Dynamical zeros in neutrino-electron elastic scattering at leading order

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Abstract

We show the existence of dynamical zeros in the helicity amplitudes for neutrino-electron elastic scattering at lowest order in the standard theory. In particular, the $\lambda = 1/2$ non-flip electron helicity amplitude in the electron antineutrino process vanishes for an incident neutrino energy $E_\nu = m_e/(4sin^2\theta_W)$ and forward electrons (maximum recoil energy). The rest of helicity amplitudes show kinematical zeros in this configuration and therefore the cross section vanishes. Prospects to search for neutrino magnetic moment are discussed

The first $\nu_i(\bar\nu_i)e^- \to \nu_i(\bar\nu_i)e^-$ collision was observed in 1973 at Gargamelle [1].In particular the observation of the process $\bar\nu_\mu e^- \to \bar\nu_\mu e^-$ represented the discovery of neutral currents, a milestone in the history of the standard model of electroweak interactions. In the year 1976 the group of Reines [2] got the first signal of the $\bar\nu_e e^- \to \bar\nu_e e^-$ process, using neutrinos from a nuclear reactor. Nowadays, there are also data from $\nu_\mu e^- \to \nu_\mu e^-$ and $\nu_e e^- \to \nu_e e^-$ reactions.

Needless to say, neutrino physics in general and these leptonic processes in particular play a crucial role in the study of the standard model of electroweak interactions, as well as in searching for effects beyond the standard model: Charm II collaboration has given values [3] of the electroweak mixing angle at a level of accuracy comparable with LEP data, the (destructive) interference among charged and neutral currents has been measured [4] in the reaction $\nu_e e^- \to \nu_e e^-$, the laboratory bound on the neutrino magnetic moment ($\mu_\nu < 2.4x10^{-10}$) has been set with $\bar\nu_e e^- \to \bar\nu_e e^-$ [2, 5, 6] in reactor experiments. Besides, several new proposals plan to reach a 1% accuracy in the value of $sin^2\theta_W$ [7], to study the $\bar\nu_e$ magnetic moment at the level of $2x10^{-11}$ Bohr magnetons [8] or even to search for flavour changing neutral currents.

Let us concentrate in the neutrino magnetic moment experiments. The differential cross section for $\bar\nu_e e^- \to \bar\nu_e e^-$ including the neutrino magnetic moment contribution [5] and neglecting neutrino mass is given by

$$\frac{d\sigma_{\bar\nu_e}}{dT} = \frac{2G^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right] + \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\frac{(1 - T/E_\nu)}{T} \qquad (1)$$

where G is the Fermi coupling constant, α the fine structure constant, μ_ν the neutrino magnetic moment in Bohr magnetons, m_e the electron mass, T the recoil kinetic energy of the electron and E_ν the antineutrino incident energy. In terms of $sin^2\theta_W$ the chiral couplings g_L and g_R can be written as

$$g_L = \tfrac{1}{2} + sin^2\theta_W; \quad g_R = sin^2\theta_W . \qquad (2)$$

The first piece in the r.h.s of eq. (1) is the standard charged and neutral current contribution (for neutrinos one should exchange g_L by g_R), the second one is due to the neutrino magnetic moment, whose contribution adds incoherently. The magnetic

moment contribution is enhanced with respect to the conventional contribution for low values of T. Then, to extract information about the neutrino magnetic moment term, it is extremely important to minimize the experimental threshold on the electron recoil energy, which is a difficult task. But from eq. (1), due to the presence of the $g_L g_R$ term, we observe that a different strategy can be used , namely, to look for kinematical configurations, if any, where the standard model contribution vanishes. Instead of looking for regions where the new physics becomes large enough to be comparable to the standard contribution we will look for configurations were the standard contribution becomes small enough.

