\text{mass}}^M$ is not invariant under $SU(2)_L \times U(1)_Y$ gauge group.
  
  $\therefore \mathcal{L}_{\text{mass}}^M$ is not allowed by SM.
- **Challenge:** To ascertain the Majorana nature of light neutrino.
Introduction
How to give neutrinos mass?

❖ **Dirac-Majorana mass:**
  ♦ **Assumptions:** \( \nu_R \) exists, and neutrino \( \equiv \) anti-neutrino.
  ♦ **Lagrangian:**

\[
\mathcal{L}^{D+M}_{\text{mass}} = \frac{1}{2} m^L_\nu \left( \overline{\nu}^C_L \nu_L \right) + \frac{1}{2} m^R_\nu \left( \overline{\nu}^C_R \nu_R \right) - m^D_\nu (\nu_R \nu_L) + \text{H.c.}
\]

\[
= \frac{1}{2} \left( m_1 \overline{\nu}^C_1 \nu_1 + m_2 \overline{\nu}^C_2 \nu_2 \right) + \text{H.c.},
\]

where \( \nu_k = \nu_{kL} + \nu^C_{kL} \) (\( k = 1, 2 \)) are Majorana neutrinos and

\[
m_{2,1} = \frac{1}{2} \left( m^L_\nu + m^R_\nu \right) \pm \sqrt{(m^L_\nu + m^R_\nu)^2 + 4|m^D_\nu|^2}.
\]

❖ **Disadvantages:**
  ➡ No explanation for small mass of neutrinos, and
  ➡ one mass out of \( m^D_\nu, m^R_\nu, m^L_\nu \) is complex, in general.

❖ **Challenges:**
  ➡ To prove that both \( \nu_1 \) and \( \nu_2 \) are Majorana neutrinos.
  ➡ What is the physical meaning of complex mass?
See-saw mechanism: A simpler version of Dirac-Majorana mass, with a nice twist.

- **Assumptions:** $m^L_\nu = 0$ and $m^D_\nu \ll m^R_\nu$.
- **Lagrangian:**

\[
L_{D+M}^{\text{mass}} = \frac{1}{2} m^R_\nu \left( \overline{\nu}^C_R \nu_R \right) - m^D_\nu \left( \overline{\nu}^C_R \nu_L \right) + \text{H.c.}
\]

\[
= \frac{1}{2} \left( m_1 \overline{\nu}^C_1 \nu_1 + m_2 \overline{\nu}^C_2 \nu_2 \right) + \text{H.c.,}
\]

where $m_1 \approx - \left( \frac{m^D_\nu}{m^R_\nu} \right)^2$ and $m_2 \approx m^R_\nu$.

- **Advantage:** $m_1 \ll m_2 \implies \nu_1$ is a light neutrino
- **Challenges:**
  - To find the heavy $\nu_2$ experimentally.
  - To prove that both the light $\nu_1$ and heavy $\nu_2$ are Majorana neutrinos.
Brief review of existing methods to study Majorana neutrinos

Neutrinos: the only known elementary fermions that can have Majorana nature ($\nu \equiv \bar{\nu}$).

All existing methods to study Majorana neutrinos can be grouped into two broad groups:

- **Study of statistical property (Fermi-Dirac statistics):** Aims to test the quantum mechanical identicalness (indistinguishability) of Majorana neutrino and anti-neutrino. *Independent of size of neutrino mass.*

- **Study of interaction property ($\Delta L = 2$ processes):** Aims to test the consequences of Majorana neutrino–anti-neutrino identicalness as non-observation of any final neutrinos (inobservability). *Dependent on size of neutrino mass.*
This is a comparatively new idea and is under active refinement now.

