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MODELS OF NEUTRINO MASSES

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RESUMEN

Experimentos como el Super Kamiokande y el Sudbury Neutrino Observatory (SNO) detectaron una masa diferente de cero para los neutrinos. Los modelos teóricos para la masa del neutrino tienen sus bases sobre dos ideas principales: la de Dirac y la de Majorana. Estas ideas, aunque diferentes, pueden combinarse en una sola dependiendo de la verdadera naturaleza de los neutrinos. La realización de experimentos como los decaimientos beta dobles pueden llegar a decidir cual de las anteriores ideas, si alguna, es la correcta.

Palabras claves: No tiene

ABSTRACT

Experiments such as the Super Kamiokande and the Sudbury Neutrino Observatory (SNO) detected a non - zero mass for neutrinos. Theoretical models of neutrino mass have their basis on two main ideas: Dirac's and Majorana's. These are different frameworks which could be combined depending on the very nature of neutrinos. Experiments such as the double beta decays could be performed to decide which idea, if any, is the correct one.

Keywords: No tiene

Introduction

It had been demonstrated [1] within experimental uncertainties that, in Nature, only neutrinos with its polarization opposed to its direction of motion exist. Those neutrinos are commonly referred to as left - handed neutrinos, ν_L. The right-handed neutrino, ν_R, is not introduced in the Standard Model because, historically, physicists wanted to keep the neutrinos massless.

Several theoretical models to explain and describe the neutrino mass had been developed in the last decades. So far, there are two main ideas of neutrino mass: Dirac's and Majorana's. Neutrino mass in $SU(2)_L \times U(1)_Y$ involve models with expanded Higgs sector (see [2] and [3]), and models with spontaneous lepton number, N, violation (these introduce the Majoron model, see [4] and [5]). There are also Grand Unified models such as $SU(5)$, $SO(10)$ and E_6 (see [6]), and models involving extra dimensions (see [7]).

Theoretical Frame

All fundamental fermions (leptons and quarks) obey the Dirac equation and are described by four component complex spinors, since all have both helicity states. As massive fermions, neutrinos should be described by the same type of four component spinors which describe the rest of the fermions [8]. However, the differences between neutrinos and other fundamental fermions is that neutrinos are electrically neutral, so the only global quantum number they can carry is the lepton number where we distinguishe the total and individual lepton number assigned to electron, muon and tau neutrinos separately. If the total lepton number is conserved, the mechanism for neutrino masses

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is essentially equivalent to the mechanism that provides mass to the quarks, through the vacuum expectation value of the Higgs boson, being then Dirac neutrinos. If lepton number is violated, then it would be an indication that neutrinos are, in fact, Majorana particles.

Dirac Mass

Let ν_α be the neutrino fields, with $\alpha = e, \mu, ..., n$. Each field can be represented as a sum of two different helicities: $\nu_\alpha = \nu_{\alpha L} + \nu_{\alpha R}$. The projectors are defined as follows[2]

$$P_L \equiv \frac{1-\gamma^5}{2}, \qquad P_R \equiv \frac{1+\gamma^5}{2}, \tag{1}$$

which, when applied to the ν_α fields, give: $P_L \nu_\alpha = \nu_{\alpha L},\ P_R \nu_\alpha = \nu_{\alpha R}$. The Dirac mass term in the Lagrangian is generated by the standard Higgs mechanism

$$\mathcal{L}^D = -\sum_\alpha m_\alpha^D \overline{\nu}_\alpha \nu_\alpha = -\sum_\alpha m_\alpha^D (\overline{\nu}_{\alpha R} \nu_{\alpha L} + \overline{\nu}_{\alpha L} \nu_{\alpha R}), \tag{2}$$

where the m_α^D are constants that depend on the Yukawa coupling coefficient and the vacuum expectation value of the Higgs field [9].

Majorana Mass

Majorana showed in the late 30's that a massive neutral fermion can be described by a spinor[3] ψ with only two independent components. Such a spinor works properly after imposing the Majorana condition[4], from which we get that the $\psi^c_{\alpha R}$ fields are left - handed and the $\psi^c_{\alpha L}$ fields are right - handed. The Majorana condition in terms of components is: $\psi_{\alpha R} + \psi_{\alpha L} = \psi^c_{\alpha R} + \psi^c_{\alpha L}$. The projector P_R operating on it gives[5]

$$\begin{aligned} \psi_{\alpha R} &= P_R \psi^c_{\alpha R} + P_R \psi^c_{\alpha L} = 0 + \psi^c_{\alpha L} \\ \psi_{\alpha R} &= \psi^c_{\alpha L}, \end{aligned} \tag{3}$$

which means that the right - handed component of a Majorana neutrino field[6] is not independent, but it is obtained from the left - handed component through charge conjugation. The Majorana fields depend only on the two independent components of ψ_L. To obtain the Majorana mass term in the Lagrangian, the constrain (3) is used on (2)

$$\mathcal{L}^M = -\frac{1}{2} \sum_\alpha m_\alpha^M \left(\overline{\psi}^c_{\alpha L} \psi_{\alpha L} + \overline{\psi}_{\alpha L} \psi^c_{\alpha L} \right), \tag{4}$$

where the $\frac{1}{2}$ is introduced to avoid double counting in the Euler Lagrange derivation of the equations for the Majorana neutrino fields [9]. The m_α^M are again constants.

