Dirac and Majorana neutrinos in neutrino-electron scattering process with New Physics

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Content

ν-e scattering in SM

The effective Lagrangian at low energies is

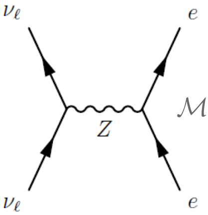
$$\mathcal{L}_{\nu_\ell e} = \frac{G_F}{\sqrt{2}} \left[\bar{u}_{\nu_\ell} \gamma^\mu \left(1 - \gamma^5\right) u_{\nu_\ell}\right] \left[\bar{u}_e \gamma_\mu \left(g_V^\ell - g_A^\ell \gamma^5\right) u_e\right], \qquad (1)$$

where the coupling constants are given by

$$g_V^\ell = -\frac{1}{2} + 2\sin^2\theta_W + \delta_{\ell e}, \quad g_A^\ell = -\frac{1}{2} + \delta_{\ell e}, \quad \ell = e, \mu, \tau. \qquad (2)$$

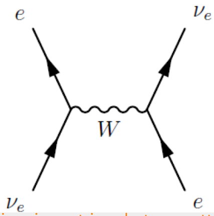
The neutral and charged currents

There are two contributions to the scattering process



$$\mathcal{M}_{cn} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma^\mu\left(1-\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma_\mu\left(g^e_V - g^e_A\gamma^5\right)u^i_e\right]$$

$$\mathcal{M}_{cc} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_e}\gamma^\mu\left(1-\gamma^5\right)u^i_{\nu_e}\right]\left[\bar{u}^f_e\gamma_\mu\left(1-\gamma^5\right)u^i_e\right]$$



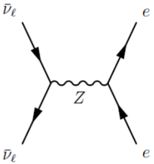
The Dirac case

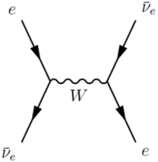
If the neutrino is a Dirac particle, then the antineutrino is a different particle from neutrino, then total amplitude for a such particle is given by

$$\mathcal{M}_D = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma^\mu\left(1-\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma_\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right], \quad (3)$$

The Majorana case

On the other hand, if the neutrino is a Majorana particle, then it is identical to its own antiparticle. In order to calculate the total amplitude for the scattering process, in that case, we need to add two additional contributions:





$$\mathcal{M}_{cn_{\bar{\nu}e}} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}_e^f\gamma^\mu\left(g_V^e - g_A^e\gamma^5\right)u_e^i\right] \times \left[\bar{v}_{\nu_\ell}^f\gamma_\mu\left(1-\gamma^5\right)v_{\nu_\ell}^i\right]$$

$$\mathcal{M}_{cc_{\bar{\nu}_e}} = -i\frac{G_F}{\sqrt{2}}\left[\bar{v}_{\bar{\nu}_e}^f\gamma^\mu\left(1-\gamma^5\right)v_{\bar{\nu}_e}^i \right. \times \left[\bar{u}_e^f\gamma_\mu\left(1-\gamma^5\right)u_e^i\right]$$

The Majorana amplitude is given by

$$\mathcal{M}_M = -\, i\frac{G_F}{\sqrt{2}}\left[\bar{u}_e^f \gamma_\mu \left(g_V^\ell - g_A^\ell \gamma^5\right) u_e^i\right] \times \left[\bar{u}_{\nu_\ell}^f \gamma^\mu \left(1-\gamma^5\right) u_{\nu_\ell}^i - \bar{v}_{\nu_\ell}^f \gamma^\mu \left(1-\gamma^5\right) v_{\nu_\ell}^i\right]. \quad (4)$$

When we consider neutrinos as a Majorana particles, the following identity is valid

$$\bar{v}^{f}_{\nu_\ell}\gamma_\mu\left(1-\gamma^5\right)v^{i}_{\nu_\ell}=\bar{u}^{f}_{\nu_\ell}\gamma_\mu\left(1+\gamma^5\right)u^{i}_{\nu_\ell}. \tag{5}$$

Now, the Majorana amplitude will be:

$$\mathcal{M}_M = i\frac{2G_F}{\sqrt{2}}\left[\bar{u}^{f}_{e}\gamma^\mu\left(g^\ell_V-g^\ell_A\gamma^5\right)u^{i}_{e}\right]\left[\bar{u}^{f}_{\nu_\ell}\gamma_\mu\gamma^5 u^{i}_{\nu_\ell}\right]. \tag{6}$$

**The functional form of the Majorana amplitude is different from the amplitude for Dirac case, in fact, this equation only contains a purely axial part in the neutrino block.

