Neutrino-electron scattering with a new source of CP violation

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Neutrino-electron scattering: Standard Model

The effective lagrangian at low energies is

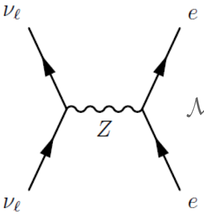
$$\mathcal{L}_{\nu_\ell e} = \frac{G_F}{\sqrt{2}} \left[\bar{u}_{\nu_\ell}\gamma^\mu \left(1-\gamma^5\right) u_{\nu_\ell}\right] \left[\bar{u}_e\gamma_\mu \left(g_V^\ell - g_A^\ell\gamma^5\right) u_e\right], \qquad (1)$$

where the coupling constants are given by

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

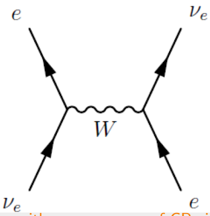
The neutral and charged currents

There are two contributions to the scattering process



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

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



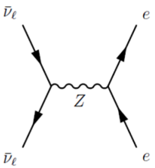
The Dirac case

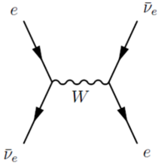
If the neutrino is a Dirac particle, then the antineutrino is a different particle than neutrino, so the total amplitude for a such particle is

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

The Majorana case

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





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

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

The Majorana amplitude is given by

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

When we consider that the neutrino is a Majorana particle, the following identity is valid

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

With this, the Majorana aplitude will be

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

The functional form of the Majorana amplitude is different than the amplitude for the 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].

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

in Dirac case, and

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

in Majorana case.

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

In order to quantify any difference between the Majorana and Dirac cases, we define the function[2]

$$D\left(E_{\nu}^{lab}, s_{\parallel}\right) = \frac{\left|\sigma^{D} - \sigma^{M}\right|}{\sigma^{D}}, \tag{9}$$

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 .

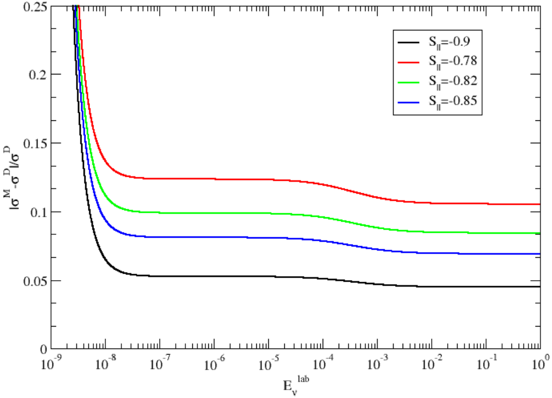


Figure: Difference between the Majorana and Dirac neutrino-electron scattering for a longitudinal polarization $s_{||} = -0.9$ and neutrino mass $m_\nu = 1eV$.

A Z' model

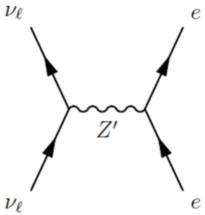
We propose a new neutral current interaction, via a Z' boson.
This model presents some particularities:

1. This is a neutral current interaction;
2. The electron coupling constants remains equal than coupling constants in SM;
3. The neutrino coupling constants are complex numbers.

The functional form for the effective lagrangian are given by

$$\mathcal{L}_{Z'} = \frac{2G'}{\sqrt{2}} \left[\bar{u}^{f}_{\nu_\ell} \gamma^{\mu} \left(g'^{\nu_\ell}_{V} - g'^{\nu_\ell}_{A} \gamma^5 \right) u_{\nu_\ell} \right] \left[\bar{u}^{f}_{e} \gamma_{\mu} \left(g^{\ell}_{V} - g^{\ell}_{A} \gamma^5 \right) u^{i}_{e} \right], (10)$$

where g'^{ℓ}_{A} and g'^{ℓ}_{V} are the neutrino coupling constants in this model. Remeber that the electron coupling constants are the same than the Standar Model case.