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[2] $P_L^2 = P_L$, $P_R^2 = P_R$, $P_R P_L = 0 = P_L P_R$.

[3] Note that ψ is used to describe Majorana neutrinos and ν is used to describe Dirac neutrinos.

[4] The Majorana condition is: $\psi = \psi^c$. Here $\psi^c = \mathcal{C} \left(\overline{\psi}\right)^T = \mathcal{C} \left(\gamma^0\right)^T \psi^*$ is the operation of charge conjugation, with the charge conjugation matrix $\mathcal{C}$ defined by the relations: $\mathcal{C} \left(\gamma^\mu\right)^T \mathcal{C}^{-1} = -\gamma^\mu$, $\mathcal{C}^\dagger = \mathcal{C}^{-1}$, $\mathcal{C}^T = -\mathcal{C}$.

[5] Since $\gamma^5 \gamma^\mu + \gamma^\mu \gamma^5 = 0$, when the projectors act on the spinor the result is: $P_L \psi^c_{\alpha L} = 0, \quad P_R \psi^c_{\alpha R} = 0, \quad P_R \psi^c_{\alpha L} = \psi^c_{\alpha L}, \quad P_L \psi^c_{\alpha R} = \psi^c_{\alpha R}$.

[6] A Majorana field can be written as: $\psi_\alpha = \psi^c_{\alpha L} + \psi_{\alpha L}$.

Majorana + Dirac mass term

In general, if both the chiral fields exist (and are independent), we can add both Majorana and Dirac terms. In the Majorana case there are two mass terms, one per field

$$\mathcal{L}_L^M = -\frac{1}{2} m_L (\overline{\nu}_L^c \nu_L + \overline{\nu}_L \nu_L^c), \qquad \mathcal{L}_R^M = -\frac{1}{2} m_R (\overline{\nu}_R^c \nu_R + \overline{\nu}_R \nu_R^c). \tag{5}$$

The total Majorana + Dirac mass term in the Lagrangian is

$$\mathcal{L}^{M+D} = \mathcal{L}^D + \mathcal{L}_L^M + \mathcal{L}_R^M = -\frac{1}{2} (\overline{\nu}_L^c \overline{\nu}_R) \left(\begin{array}{cc} m_L & m_D \\ m_D & m_R \end{array} \right) \left(\begin{array}{c} \nu_L \\ \nu_R^c \end{array} \right) + h.c.. \tag{6}$$

The squared matrix is made up of four squared matrices, each having information of the Dirac constants, m_D, and the Majorana constants, m_L and m_R.

Double-β decay

With the information acquired in the previous sections, one open problem in neutrino physics is the Dirac or Majorana's nature of neutrinos. From the theoretical point of view it is expected that neutrinos are Majorana particles, with masses generated by the see - saw mechanism [10]. The best known way to search for Majorana neutrino masses is neutrinoless double-β decay. Double-β ($\beta\beta$) decays are second order processes in the Fermi coupling constant in the amplitude. There are two different kinds of $\beta\beta$ decays: with neutrinos in the final state, $\beta\beta_{2\nu}$, and without neutrinos in the final state, $\beta\beta_{0\nu}$. The $\beta\beta_{2\nu}$ has already been observed and studied (See [11] for further details). The $\beta\beta_{0\nu}$ process is kinematically more favored because there are only three final states instead of the five as in the $\beta\beta_{2\nu}$. The energy spectrum of the $\beta\beta_{2\nu}$ decay is a continuous, rather, the energy spectrum of the $\beta\beta_{0\nu}$ decay is a sharp peak [9]. This difference in the energy spectrum can be used to identify $\beta\beta_{0\nu}$ in future experiments.

Conclusions

A study of $\beta\beta_{0\nu}$, can probe the fundamental nature of neutrinos. The $\beta\beta_{0\nu}$ process can occur, with a high level of confidence, if and only if the neutrinos are Majorana particles. The important fact is that $\beta\beta_{0\nu}$ requires new physics beyond the Standard Model because it is possible only when the lepton number is violated by two units and $\overline{\nu}_e$ can turn into ν_e. Therefore, $\beta\beta_{0\nu}$ processes are impossible if neutrinos are Dirac particles [12], that is why these decays are gaining importance in the experimental community, at the end, they can help to clarify which is the nature of neutrinos.

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