If the polarization of the incident neutrino is considered, the cross section are [1].

$$\frac{d\sigma_D}{d\Omega} = \frac{G_F^2}{8\pi^2 s}\Big\{\Big[\left(E_{\nu_\ell}E_e + p^2\right)^2\left(g_A^\ell + g_V^\ell\right)^2 + \left(E_{\nu_\ell}E_e + p^2\cos\theta\right)^2\left(g_V^\ell - g_A^\ell\right)^2$$
$$+ m_e^2\left(E_{\nu_\ell}^2 - p^2\cos\theta\right)\left({g_A^\ell}^2 - {g_V^\ell}^2\right)\Big] - p\Big[s^{\frac{1}{2}}\left(E_{\nu_\ell}E_e + p^2\right)s_\parallel\left(g_V^\ell + g_A^\ell\right)^2$$
$$+ \left(E_{\nu_\ell}E_e + p^2\cos\theta\right)\left[\left(E_e + E_{\nu_\ell}\cos\theta\right)s_\parallel + m_{\nu_\ell}|s_\perp|\sin\theta\cos\phi\right]\left(g_V^\ell - g_A^\ell\right)^2$$
$$+ m_e^2\left[E_{\nu_\ell}\left(1-\cos\theta\right)s_\parallel - m_{\nu_\ell}|s_\perp|\sin\theta\cos\phi\right]\left({g_A^\ell}^2 - {g_V^\ell}^2\right)\Big]\Big\}, \tag{7}$$

in Dirac case, and

$$\frac{d\sigma_M}{d\Omega} = \frac{G_F^2}{4\pi^2 s}\Big\{\Big[\left(E_{\nu_\ell}E_e + p^2\right)^2 + \left(E_{\nu_\ell}E_e + p^2\cos\theta\right)^2 + m_{\nu_\ell}^2\left(E_e^2 - p^2\cos\theta\right)\Big]\left({g_V^\ell}^2 + {g_A^\ell}^2\right)$$
$$+ m_e^2\left(E_{\nu_\ell}^2 - p^2\cos\theta + 2m_{\nu_\ell}^2\right)\left({g_A^\ell}^2 - {g_V^\ell}^2\right) - 2g_V^\ell g_A^\ell p\left[2E_{\nu_\ell}E_e + p^2\left(1+\cos\theta\right)\right]$$
$$\times\left[E_{\nu_\ell}s_\parallel\left(1-\cos\theta\right) - m_{\nu_\ell}|s_\perp|\sin\theta\cos\phi\right]\Big\}, \tag{8}$$

in Majorana case.

[1] B. Kaayser and R. E. Shrock, Phys. Lett. B **112 (1982) 137**

The differential cross sections for this process, in the laboratory frame, in Dirac and Majorana cases are given by,

$$\frac{d^2\sigma^D}{dEdT} = \frac{d^2\sigma^D}{dEdT}\left(s_{\parallel} = -1\right) + \left(s_{\parallel} + 1\right)\frac{m_e G_F^2}{4\pi P^3}\left\{m_\nu^2\left[\left(g_A - g_V\right)^2\left(E_\nu - T\right)\left(1 + \frac{T}{m_e}\right) - \left(g_A^2 - g_V^2\right)T\right] - E_\nu\left[\left(g_A + g_V\right)^2 P^2 + \left(g_A - g_V\right)^2\left(E_\nu - T\right)^2 + \left(g_A^2 - g_V^2\right)m_e T\right]\right\}; \quad (9)$$

$$\frac{d^2\sigma^M}{dEdT} = \frac{d^2\sigma^M}{dEdT}\left(s_{\parallel} = -1\right) + \left(s_{\parallel} = -1\right)\frac{m_e G_F^2}{\pi P^3}E_\nu T g_A g_V\left(T - 2E_\nu\right)\left(1 + \frac{m_\nu^2}{E_\nu m_e}\right) \quad (10)$$

respectively.

