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MAJORANA NEUTRINO. IS DOUBLE NEUTRINOLESS BETA DECAY POSSIBLE IN THE FRAMEWORK OF THE WEAK INTERACTIONS? HOW TO PROVE THAT NEUTRINO IS A MAJORANA PARTICLE

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Майорановское нейтрино. Возможен ли в рамках слабых взаимодействий безнейтринный двойной бета-распад? Как доказать, что нейтрино является майорановской частицей

Обычно предполагается, что майорановское нейтрино рождается в суперпозиционном состоянии $\chi_L = \nu_L + (\nu_L)^c$, и тогда будет иметь место безнейтринный двойной бета-распад. Но так как слабые взаимодействия являются кирально-инвариантными, нейтрино при рождении имеет определенную спиральность (т. е. ν_L- и $(\nu_L)^c$-нейтрино рождаются по отдельности, и тогда нейтрино не может рождаться в суперпозиционном состоянии). После рождения нейтрино его спиральность не может изменяться без его участия во взаимодействиях (ν_L и $(\nu_L)^c$ имеют противоположные спиральности). Итак, мы видим, что из-за неподходящей спиральности безнейтринный двойной бета-распад невозможен, даже если нейтрино является майорановской частицей. Также переход майорановского нейтрино в антинейтрино при их осцилляциях запрещен из-за того, что спиральность нейтрино в вакууме должна сохраняться. Тогда мы можем доказать, что нейтрино является дираковской, а не майорановской частицей только по переходу нейтрино в (стерильное) антинейтрино при нейтринных осцилляциях. Переход майорановского нейтрино ν_L в $(\nu_R)^c$-нейтрино (т. е. $\nu_L \to (\nu_R)^c$) при осцилляциях является ненаблюдаемым, так как предполагается, что масса $(\nu_R)^c$-нейтрино должна быть очень большой.

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Majorana Neutrino. Is Double Neutrinoless Beta Decay Possible in the Framework of the Weak Interactions? How to Prove that Neutrino is a Majorana Particle

Usually it is supposed that Majorana neutrino is produced in the superposition state $\chi_L = \nu_L + (\nu_L)^c$ and then follows the neutrinoless double beta decay. But since weak interactions are chiral-invariant, the neutrino at production has definite helicity (i. e., ν_L and $(\nu_L)^c$ neutrinos are separately produced and then neutrino is not in the superposition state). This helicity cannot change after production without any external interactions. Thus, we see that for unsuitable helicity the neutrinoless double β decay is not possible even if neutrino is a Majorana particle. Also transition of Majorana neutrino into antineutrino at their oscillations is forbidden since helicity in vacuum holds. Then the only possibility to prove that neutrino is a Dirac but not Majorana particle is detection of transition of ν_L neutrino into (sterile) antineutrino $\bar{\nu}_R$ (i.e., $\nu_L \to \bar{\nu}_R$) at neutrino oscillations. Transition of Majorana neutrino ν_L into $(\nu_R)^c$ (i.e., $\nu_L \to (\nu_R)^c$) at oscillations is unobserved since it is supposed that the mass of $(\nu_R)^c$ is very big.

The investigation has been performed at the Laboratory of Particle Physics, JINR.

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INTRODUCTION

The equation for particle with spin $\frac{1}{2}$ was first formulated by Dirac [1] in 1928. Afterwards it turned out that this representation was adequate to describe neutral and charged fermions, i.e., fermions are Dirac particles. Later Majorana found an equation [2] for fermion with spin $\frac{1}{2}$. Then it became clear that this fermion could be only a neutral particle since in one representation the particle and antiparticle are joined.

In the 1950s the Majorana neutrino study was very extensive [3]. Later it stopped.

The suggestion that in analogy with $K^0, \bar{K}^0$ oscillations there could be neutrino–antineutrino oscillations ($\nu \to \bar{\nu}$) was considered by Pontecorvo [4] in 1957. It was subsequently considered by Maki et al. [5] and Pontecorvo [6] that there could be mixings (and oscillations) of neutrinos of different flavors, i.e., $\nu_e \to \nu_\mu$ transitions. A complete consideration of Majorana neutrino oscillations was given in [7].