With this motivation , we study in this paper the dynamical zeros of the helicity amplitudes for neutrino and antineutrino scattering with electrons at lowest order in the standard model. By dynamical zeros we mean the ones which appear inside the physical region of the kinematical variables describing the scattering [9]. The location of these dynamical zeros depends on the values of the fundamental parameters of the electroweak theory, namely, g_L and g_R in our case. Besides dynamical zeros, the helicity amplitudes are constrained by the kinematical zeros [10] which appear at the boundary of the physical region and do not depend on dynamical parameters.

On searching for dynamical zeros in neutrino and antineutrino electron scattering one can make a first attempt by selecting a kinematical configuration where only one spin amplitude contributes to the standard model cross section in eq. (1). In particular, in a general collinear frame the helicity amplitude $M_{\lambda'\lambda}^{\nu_i}$ for $\nu_i e^- \to \nu_i e^-$, $i = e, \mu, \tau$, with $\lambda = \lambda' = -1/2$ is the only one that contributes for backward outgoing neutrino (forward electron), being λ and λ' the initial and final electron helicities respectively. This follows from angular momentum conservation arguments. For $\bar{\nu}_i e^- \to \bar{\nu}_i e^-$ the helicity amplitude $M_{1/2,1/2}^{\bar{\nu}_i}$ is the only one that contributes for backward neutrino.

In the LAB frame, the backward cross section for $\nu_i e^- \to \nu_i e^-$ can be written as follows

$$\left(\frac{d\sigma_{\nu_i}}{dT} \right)_{back} = \frac{2G^2 m_e}{\pi} \left[g_L^i - g_R^i \frac{m_e}{2E_\nu + m_e} \right]^2 \tag{3}$$

which is proportional to $\mid M_{-1/2,-1/2}^{\nu_i}(back) \mid^2$. Eq. (3) is easily obtained from the

standard piece of eq. (1) considering that the value of T in the backward configuration is

$$T_{max} = \frac{2E_\nu^2}{2E_\nu + m_e}.$$

(4)

In eq. (3) there are no dynamical zeros for this backward cross section with g_L^e and g_R^e satisfying $g_L^e > g_R^e > 0$, which is the case for ν_e as seen from equation (2). On the other hand, for $\bar{\nu}_i e^-$ backward elastic scattering we have

$$\left(\frac{d\sigma_{\bar{\nu}_i}}{dT}\right)_{back} = \frac{2G^2 m_e}{\pi}\left[g_R^i - g_L^i \frac{m_e}{2E_\nu + m_e}\right]^2$$

(5)

which is proportional to $\mid M_{1/2,1/2}^{\bar{\nu}_i}(back)\mid^2$ and vanishes for $\bar{\nu}_e$ at

$$E_\nu = \frac{m_e}{4sin^2\theta_W}.$$

(6)

Therefore we have found that for the antineutrino energy E_ν given by equation (6) and the corresponding maximum electron recoil energy given by equation (4) the differential cross section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ vanishes exactly at leading order. It is worthwhile to emphasize that $E_\nu \simeq m_e$ lies inside the range of reactor antineutrino spectra and $T = T_{max} \simeq \frac{2}{3}m_e$ is in the range of the proposed experiments to detect recoil electrons [8].

For ν_μ and $\bar{\nu}_\mu$ elastic scattering (or ν_τ and $\bar{\nu}_\tau$) the corresponding g_L^μ, g_R^μ parameters are

$$g_L^\mu = -\tfrac{1}{2} + sin^2\theta_W; \;\; g_R^\mu = sin^2\theta_W$$

(7)

These values prevent the corresponding cross sections from dynamical zeros for backward neutrinos. It is therefore evident that the contribution of charged currents to the values of g_L^i and g_R^i is essential in the existence of the dynamical zeros given by eqs. (4) and (6) in $\bar{\nu}_e e^-$ scattering.

In what follows we will present a systematic analysis of the dynamical zeros of the helicity amplitudes for neutrino and antineutrino - electron scattering at lowest order in electroweak interactions. As a consequence of this analysis one obtains all

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the information about dynamical zeros for polarized and unpolarized differential cross sections.