Dirac case

The first step is to calculate the amplitude for $\nu_\ell e \to \nu_\ell e$ scattering via Z', that is given by

$$\mathcal{M}_{Z'} = -i\frac{2G'}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma^\mu\left(g'^{\nu_\ell}_V - g'^{\nu_\ell}_A\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma_\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right]. \quad (11)$$

Now, if we add this new contribution to Dirac amplitude in SM, the following result is obtained

$$\mathcal{M}_{DZ'} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma^\mu\left(\tilde{g}^{\nu_\ell}_V - \tilde{g}^{\nu_\ell}_A\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma_\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right]. \quad (12)$$

where

$$\tilde{g}^{\nu_\ell}_V = 1 + \epsilon g'^{\nu_\ell}_V, \qquad \tilde{g}^{\nu_\ell}_A = 1 + \epsilon g'^{\nu_\ell}_A. \quad (13)$$

Majorana case

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

$$\begin{aligned}\mathcal{M}_{MZ'} &= -i\frac{G_F}{\sqrt{2}}\left[\bar{u}_e^f\gamma_\mu\left(g_V^\ell - g_A^\ell\gamma^5\right)u_e^i\right] \\ &\times\left[\bar{u}_{\nu_\ell}^f\gamma^\mu\left(\tilde{g}_V^{\nu_\ell} - \tilde{g}_A^{\nu_\ell}\gamma^5\right)u_{\nu_\ell}^i - \bar{v}_{\nu_\ell}^f\gamma^\mu\left(\tilde{g}_V^{\nu_\ell^*} - \tilde{g}_A^{\nu_\ell^*}\gamma^5\right)v_{\nu_\ell}^i\right],\end{aligned} \tag{14}$$

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

$$\bar{v}^f_{\nu_\ell}\gamma^\mu\left(\tilde{g}^{\nu_\ell^*}_V - \tilde{g}^{\nu_\ell^*}_A\gamma^5\right)v^i_{\nu_\ell} = \bar{u}^f_{\nu_\ell}\gamma^\mu\left(\tilde{g}^{\nu_\ell^*}_V + \tilde{g}^{\nu_\ell^*}_A\gamma^5\right)u^i_{\nu_\ell}. \qquad (15)$$

Putting this equation into Majorana amplitude, we obtain

$$\mathcal{M}_{MZ'} = -i\frac{G_F}{\sqrt{2}}\left[\bar{u}^f_{\nu_\ell}\gamma_\mu\left(\xi_V - \xi_A\gamma^5\right)u^i_{\nu_\ell}\right]\left[\bar{u}^f_e\gamma^\mu\left(g^\ell_V - g^\ell_A\gamma^5\right)u^i_e\right], \qquad (16)$$

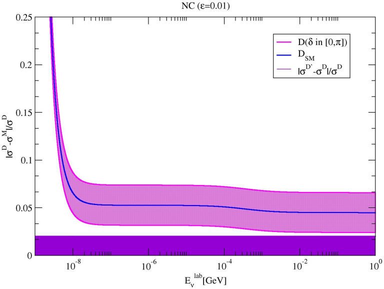
where the new effective coupling constants are given by

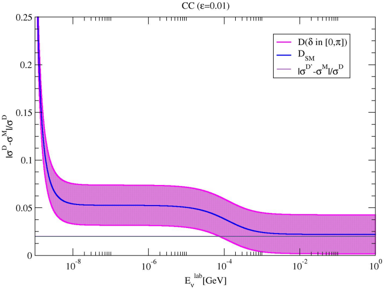
$$\xi_V = \tilde{g}^{\nu_\ell}_V - \tilde{g}^{\nu_\ell^*}_V = -2i\epsilon\sin(\beta); \qquad \xi_A = \tilde{g}^{\nu_\ell}_A + \tilde{g}^{\nu_\ell^*}_A = 2\left[1+\epsilon\cos(\alpha)\right].$$

Results

The total cross sections refered to the lab frame, are three-parametric families that depends on ϵ, δ and $s_{\|}$.

We construct the $D\left(E_{\nu}^{lab}, s_{\|}, \delta\epsilon\right)$ anew for quantify the difference between both cases. ($s \| = -0.9$, $\epsilon = 0.01$ and $m_{\nu} = 1eV$)





Conclusions

1. With the appropriate parameters we can reproduce either Majorana or Dirac cross sections in the Standard Model from the expressions obtained when an additional interaction is taken into account.
2. (Very optimistic) We can't discard the presence of new physics

Thank you!