The $M_1^+ \to M_2^- \ell_1^+ \ell_2^+$ decay.

Marxil Sánchez García

IFUNAM

asesorado por
Dr. Genaro Toledo Sánchez.

Mayo, 2018

Motivation

- Are neutrinos Dirac or Majorana particles?
- Various $\Delta L = 2$ processes have been studied in the literature:$0\nu\beta\beta$, $M^+ \to M^- l^+ l^+$, $\tau^- \to \ell^+ M_1^- M_2^-$.
- Rare meson decays K^+, D^+, D_s^+, B^+, B_c^+.
  - Experiment E865 at the Brookhaven Alternating Gradient Synchrotron (AGS) [PRL.,85,2877 (2000)] :

$$\mathcal{B}(K^+ \to \pi^- e^+ \mu^+) < 5 \times 10^{-10} \tag{1}$$

  - BABAR detector at the SLAC National Accelerator Laboratory [PR.,D84,072006 (2011)] :

$$\mathcal{B}(D_s^+ \to \pi^- e^+ e^+) < 4.1 \times 10^{-6} \tag{2}$$

  - LHCb detector at the LHC. [PRL.,112,131802 (2014)] :

$$\mathcal{B}(B^+ \to \pi^- \mu^+ \mu^+) < 4 \times 10^{-9} \tag{3}$$

  - Belle detector at the KEKB $e^+ e^-$ collider. [PR.,D84,071106 (2011)] :

$$\mathcal{B}(B^+ \to D^- e^+ \mu^+) < 1.8 \times 10^{-6} \tag{4}$$

Mass terms

- The full neutrino mass terms read:

$$
\begin{aligned}
-\mathcal{L}^{\nu}_{m_{tot}} &= \frac{1}{2}(2\bar{\nu}^0_L M^{\nu} \nu^0_R + \bar{\nu}^{0c}_L M^A \nu^{0c}_R + \bar{\nu}^{0c}_L M^S \nu_R) + h.c. \\
&= \frac{1}{2}\begin{pmatrix} \bar{\nu}^0_L & \bar{\nu}^{0c}_L \end{pmatrix} \begin{pmatrix} M^A & M^{\nu} \\ M^{T\nu} & M^S \end{pmatrix} \begin{pmatrix} \nu^{0c}_R \\ \nu^0_R \end{pmatrix} + h.c., \qquad (5)
\end{aligned}
$$

- Where the mass eigenvalues are of the order:

$$m^{\nu} \approx \frac{M_D^2}{M_S} \quad M^N \approx M_S. \qquad (6)$$

.

- In terms of the mass eigenstates, the charged currents can be written as:

$$-\mathcal{L}^{\nu}_W = \frac{1}{\sqrt{2}} W^+_{\mu}(U_{\nu e}\bar{\nu}_L \gamma^{\mu} e_L + V_{Ne}\bar{N}^c_L \gamma^{\mu} e_L) + h.c. \qquad (7)$$

[JHEP.,05,030(2009)]

Lepton-number violation $\Delta L = 2$.

- The basic process with $\Delta L = 2$ can be generically expressed by:

$$W^- W^- \to \ell_1^- \ell_2^- . \quad (8)$$

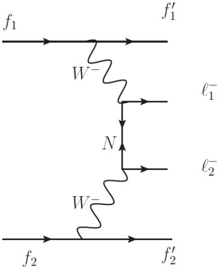

Figura: A generic diagram for $\Delta L = 2$ processes via Majorana neutrino (N) exchange.

- $0\nu\beta\beta$, $\tau^- \to \ell^+ M_1^- M_2^-$, $M_1^+ \to \ell_1^+ \ell_2^+ M_2^-$, $\sum^- \to \sum^+ e^- e^-$.