For $\nu_i e^- \rightarrow \nu_i e^-$ the helicity amplitudes are

$$M^{\nu_i}_{\lambda',\lambda} = \frac{G}{\sqrt{2}}(g^i_L M^{\nu_i}_L + g^i_R M^{\nu_i}_R) \tag{8}$$

where

$$\begin{aligned}M^{\nu_i}_L &= [\bar{u}'_e(\lambda')\gamma_\alpha(1-\gamma_5)u_e(\lambda)][\bar{u}'_{\nu_i}\gamma^\alpha(1-\gamma_5)u_{\nu_i}]\\ M^{\nu_i}_R &= [\bar{u}'_e(\lambda')\gamma_\alpha(1+\gamma_5)u_e(\lambda)][\bar{u}'_{\nu_i}\gamma^\alpha(1-\gamma_5)u_{\nu_i}]\end{aligned} \tag{9}$$

We carry out the explicit calculation in the LAB frame, by using a standard representation of the Dirac matrices and spinors [11]. The final result for the helicity amplitudes reads as follows

$$M^{\nu_i}_{+,+} = N g^i_R \left(1 + \frac{T}{|\vec{p'}|}\right) sin\frac{\theta}{2} cos\frac{\beta}{2}$$

$$M^{\nu_i}_{-,-} = N \left[g^i_L \left(1 + \frac{T}{|\vec{p'}|}\right) sin\frac{\theta-\beta}{2} + g^i_R \left(1 - \frac{T}{|\vec{p'}|}\right) cos\frac{\theta}{2} sin\frac{\beta}{2}\right]$$

$$M^{\nu_i}_{+,-} = N \left[-g^i_L \left(1 - \frac{T}{|\vec{p'}|}\right) cos\frac{\theta-\beta}{2} + g^i_R \left(1 + \frac{T}{|\vec{p'}|}\right) sin\frac{\theta}{2} sin\frac{\beta}{2}\right]$$

$$M^{\nu_i}_{-,+} = N g^i_R \left(1 - \frac{T}{|\vec{p'}|}\right) cos\frac{\theta}{2} cos\frac{\beta}{2}$$

$$\tag{10}$$

where $N = 8G\sqrt{E_\nu E'_\nu m_e(T+2m_e)}$, $|\vec{p'}|$ is the outgoing electron momentum and θ and β are the counterclockwise angles in the scattering plane of the final electron and neutrino with respect to the incoming neutrino direction. We note that the helicity of the target electron (at rest) is referred to the backward direction. In eq. (10) we have used the helicity signs instead of its values.

We have the following relation between neutrino and antineutrino helicity amplitudes

$$M^{\bar{\nu}_i}_{\lambda',\lambda}(g^i_L, g^i_R) = (-)^{\lambda'-\lambda} M^{\nu_i}_{-\lambda',-\lambda}(g^i_R, g^i_L) \tag{11}$$

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i.e., apart from the phase factor $(-)^{\lambda'-\lambda}$, one has to replace $g_R^i \leftrightarrow g_L^i$ and change the sign of helicities going from neutrino to antineutrino amplitudes.

From eqs. (10) and (11) it is clear that the amplitudes $M_{\pm,-}^{\nu_i}$ and $M_{\pm,+}^{\bar{\nu}_i}$ are the only ones that get contribution from both M_L and M_R. Therefore, these are the only amplitudes which may have dynamical zeros, while the others will not exhibit any unless g_R^i or g_L^i vanish. The conditions that define the dynamical zeros for the helicity amplitudes are the following:

$$M_{\pm,-}^{\nu_i} = 0 \quad \leftrightarrow \quad cos\theta = \mp \frac{m_e + E_\nu}{m_e \frac{g_R^i}{g_L^i} - E_\nu} \tag{12}$$

and

$$M_{\pm,+}^{\bar{\nu}_i} = 0 \quad \leftrightarrow \quad cos\theta = \pm \frac{m_e + E_\nu}{m_e \frac{g_L^i}{g_R^i} - E_\nu} \tag{13}$$