- **Process:** \( X \rightarrow Y \nu \bar{\nu} \)
- **Signature:** The ‘effective’ Dalitz plot should be symmetric under \( \nu \leftrightarrow \bar{\nu} \) exchange for Majorana neutrinos.
- **Advantage:** The size of neutrino mass does not affect its statistical property.
- **Challenges:** Finding ways to measure neutrino and anti-neutrino 4-momenta without affecting their indistinguishability.
Study of interaction property ($\Delta L = 2$ processes)

- Majorana neutrino: very unique phenomenology (lepton number non-conservation), they mediate $\Delta L = 2$ processes.

\[ \nu_k \equiv \bar{\nu}_k \]

\[ \Delta L = 2 \text{ processes play crucial role to probe Majorana nature of } \nu \text{’s.} \]

- neutrinoless double-beta ($0\nu\beta\beta$) decay
- Rare meson decays with $\Delta L = 2$
- Collider searches at LHC
- rare tau decays with LFV and LNV
Looking for Majorana neutrinos via $\Delta L = 2$ processes

- Decay rate of any $\Delta L = 2$ process with final leptons $\ell_1^+ \ell_2^+$:

$$
\Gamma_{\Delta L=2} \propto \left| \sum_k U_{\ell_1 k} U_{\ell_2 k} \frac{m_k}{p^2 - m_k^2 + i m_k \Gamma_k} \right|^2,
$$

where we have used the fact that $(1 - \gamma^5) \not{p}(1 - \gamma^5) = 0$.

- **Light $\nu$:**

$$
\Gamma_{\Delta L=2} \propto \left| \sum_k U_{\ell_1 k} U_{\ell_2 k} m_k \right|^2 = |m_{\ell_1 \ell_2}|^2.
$$

- **Heavy $\nu$:**

$$
\Gamma_{\Delta L=2} \propto \left| \sum_k \frac{U_{\ell_1 k} U_{\ell_2 k}}{m_k} \right|^2.
$$

- **Resonant $\nu$:**

$$
\Gamma_{\Delta L=2} \propto \frac{\Gamma(N \to i) \Gamma(N \to f)}{m_N \Gamma_N}.
$$
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Neutrinoless double-beta ($0\nu\beta\beta$) decay

A comparison with beta decay and double-beta decay:

$2\nu\beta\beta$-decay

$\beta$-decay

$0\nu\beta\beta$-decay

$\equiv$ proton ($p$)

$\equiv$ neutron ($n$)

$\equiv$ electron ($e^-$)

$\equiv$ electron-antineutrino ($\bar{\nu}_e$)
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Neutrinoless double-beta ($0\nu\beta\beta$) decay

Mechanism for $0\nu\beta\beta$ decay:

Black-box diagrams for $0\nu\beta\beta$:
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Neutrinoless double-beta ($0\nu\beta\beta$) decay

- Double-beta ($2\nu\beta\beta$) decay has been observed in 10 isotopes, $^{48}\text{Ca}$, $^{76}\text{Ge}$, $^{82}\text{Se}$, $^{96}\text{Zr}$, $^{100}\text{Mo}$, $^{116}\text{Cd}$, $^{128}\text{Te}$, $^{130}\text{Te}$, $^{150}\text{Nd}$, $^{238}\text{U}$, with half-life $T_{1/2} \approx 10^{18} - 10^{24}$ years.

- $0\nu\beta\beta$ (forbidden in SM) is yet to be observed in any experiment.

$$T_{1/2}^{0\nu}\left[^{76}\text{Ge}\right] > 2.1 \times 10^{25} \text{ years (90\% C.L.)}.$$
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Neutrinoless double-beta ($0\nu\beta\beta$) decay

- The half-life of a nucleus decaying via $0\nu\beta\beta$ is,

$$\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} |M_{0\nu}|^2 |m_{\beta\beta}|^2,$$

where
- $G_{0\nu}$ is phase space factor,
- $M_{0\nu}$ is the nuclear matrix element, (large theoretical uncertainty)
- $m_{\beta\beta}$ is effective Majorana mass. $m_{\beta\beta} = \sum_{k=1}^{3} U_{ek}^2 m_k$ is complex, in general, and can be zero due to possible cancellations arising from phases in $U_{ek}$.
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Neutrinoless double-beta ($\nu\beta\beta$) decay

If $m_{\beta\beta} < 10^{-2}$, only NH is viable and the $T^{0\nu}_{1/2}$ will be much larger than the current experimental lower bound.