Lepton-number violating rare meson decays: $M^+ \to M'^- l_1^+ l_2^+$

- At the quark level, the decay occurs via two types of amplitudes [PR.,D82,053010 (2010)] :

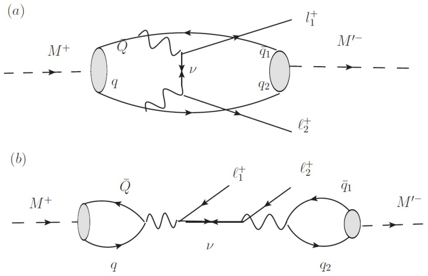

Figura: The t-type and s-type weak amplitudes at the quark level that enter in the process $M^+ \to M'^- l_1^+ l_2^+$ (plus the same diagrams with leptons exchanged if they are identical).

- If $m_N < m_\pi$ then the decay rate is suppressed: $\propto m_N^2/M_W^2$.
- If $m_N > m_{B_c}$ then the decay rate is suppressed: $\propto |V_{\ell_1 N} V_{\ell_2 N}|^2/m_N^2$.
- If $m_\pi < m_N < m_{B_c}$ then the intermediate neutrino goes on it mass shell.

s channel.

- If the two leptons are identical, the amplitude is $\mathcal{M} = \mathcal{M}_1 - \mathcal{M}_2$ and the allowed mass region for the majorana neutrino (in resonance) is

$$m_{M_2} + m_l < m_N < m_{M_1} - m_l. \tag{9}$$

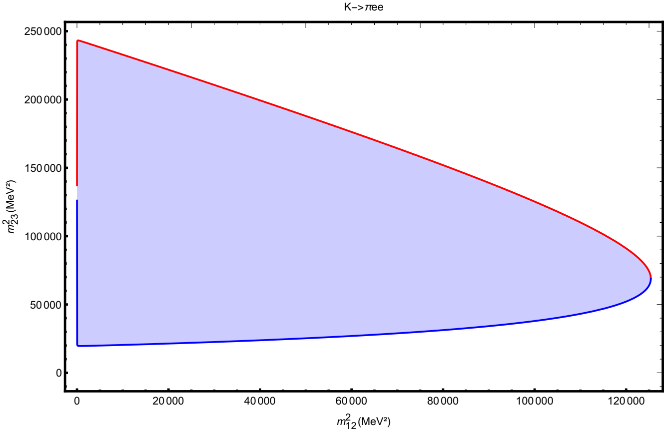

Figura: Dalitz plot for $K^+ \to \pi^- e^+ e^+$.

- If the leptons are of different flavour, the amplitude is $\mathcal{M} = \mathcal{M}_1 + \mathcal{M}_2$ and we have two allowed mass regions,

$$m_{M_2} + m_{l_2} < m_N < m_{M_1} - m_{l_1} \quad m_{M_2} + m_{l_1} < m_N < m_{M_1} - m_{l_2}. \qquad (10)$$

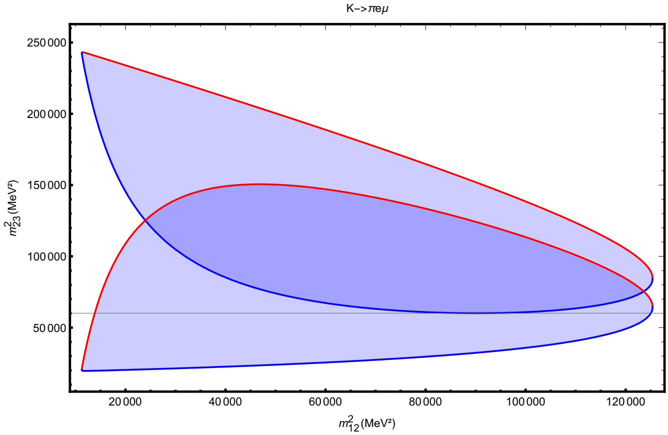

Figura: Dalitz plot for $K^+ \to \pi^- e^+ \mu^+$ and $K^+ \to \pi^- \mu^+ e^+$.

Decay width.