A posteriori Majorana neutrino can be introduced in two ways:

1. To suppose that Majorana neutrino is superposition of ν_L and $(\nu_L)^c$ [2, 8]:

$$\chi = \nu_L + (\nu_L)^c, \quad (\nu_L)^c \equiv C\bar{\nu}_L^T.$$

Here arises a question: is neutrino production possible by weak interactions in this superposition state? Unfortunately, this wave function is normalized to two. The definition of Majorana neutrino normalized to one was given in [9] and then

$$\chi = \frac{1}{\sqrt{2}}(\nu_L + (\nu_L)^c).$$

Experimental consequences of this definition of Majorana neutrino were considered in [10].

2. To suppose that the standard definition of Majorana neutrino

$$\chi = \nu_L + (\nu_L)^c$$

is a formal recording and it has no physical realization. Such a supposition is a direct consequence of the weak interactions where neutrino can be produced only with definite helicity; it means that neutrino cannot be produced in the superposition state. The weak interactions cannot produce neutrino in the mixing helicity states since these interactions are chiral-invariant; i. e., the weak interactions cannot produce neutrino in the superposition state. From all known experiments the neutrinos in weak interactions are produced with definite spirality (helicity) [11]. It is necessary to remark that this result is a right consequence of weak interactions which cannot produce neutrino χ which is a superposition of ν_L and $(\nu_L)^c$ neutrinos.

A review of tasks related the problem of distinguishing between Dirac and Majorana neutrinos was given in [12], with a big quantity of references.

At the present time after detection that there are transitions between different types of neutrino a very important problem appears: is neutrino a Dirac or Majorana particle?

This work is purposed to clarify the questions connected with Majorana neutrino and therefore these should be discussed.

1. MAJORANA NEUTRINO

Gamma matrices have the following form (we follow the notation used in [8]):

$$\gamma^0 = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}, \; \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix},$$
$$\gamma^5 = -i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}, \tag{1}$$

where $i = 1 \div 3$ and σ_i are Pauli matrices. And

$$\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2g^{\nu\mu}, \quad \gamma^\mu\gamma^5 + \gamma^5\gamma^\mu = 0, \tag{2}$$

where $\mu, \nu \div 0, 1, 2, 3$, $g^{\nu\mu} = 0$ if $\nu \neq \mu$ and $g^{\nu\mu} = (1, -1, -1, -1)$ if $\nu = \mu$.

Usually a Majorana neutrino (antineutrino) is connected with Dirac antineutrino $\bar{\nu}_L, \bar{\nu}_R$ in the following manner (it is necessary to draw attention to the fact that in this section we use the notation of work [8]):

$$\nu_L, (\nu_L)^c \equiv C\bar{\nu}_L^T; \quad \nu_R, (\nu_R)^c \equiv C\bar{\nu}_R^T, \tag{3}$$

where C is a charge-conjugation matrix, and this matrix satisfies the conditions ($C \sim \gamma^4\gamma^2$)

$$C\gamma^{\mu T}C^{-1} = -\gamma^\mu, \quad C^+C = 1, \quad C^T = -C. \tag{4}$$

Using (3), (4) we can obtain

$$\overline{(\nu_L)^c} = -\nu_L^T C^{-1}, \quad \overline{(\nu_R)^c} = -\nu_R^T C^{-1}. \tag{5}$$

Now it is necessary to find out what type of fermions are the above Majorana $(\nu_L)^c, (\nu_R)^c$ neutrinos. For this purpose to these states projection operators are applied:

$$\frac{1}{2}(1-\gamma^5)(\nu_L)^c = C\left[\bar{\nu}_L \frac{1}{2}(1-\gamma^5)\right]^T, \tag{6}$$

where we used

$$C^{-1}\gamma^5 C = \gamma^{5T}. \tag{7}$$

Since $\bar{\nu}_L \frac{1}{2}(1-\gamma^5) = \bar{\nu}_L$, from (6) we get

$$\frac{1}{2}(1-\gamma^5)(\nu_L)^c = (\nu_L)^c. \tag{8}$$

So we come to a conclusion that $(\nu_L)^c$ neutrino is a right-sided neutrino. In a similar way we can get that neutrino $(\nu_R)^c$ is a left-sided neutrino:

$$\frac{1}{2}(1+\gamma^5)(\nu_R)^c = (\nu_R)^c. \tag{9}$$

So, instead of four neutrino (fermion) states in the case of Dirac fermions $\bar{\nu}_R, \bar{\nu}_L, \nu_R, \nu_L$, in the Majorana case four neutrino states $(\nu_R)^c, \nu_R, (\nu_L)^c, \nu_L$ appear here.