S. M. Bilenky and C. Giunti
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Rare meson decays: $M^+ \to M'^- \ell_1^+ \ell_2^+$

- **Processes:** $M^+ \to M'^- \ell_1^+ \ell_2^+$, where $M = K, D, D_s, B, B_c$ and $M' = \pi, K, D, \ldots$


- **No nuclear matrix element unlike** $0\nu\beta\beta$, but probes Majorana nature of massive neutrino(s) $N$. 
Looking for Majorana neutrinos via $\Delta L = 2$ processes

Rare meson decays: $M^+ \rightarrow M'^- \ell_1^+ \ell_2^+$
Looking for Majorana neutrinos via $\Delta L = 2$ processes
Collider searches at LHC

流程：$W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu$, $W^+ \rightarrow \mu^+ \mu^+ e^- \bar{\nu}_e$. 涉及重的中微子 $N$，它也可以有Majorana性质。

C. Dib, C.S. Kim, arXiv:1509.05981 (PRD 92, 093009, 2015);

- 流程图

- 衰变宽度:
  - LNV: $\Gamma(W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu) = |U_{Ne}|^4 \hat{\Gamma}$,
  - LNC: $\Gamma(W^+ \rightarrow e^+ e^+ \mu^- \bar{\nu}_\mu) = |U_{Ne}U_{N\mu}|^2 \hat{\Gamma}$,

  其中 $\hat{\Gamma} = \frac{G_F^3 M_W^3}{12 \times 96 \sqrt{2} \pi^4} \frac{m_N^5}{\Gamma_N} \left(1 - \frac{m_N^2}{M_W^2}\right)^2 \left(1 - \frac{m_N^2}{2M_W^2}\right)$. 

(Lepton Number Violating) (Lepton Number Conserving)
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Feynman diagrams

- Possible iff $\exists$ a sterile neutrino $N$ of mass $m_N$:
  $$(m_\mu + m_e) \leq m_N \leq (m_\tau - m_\pi) \approx 0.1061 \text{ GeV} \leq m_N \leq 1.6372 \text{ GeV}.$$  
- Feynman diagrams:
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Distinguishing amongst the Feynman diagram contributions

By using pion and muon energy spectrum we can distinguish among the four Feynman diagrams.

(a)
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Distinguishing amongst the Feynman diagram contributions

By using pion and muon energy spectrum we can distinguish among the four Feynman diagrams.

\[ N \equiv N^{W'^-} - \bar{N}^{W'^-} \tau^- \nu^\mu \mu^- e^+ \pi^- \]

\[ m_N \text{ (GeV)} \quad E_{\pi} \quad E_{\mu,\text{max}} \quad E_{\mu,\text{min}} \]

(b)
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Distinguishing amongst the Feynman diagram contributions

By using pion and muon energy spectrum we can distinguish among the four Feynman diagrams.
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Distinguishing amongst the Feynman diagram contributions

By using pion and muon energy spectrum we can distinguish among the four Feynman diagrams.
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Expression for decay rate (Feynman diagrams (a) and (b) only)

Using the narrow-width approximation for $N$, the partial decay width of tau decay in our case is given by:

$$
\Gamma \left( \tau^- \rightarrow \pi^- \mu^- e^+ \nu \right) = \Gamma \left( \tau^- \rightarrow \pi^- N \right) \frac{\Gamma \left( N \rightarrow \mu^- e^+ \nu (\text{or} \ \bar{\nu}) \right)}{\Gamma_N},
$$

where $\Gamma_N$ is the full width of the sterile neutrino, and

$$
\Gamma \left( \tau^- \rightarrow \pi^- N \right) = \frac{G_F^2 f^2 \pi m^3_\tau |V_{ud}|^2}{8\pi} |V_{\tau N}|^2 \sqrt{\lambda \left(1, r_N, r_\pi \right)} \left[ (1-r_N)^2 - r_\pi (1+r_N) \right],
$$