Taking into account that the physical region is restricted by $0 \leq cos\theta \leq 1$, and the g_L^i and g_R^i values it is straightforward to arrive to the following conclusions:

i) $M_{++}^{\bar{\nu}_e}$ shows dynamical zeros given by eq. (13) in the energy range $0 \leq E_\nu \leq m_e/4sin^2\theta_W$. The upper value corresponds to the phase space point $cos\theta = 1$. At this end point the other three helicity amplitudes have kinematical zeros as can be explicitly seen from eq. (10). This is the reason why this dynamical zero shows up in the unpolarized cross section in the backward configuration as we already pointed out in eqs. (5) and (6).

ii) $M_{-+}^{\bar{\nu}_\mu, \bar{\nu}_\tau}$ show dynamical zeros given by eq. (13) in the whole range of energies $0 \leq E_\nu < \infty$. In this case the helicity amplitudes never vanish simultaneously. Then, the dynamical zeros will only show up in polarized cross sections.

iii) There are no more solutions of eqs. (12) and (13) in the physical region.

These results are summarized in figure 1, where the dynamical zeros are plotted in the plane $(E_\nu, cos\theta)$, together with the kinematical zeros.

It seems difficult to design a $\bar{\nu}_e e^-$ experiment where electron polarizations are involved. So we shall concentrate in the dynamical zero defined by eqs. (4) and (6);

the only one we consider relevant for realistic experimental proposals.

The fact that the weak backward cross section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ vanishes at leading order for $E_\nu = m_e/(4 sin^2\theta_W)$ clearly points out that this kinematical configuration must be a good place to study new physics or even higher order electroweak radiative corrections [12]. It is worthwhile to emphasize once again that backward neutrinos correspond to forward electrons with maximum recoil kinetic energy which is a very interesting situation from the experimental point of view. This configuration, showing the dynamical zero, is of particular interest to look for those contributions which add incoherently to the standard amplitude.

To illustrate the interest of this dynamical zero we shall concentrate in the possibility of searching for neutrino magnetic moment . In Figure 2 we denote by $(d\sigma_W/dT)_{back}$ the standard contribution in the r.h.s. of eq. (1) and by $(d\sigma_M/dT)_{back}$ the magnetic moment contribution , both for $T = T_{max}$. The solid line represents the boundary where $(d\sigma_W/dT)_{back} = (d\sigma_M/dT)_{back}$ for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$. The regions below the other lines are those for which $(d\sigma_M/dT)_{back} > (d\sigma_W/dT)_{back}$ for the rest of neutrino species. It is quite apparent from this figure that electron antineutrinos with energies around 0.5 MeV give the possibility of studying low values for neutrino magnetic moment. With other kind of neutrinos this is only possible by going to much lower values of neutrino energy.

In conclusion we have discussed all the dynamical zeros in the helicity amplitudes for neutrino (antineutrino)-electron scattering. Particularly interesting is the electron antineutrino backward configuration, where the only allowed helicity amplitude has a dynamical zero for $E_\nu = m_e/(4 sin^2\theta_W)$, so the backward unpolarized cross section vanishes at lowest order in the standard theory. This result clearly points out a favourable kinematical configuration to look for new physics in $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$. Results have been presented for the expectations to search for neutrino magnetic moment.

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Figure Captions.

- **Fig. 1)** Kinematical and dynamical zeros for the helicity amplitudes in the plane $(E_\nu, cos\theta)$.

- **Fig. 2)** Regions of dominance of weak or magnetic backward differential cross sections in the plane (μ_ν, E_ν) for $\bar{\nu}_e$; there are three different zones divided by the solid line. For the rest of (anti-)neutrinos there are only two regions, being the magnetic backward cross section dominant above the corresponding line (long-dashed for ν_e, dashed-dotted for $\bar{\nu}_\mu$ and short-dashed for ν_μ) and the opposite below the line.