In order to quantify differences between Majorana and Dirac cases, the next function has been defined[2]

$$D\left(E_{\nu}^{lab}, s_{\parallel}\right) = \frac{\left|\sigma^{D} - \sigma^{M}\right|}{\sigma^{D}}, \tag{11}$$

where σ^D and σ^M are the total cross sections in the lab frame, for Dirac and Majorana cases, respectively. The following graph shows some examples for differentes values of $s_{\parallel}$.

[2] J. Barranco, D. Delepine, V. G. Macias, C. Lujan-Peschard and M. Napsuciale. Phys. Lett. B739: 343-347, 2014 .

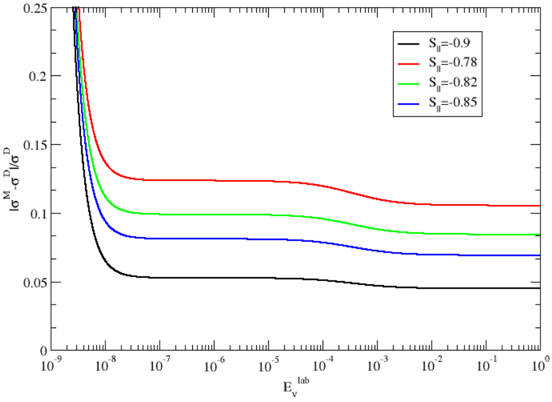


Figure: Difference between the Majorana and Dirac neutrino-electron scattering for a longitudinal polarization $s_{||} = -0.9$ and neutrino mass $m_\nu = 1eV$.

New Physics in ν-e scattering

A simple way to introduce New Physics (NP) through ν-e scattering process is we suppose that there is an effective interaction described by the Lagrangian at low energies:

$$\mathcal{L}_{NP} = \frac{G'}{\sqrt{2}} \left[\bar{u}^f_{\nu_\ell} \gamma^\mu \left(g'^{\nu_\ell}_V - g^{\nu_\ell}_A \gamma^5 \right) u^i_{\nu_\ell} \right] \left[\bar{u}^f_e \gamma_\mu \left(g^\ell_V - g^\ell_A \gamma^5 \right) u^i_e \right] \tag{12}$$

1. Its functional form remains equal than SM neutral current interaction;
2. Neutrino coupling constant that appear in 1 are complex numbers given by $g'^{\nu_\ell}_A = e^{i\alpha}$ and $g'^{\nu_\ell}_V = e^{-i\beta}$;
3. There is no change in electron vector and axial coupling constants, then we assume that they are real numbers and have the standard values.

Dirac case

Incorporating this effective interaction to the SM we can compute the corresponding amplitudes for Dirac and Majorana cases. For Dirac we have

$$\mathcal{M}_{D'} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma^\mu\left(\tilde{g}^{\nu_\ell}_V - \tilde{g}^{\nu_\ell}_A\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma_\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right], \tag{13}$$

where

$$\tilde{g}^{\nu_\ell}_V = 1 + \epsilon g'^{\nu_\ell}_V \quad \text{and} \quad \tilde{g}^{\nu_\ell}_A = 1 + \epsilon g'^{\nu_\ell}_A. \tag{14}$$

Here, $\epsilon = G'/G_F$ is related to the strength of the interaction.