$$
\Gamma \left( N \rightarrow \mu^- e^+ \nu (\text{or} \ \bar{\nu}) \right) = \Gamma \left( N \rightarrow \mu^- e^+ \nu_e \right) + \Gamma \left( N \rightarrow \mu^- e^+ \bar{\nu}_\mu \right)
$$

$$
= \frac{G_F^2 m^5_N |V_{\mu N}|^2}{192\pi^3} \left( 1 - 8r_\mu + 8r^3_\mu - r^4_\mu - 12r^2_\mu \ln r_\mu \right) \left( 1 + \alpha R_{e\mu} \right),
$$

$$
= \begin{cases} 
\frac{G_F^2 m^5_N |V_{\mu N}|^2}{192\pi^3} \left( 1 - 8r_\mu + 8r^3_\mu - r^4_\mu - 12r^2_\mu \ln r_\mu \right), & \text{(Dirac } N, \ \alpha = 0) \\
\frac{G_F^2 m^5_N |V_{\mu N}|^2}{192\pi^3} \left( 1 - 8r_\mu + 8r^3_\mu - r^4_\mu - 12r^2_\mu \ln r_\mu \right) \left( 1 + R_{e\mu} \right), & \text{(Majorana } N, \ \alpha = 1) 
\end{cases}
$$
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Expression for decay rate (Feynman diagrams (a) and (b) only)

In the decay width expressions we have,

- $f_{\pi} = 130.2 \text{ MeV},$
- $r_{N,\pi} = \frac{m_{N,\pi}^2}{m_{\pi}^2},$
- $r_{\mu} = \frac{m_{\mu}^2}{m_N^2},$
- $|V_{\ell N}|^2$ denotes the mixing of active neutrino of flavor $\ell = e, \mu, \tau$ with the sterile neutrino $N,$
- $\alpha$ is a parameter that allows to distinguish the sterile intermediate Dirac ($\alpha = 0$) and Majorana ($\alpha = 1$) neutrinos,
- $R_{e\mu} = \frac{|V_{eN}|^2}{|V_{\mu N}|^2},$ and
- $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$ is the Källén function.
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Total decay width of $N$

From the paper G. Cvetic, C. S. Kim and J. Zamora-Saá, Phys. Rev. D 89, no. 9, 093012 (2014) we take the upper limits on values of $V_{\ell N}$ and calculate the $\Gamma_N$ for two chosen values of $m_N$:

$$\Gamma_N \approx \frac{G_F^2 m_N^5}{96\pi^3} \left( 15 |V_{eN}|^2 + 8 |V_{\mu N}|^2 + 2 |V_{\tau N}|^2 \right), \quad \text{(for } m_N = 0.25 \text{ GeV})$$

$$\Gamma_N \approx \frac{G_F^2 m_N^5}{96\pi^3} \left( 7 |V_{eN}|^2 + 7 |V_{\mu N}|^2 + 2 |V_{\tau N}|^2 \right). \quad \text{(for } m_N = 1 \text{ GeV})$$

| $m_N$ (in GeV) | $|V_{eN}|^2$ | $|V_{\mu N}|^2$ | $|V_{\tau N}|^2$ | $\Gamma_N$ (in GeV) |
|---------------|-------------|----------------|----------------|-------------------|
| 0.25          | $10^{-8}$   | $10^{-7}$      | $10^{-4}$      | $8.97 \times 10^{-21}$ |
| 1.0           | $10^{-7}$   | $10^{-7}$      | $10^{-2}$      | $9.14 \times 10^{-16}$ |
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\nu$) decays