The Majorana equation for neutrino is [2]

$$\begin{aligned} &i(\widehat{\sigma}^\mu d_\mu)\nu_R - m_R^M \epsilon \nu_R^* = 0, \\ &i(\widehat{\sigma}^\mu d_\mu)\nu_L - m_L^M \epsilon \nu_L^* = 0, \end{aligned} \tag{10}$$

where $\widehat{\sigma}^\mu \equiv (\sigma^0, \boldsymbol{\sigma})$, $\sigma^\mu \equiv (\sigma^0, -\boldsymbol{\sigma})$, $\boldsymbol{\sigma}$ is Pauli matrices,

$$\epsilon = \begin{pmatrix} 0, 1 \\ -1, 0 \end{pmatrix}.$$

These equations describe two completely different neutrinos with masses m_R^M and m_L^M which do not possess any additive numbers and neutrinos are their own antineutrinos; i. e., particles differ from antiparticles only in spin projections. Now it is possible to introduce the following two Majorana neutrino states:

$$\begin{aligned} \chi_L &= \nu_L + (\nu_L)^c, \\ \chi_R &= \nu_R + (\nu_R)^c. \end{aligned} \tag{11}$$

Formally the above Majorana equation (10) can be rewritten in the form

$$(\gamma^\mu \partial_\mu + m)\chi(x) = 0, \tag{12}$$

with the Majorana condition ($\chi \equiv \chi_{LR}$)

$$C\bar{\chi}^T(x) = \xi\chi(x), \tag{13}$$

where ξ is a phase factor ($\xi = \pm 1$) and C is matrix (2).

It is necessary to stress that

$$\bar{\chi}(x)\gamma^\mu\chi(x) = 0; \tag{14}$$

i. e., vector current of Majorana neutrino is equal to zero.

At the beginning in the Dirac representation we have two states: neutrino state Ψ_L and antineutrino state $\bar{\Psi}_L$, then by using Majorana condition (3) we come to two new neutrino states: Ψ_L and $(\Psi_L)^c$. The question is: can we construct one Majorana neutrino state from these two states, as was done in the above consideration while obtaining expressions (11), (12). As a matter of fact, it is necessary to introduce two Majorana neutrino states:

$$\begin{aligned} \chi_{1L} &= \frac{1}{\sqrt{2}}(\nu_L + (\nu_L)^c), \\ \chi_{2L} &= \frac{1}{\sqrt{2}}(-\nu_L + (\nu_L)^c), \end{aligned} \tag{15}$$

as was considered in [9]; i. e., these must be two Majorana neutrino states but not one Majorana neutrino state.

As noted above, the neutrino states $\chi_{LR}(x)$ in (11) are normalized to 2. It is well known that state functions of particles must be normalized to one. It is well seen in the example of neutrino antineutrino mixing considered by Pontecorvo [4], where two normalized states $\nu_1 = \frac{1}{\sqrt{2}}(\bar{\nu}_e + \nu_e)$, $\nu_2 = \frac{1}{\sqrt{2}}(\bar{\nu}_e - \nu_e)$ appear. It is clear that when formulating Majorana neutrino the second state in (15) was not taken into account.

Majorana mass Lagrangian can be written in the following form:

$$\mathcal{L}^M = -\frac{1}{2}\overline{(\nu_L)^c} m_L^M \nu_L - \frac{1}{2}\overline{(\nu_R)^c} m_R^M \nu_R + \text{h.c.} \tag{16}$$

Lagrangian $\mathcal{L}_I^M(\chi ...)$ of interaction of Majorana electron neutrinos with electrons usually has the following form:

$$\mathcal{L}_I^M(e, \chi_L) = \frac{ig}{2\sqrt{2}}\bar{e}_L(x)\gamma^\mu\chi_L(x)W_\mu^- + \text{h.c.} \tag{17}$$