Majorana case

If the neutrino is a Majorana particle, it is necessary to incorporate the contribution from antineutrito to the total amplitud:

$$\mathcal{M}_{M'} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}_e^f \gamma_\mu \left(g_V^\ell - g_A^\ell \gamma^5\right) u_e^i\right] \times \left[\bar{u}_{\nu_\ell}^f \gamma^\mu \left(\tilde{g}_V^{\nu_\ell} - \tilde{g}_A^{\nu_\ell}\gamma^5\right) u_{\nu_\ell}^i - \bar{v}_{\nu_\ell}^f \gamma^\mu \left(\tilde{g}_V^{\nu_\ell^*} - \tilde{g}_A^{\nu_\ell^*}\gamma^5\right) v_{\nu_\ell}^i\right], \quad (15)$$

Considering that the neutrino coupling constants are complex numbers, the following identity is valid

$$\bar{v}_{\nu_\ell}^f \gamma^\mu \left(\tilde{g}_V^{\nu_\ell^*} - \tilde{g}_A^{\nu_\ell^*}\gamma^5\right) v_{\nu_\ell}^i = \bar{u}_{\nu_\ell}^f \gamma^\mu \left(\tilde{g}_V^{\nu_\ell^*} + \tilde{g}_A^{\nu_\ell^*}\gamma^5\right) u_{\nu_\ell}^i. \quad (16)$$

Putting this equation into Majorana amplitude, we obtain

$$\mathcal{M}_{M'} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma_\mu\left(\xi_V - \xi_A\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma^\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right], \tag{17}$$

where the new effective coupling constants are given by

$$\xi_V = \tilde{g}^{\nu_\ell}_V - \tilde{g}^{\nu^*_\ell}_V = -2i\epsilon\sin(\beta)\,; \qquad \xi_A = \tilde{g}^{\nu_\ell}_A + \tilde{g}^{\nu^*_\ell}_A = 2\left[1 + \epsilon\cos(\alpha)\right].$$

Confusing problem

We can compute the percentage of difference between Majorana and Dirac neutrinos with NP from Dirac neutrinos in SM.

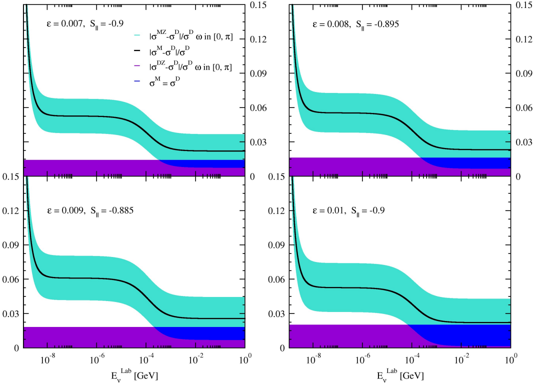


Figure: Differences between Dirac and Majorana neutrinos with NP from Dirac neutrino in SM. Neutrino mass $m_\nu = 1eV$.

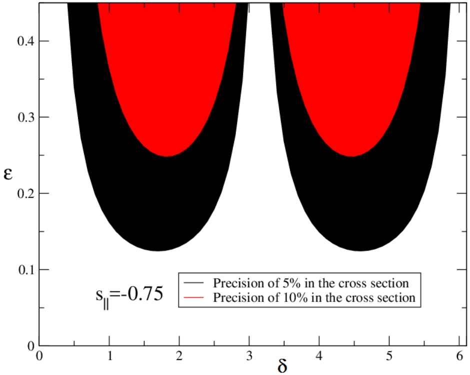


Figure: The relation between ϵ and ω for a fixed value of the longitudinal neutrino polarization $s_{\|} = -0.75$ and neutrino mass $m_\nu = 1eV$.

Conclusions

1. Even with a fixed value of $s_{||}$ it is possible to enhance the difference between Dirac from Majorana neutrinos if we introduce NP in the way described above.
2. With the appropriate parameters we can reproduce either Majorana or Dirac cross sections in the SM from the expressions that contain NP.

Prospects

Difference between Dirac and Majorana process in SM can help us to establish a new upper bound for neutrino magnetic moment.

How? Since neutrino helicity changes when it interacts with a magnetic field, the left-handed neutrinos born inside the sun are expected to evolve leaving the sun with a different helicity. Using a model for the magnetic field of the sun, from the number of ^{7}Be solar neutrino events detected by Borexino Collaboration it can be used to set a new upper bound for the neutrino magnetic moment.

Thank you!