Muon energy spectrum

$$\frac{1}{\Gamma (N \rightarrow \mu^- e^+ \nu (\text{or } \nu))} \frac{d\Gamma (N \rightarrow \mu^- e^+ \nu (\text{or } \nu))}{dE_\mu} =$$

$$96m_N^3 \left( \frac{-1}{3} m_N m_\mu^2 + \left( \frac{1}{2} + \alpha R_{e\mu} \right) \left( m_N^2 + m_\mu^2 \right) E_\mu - \left( \frac{2}{3} + 2\alpha R_{e\mu} \right) m_N E_\mu^2 \right) \sqrt{E_\mu^2 - m_\mu^2}$$

$$\frac{\left( (m_N^4 - m_\mu^4) (m_N^4 + m_\mu^4 - 8m_\mu^2 m_N^2) - 24m_\mu^4 m_N^4 \log \left( \frac{m_\mu}{m_N} \right) \right) (1 + \alpha R_{e\mu})}{\left( m_N^4 - m_\mu^4 \right) \left( m_N^4 + m_\mu^4 - 8m_\mu^2 m_N^2 \right) - 24m_\mu^4 m_N^4 \log \left( \frac{m_\mu}{m_N} \right) (1 + \alpha R_{e\mu})}.$$
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Muon energy spectrum for $M_N = 0.25$ GeV

$N \rightarrow \mu^- e^+ \nu$(or $\bar{\nu}$) with $m_N = 0.25$ GeV

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dE_\mu} = \frac{|V_{eN}|^2}{|V_{\mu N}|^2}
\]
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\nu$) decays

Muon energy spectrum for $M_N = 1.0$ GeV

$N \rightarrow \mu^- e^+ \nu$ (or $\bar{\nu}$) with $m_N = 1$ GeV

$$\frac{1}{\Gamma} \frac{d\Gamma}{dE_\mu}$$

- Dirac $N$
- $R_{e\mu} = 0.25$
- $R_{e\mu} = 0.50$
- $R_{e\mu} = 0.75$
- $R_{e\mu} = 1.00$

$$R_{e\mu} = \frac{|V_{eN}|^2}{|V_{\mu N}|^2}$$

$E_\mu$ (GeV) vs. $m_\mu$
Search for intermediate mass sterile Majorana neutrino in $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays

Flowchart

START

Look for $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) in experiments

Observed?

NO

No massive sterile neutrino $N$ in the mass range $m_e + m_\mu \leqslant m_N \leqslant m_\tau - m_\pi$

STOP

YES

There is a massive sterile neutrino $N$ in the mass range $m_e + m_\mu \leqslant m_N \leqslant m_\tau - m_\pi$

STOP

Is $\pi^-$ mono-energetic, in the rest frame of $\tau^-$?

NO

Figs. 1c and 1d

YES

Figs. 1a and 1b

STOP

Does the muon energy spectrum in the rest frame of $N$ have maximum at the kinematical endpoint of $E_\mu$?

NO

Both Figs. 1a and 1b

STOP

YES

Fig. 1a only

$N$ is a Dirac neutrino

STOP

STOP

STOP
Comparison with $\tau^- \rightarrow \pi^- \pi^+ \mu^-$ decay

The decay $\tau^- \rightarrow \pi^- \pi^+ \mu^-$ and subsequent $\pi^+ \rightarrow e^+ \nu_e$ can give rise to background events for our process.

In the mass range $m_e + m_\mu \leq m_N \leq m_\mu + m_\pi$ the $\tau^- \rightarrow \pi^- \mu^- e^+ \nu_e$ is allowed, but $\tau^- \rightarrow \mu^- \pi^+ \pi^-$ is not.
Discussion on miscellaneous new physics contributions
Discussion on miscellaneous new physics contributions

By taking mono-energetic pions we can get rid of all these possible new physics scenarios completely.
Conclusion

By looking at the pion and muon energy spectrum in the $\tau^- \rightarrow \pi^- \mu^- e^+ \nu$ (or $\bar{\nu}$) decays one can conclusively search for Majorana nature of the intermediate mass sterile neutrino which facilitates this decay.

Thank you