It is necessary to remark that Lagrangian (17) for the Majorana neutrino interaction, in contrast to the Lagrangian for the Dirac neutrino interaction in the electroweak model [13], is not invariant relative to the weak isospin transformation (Majorana neutrino has zero weak isospin). Also, a relation analogous to the Gell-Mann–Nishigima in this case is absent. Besides, here the global gauge invariance is absent since the Majorana neutrino state is a superposition of neutrino and antineutrino. Most sorrowful is that in this Lagrangian the local gauge invariance is violated (the local gauge invariance can be fulfilled in the case when there are a Dirac particle and antiparticle). Hardly violation of local gauge invariance by hand has a sense. This violation requires a serious substantiation. Neutrinos are right produced together with leptons and quarks at the energies where electroweak model works very well. So, a supposition that neutrinos are Majorana neutrinos is absolutely groundless. For Majorana neutrinos there is only one possibility: if in reality in the nature the Majorana neutrinos exist then at very high energies, if local gauge invariance is violated, Dirac neutrinos can be converted into Majorana neutrinos.

2. IS NEUTRINOLESS DOUBLE β DECAY POSSIBLE IF NEUTRINOS ARE MAJORANA NEUTRINOS?

A reaction with a double beta decay with two electrons

$$(Z, A) \to (Z+2, A) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2},$$

is possible if $M_A(Z, A) > M_A(Z+2, A)$.

In analogy with the electron double beta decay there can be reactions with double neutrino radiation by electron capture or positron radiation

$$(Z, A) + e_1^- + e_2^- \to (Z-2, A) + \nu_{e1} + \nu_{e2},$$

if $M_A(Z, A) > M_A(Z-2, A) + 2\Delta$;

$$(Z, A) + e_1^- \to (Z-2, A) + e_2^+ + \nu_{e1} + \nu_{e2},$$

if $M_A(Z, A) > M_A(Z-2, A) + 2m_e + \Delta$;

$$(Z, A) \to (Z-2, A) + e_1^+ + e_2^+ + \nu_{e1} + \nu_{e2},$$

if $M_A(Z, A) > M_A(Z-2, A) + 4m_e$, where Δ is the binding energy of electron.

If neutrino is a Majorana particle ($\chi_L = \nu_L + (\nu_L)^c$), then the following neutrinoless double beta decays are possible:

$$(Z, A) \to (Z+2, A) + e_1^- + e_2^-,$$

if $M_A(Z, A) > M_A(Z+2, A)$;

and

$$(Z, A) + e_1^- + e_2^- \to (Z-2, A),$$

if $M_A(Z, A) > M_A(Z-2, A) + 2\Delta$;

$$(Z, A) + e_1^- \to (Z-2, A) + e_2^+$$

is possible if $M_A(Z, A) > M_A(Z-2, A) + 2m_e + \Delta$;

$$(Z, A) \to (Z-2, A) + e_1^+ + e_2^+,$$

if $M_A(Z, A) > M_A(Z-2, A) + 4m_e$.

The lepton part of the amplitude of the two neutrino decay has the following form [9], [14]:

$$\bar{e}(x)\gamma_\rho \frac{1}{2}(1 \pm \gamma_5)\nu_j \bar{e}(y)\gamma_\sigma \frac{1}{2}(1 \pm \gamma_5)\nu_k(y). \tag{18}$$

After substituting of the neutrino propagator and its integrating on the momentum of virtual neutrino, the lepton amplitude gets the following form:

$$-i\delta_{jk} \int \frac{d^4q}{(2\pi)^4} \frac{e^{-iq(x-y)}}{q^2 - m_j^2} \bar{e}(x)\gamma_\rho \frac{1}{2}(1 \pm \gamma_5)(q^\mu \gamma_\mu + m_j)\frac{1}{2}(1 \pm \gamma_5)\gamma_\sigma e(y). \tag{19}$$

If we use the following expressions:

$$\frac{1}{2}(1 - \gamma_5)(q^\mu \gamma_\mu + m_j)\frac{1}{2}(1 - \gamma_5) = m_j \frac{1}{2}(1 - \gamma_5), \tag{20}$$

$$\frac{1}{2}(1 - \gamma_5)(q^\mu \gamma_\mu + m_j)\frac{1}{2}(1 + \gamma_5) = q^\mu \gamma_\mu \frac{1}{2}(1 + \gamma_5), \tag{21}$$

then we see that in the case when there are only left currents (expression (20)) we get a deposit only from the neutrino mass part,

$$-i\delta_{jk} \int \frac{d^4q}{(2\pi)^4} \frac{e^{-iq(x-y)}}{q^2 - m_j^2} \bar{e}(x)\gamma_\rho \frac{1}{2}(1 - \gamma_5)(q^\mu \gamma_\mu + m_j)\frac{1}{2}(1 - \gamma_5)\gamma_\sigma e(y) =$$