- The decay width can be computed as follows [JHEP.,05,030 (2009)] :

$$\Gamma = \frac{1}{(2\pi)^3 32 m_{M_1}^3}\left[\int f_1 dm_{12}^2 dm_{23}^2 + \int f_2 dm_{12}^2 dm_{13}^2\right]. \tag{11}$$

where

$$f_i = \frac{|\mathcal{M}_i^2|}{\sum_i |\mathcal{M}_i|^2} |\sum_i \mathcal{M}_i|^2 \tag{12}$$

$$\begin{aligned} \mathcal{M}_{Tot} &= G_F^2 f_{M_1} f_{M_2} V_{M_1}^{CKM} V_{M_2}^{CKM} V_{\ell_1 N} V_{\ell_2 N} m_N \\ &\times \left[\frac{\bar{u}_{\ell_1}^c \not{q}_1 (1+\gamma^5) \not{q}_2 v_{\ell_2}}{(q_1 - p_1)^2 - m_N^2 + i\Gamma_N m_N} + \frac{\bar{u}_{\ell_1}^c \not{q}_1 (1+\gamma^5) \not{q}_2 v_{\ell_2}}{(q_1 - p_2)^2 - m_N^2 + i\Gamma_N m_N}\right] \end{aligned} \tag{13}$$

- We can apply the narrow-width approximation,

$$\int \frac{dm_{c_i}^2}{(m_{c_i}^2 - m_4^2)^2 + \Gamma_{N_4}^2 m_4^2}\Bigg|_{\Gamma_{N_4}\to 0} = \int \delta(m_{c_i}^2 - m_4^2) dm_{c_i}^2 \frac{\pi}{\Gamma_{N_4} m_4} \tag{14}$$

- Integrating over the δ -funtion we get:

$$\Gamma = \frac{1}{(2\pi)^3 32 m_{M_1}^3}\left[\int f_1 dm_{12}^2 + \int f_2 dm_{12}^2\right] \tag{15}$$

Branching ratio

- We explore the branching ratio as a function of the m_N and Γ_N.
- The total width of the heavy neutrino is given by [JHEP.,05,030 (2009)]

$$\Gamma_N \backsim (10^{-8} |V_{\ell_1 N} V_{\ell_2 N}|)\text{MeV}. \quad (16)$$

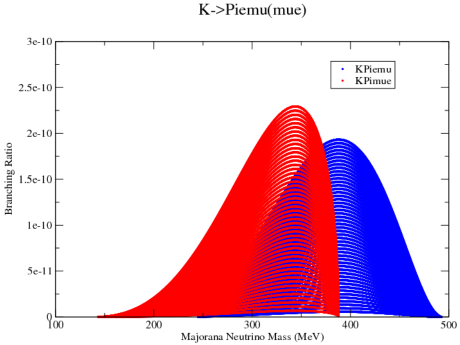

Figura: Contributions from $\mathcal{M}_1$ and $\mathcal{M}_2$ to the branching ratio of the process $K^+ \to \pi^- e^+ \mu^+$ in the region of $\Gamma_N = [10^{-16}, 10^{-14}]$.

- Upper limit on branching ratio for various decays $M_1^+ \to M_2^- l_1^+ l_2^+$. All three lepton flavors are considered. Entries with X are decays that are kinematically forbidden. Empty entries don't have upper limit yet.

Process	BrExp(ee) <	BrExp(eμ) <	BrExp(μμ) <	BrExp(eτ) <	BrExp(μτ) <	BrExp(ττ) <
K→πll	6.40E-10	5.00E-10	1.10E-09	X	X	X
D→πll	1.10E-06	2.00E-06	2.20E-08	X	X	X
D→Kll	9.00E-07	1.90E-06	1.00E-05	X	X	X
Ds→πll	4.10E-06	8.40E-06	1.20E-07		X	X
Ds→Kll	5.20E-06	6.10E-06	1.30E-05	X	X	X
Ds→Dll		X	X	X	X	X
B→πll	2.30E-08	1.50E-07	4.00E-09			
B→Kll	3.00E-08	1.60E-07	4.10E-08			
B→Dll	2.60E-06	1.80E-06	6.90E-07			X
B→Dsll			6.90E-07			X
Bc→πll						
Bc→Kll						
Bc→Dll						
Bc→Dsll						
Bc→Bll				X	X	X

Figura: The decay modes of leptonic-number violating decays $M_1^+ \to M_2^- l_1^+ l_2^+$.

Neutrino Majorana mass region.

- Using the decay ratio of all processes we can map the mass of the nuetrino and divide it into 13 regions.

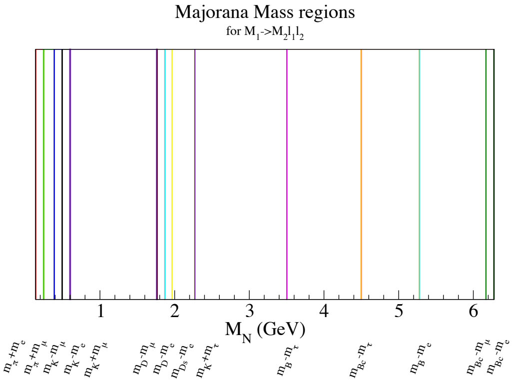

Figura: All neutrino mass region.

- We choose the process with better branching ratio upper limit, next we used its corresponding information on m_N and Γ_N for that we can indirectly calculate a upper limit for the other processes.

Region mN (MeV)	Process	mN (MeV)	ΓN (MeV)	MaxBrTeo
[mπ+me,mπ+mμ] [140.08, 245.23]	K→πeμ	245.23	6.44E-14	4.86E-10
	K→πee	245.23	6.44E-14	8.04E-10
	D→πee	245.23	6.44E-14	7.06E-13
	D→πμe	245.23	6.44E-14	4.18E-13
	Ds→πee	245.23	6.01E-14	1.08E-11
	Ds→πμe	245.23	6.01E-14	6.41E-12
	Ds→πτe	180	6.01E-13	5.48E-12
	B→πee	245.23	6.01E-14	7.58E-16
	B→πμe	245.23	6.01E-14	2.23E-16
	B→πτe	245.23	6.01E-14	1.90E-14
	Bc→πee	245.23	6.01E-14	8.87E-14
	Bc→πμe	245.23	6.40E-14	3.69E-14

Figura: These mass region is: $[m_\pi + m_e, m_\pi + m_\mu]$.

Majorana Neutrino Mass exclusion region.

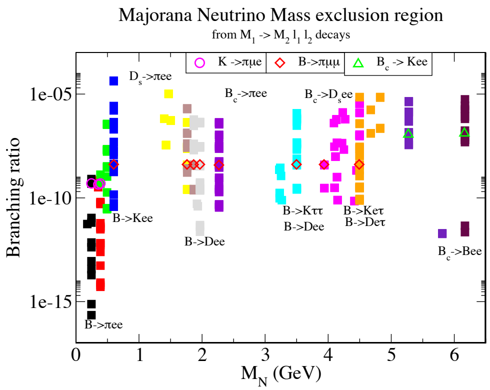

Figura: Mapping in the mass region of the Majorana neutrino using the branching ratio of all processes, $M_1^+ \to M_2^- l_1^+ l_2^+$

Conclusion

- The nature of the Majorana neutrino can be verified through processes with $\Delta L = 2$.
- The case of different leptons is richer in the sense there are sensitive to the relative phase and the different channels can scan different mass regions. In this case the interference may take a relevant role to either suppress or enhance the branching ratio.
- For each region of the mass of the Majorana neutrino, the most restrictive experimental upper limits on the branching ratio of the processes is used, in each region we impose a indirectly better upper limit on the other processes, in the case where there are still no exist experimental upper limits we can impose one indirectly.
- Procces like $D_s^+ \to \pi^- e^+ e^+$, and $B_c^+ \to \pi^- \mu^+ \mu^+$, $B_c^+ \to K^- e^+ e^+$ are interesting for your experimetal search becouse they can give us information indirectly about the other processes.