$$= -i\delta_{jk} \int \frac{d^4q}{(2\pi)^4} \frac{e^{-iq(x-y)}}{q^2 - m_j^2} \bar{e}(x)\gamma_\rho m_j \frac{1}{2}(1 - \gamma_5)\gamma_\sigma e(y), \tag{22}$$

while in the presence of the right currents (expression (21))

$$-i\delta_{jk} \int \frac{d^4q}{(2\pi)^4} \frac{e^{-iq(x-y)}}{q^2 - m_j^2} \bar{e}(x)\gamma_\rho \frac{1}{2}(1 - \gamma_5)(q^\mu \gamma_\mu + m_j)\frac{1}{2}(1 + \gamma_5)\gamma_\sigma e(y) =$$

$$= -i\delta_{jk} \int \frac{d^4q}{(2\pi)^4} \frac{e^{-iq(x-y)}}{q^2 - m_j^2} \bar{e}(x)\gamma_\rho q^\mu \gamma_\mu \frac{1}{2}(1+\gamma_5)\gamma_\sigma e(y), \tag{23}$$

the amplitude includes in the neutrino propagator a term proportional to four momentum q.

We see that if Majorana neutrino is a superposition of ν_L and $(\nu_L)^c$, then the neutrinoless double beta decay will take place.

Now we come to another consideration: is neutrinoless double β decay possible if neutrinos are Majorana neutrinos in the case when it is taken into account that in the weak interactions neutrino is produced in definite spirality (helicity)?

Our consideration begins with an example of $\pi^\pm$ decays:

$$\begin{array}{l} \pi^+ \to e^+ + \nu_e, \\ \pi^- \to e^- + \bar{\nu}_e. \end{array} \tag{24}$$

If neutrino is a Dirac particle, then ν_e is described by wave function Ψ_{eL} and $\bar{\nu}_e$ is described by wave function $\bar{\Psi}_{eL}$. If neutrino is a Majorana particle, then ν_e is described by wave function Ψ_{eL} and $\bar{\nu}_e$ is described by wave function $(\Psi_{eL})^c$. If Majorana neutrino is $\chi_e = \Psi_{eL} + (\Psi_{eL})^c$ as is usually supposed, then in the above two processes the Majorana electron neutrino state Ψ_{eL} is produced in the first case and the Majorana electron neutrino state $(\Psi_{eL})^c$ is produced in the second case.

So, since in the weak interactions neutrino can be produced only in definite spirality (helicity) state but not in a mixing state with spirality (helicity) as supposed in exp. (11), then neutrino will be produced in state ν_L or $(\nu_L)^c$.

For example, the double nuclear beta decay with electron radiation takes place in the following double transition:

$$\begin{array}{c} (Z, A) \to (Z+1, A) + e_1^- + \bar{\nu}_e, \\ (Z+1, A) \to (Z+2, A) + e_2^- + \bar{\nu}_e. \end{array} \tag{25}$$

If neutrino is a Majorana neutrino, then we can rewrite the above two expressions in the following form:

$$(Z, A) \to (Z+1, A) + e_1^- + \bar{\nu}_e((\Psi_{eL})^c) \to$$

$$\to e_1^- + \bar{\nu}_e((\Psi_{eL})^c) + (Z+1, A) \to (Z+2, A) + e_1^- + e_2^-, \tag{26}$$

but for realization of the second process it is necessary to have neutrino state Ψ_{eL}

$$\nu_e(\Psi_{eL}) + (Z+1, A) \to (Z+2, A) + e_2^-, \tag{27}$$

but not $(\Psi_{eL})^c$ neutrino state (it is clear that if weak interactions radiate neutrino in the superposition state, then this process can be realized). Since the first reaction produces $(\Psi_{eL})^c$ but not the Ψ_{eL} neutrino state, their convolutions

$$(\overline{\Psi_{eL})^c(\Psi}_{eL})^c = 0, \quad \overline{\Psi_{eL}\Psi}_{eL} = 0$$

are zero and therefore the above second reaction is forbidden:

$$\nu_e(\Psi_{eL}) + (Z+1, A) \not\to (Z+2, A) + e_2^- . \tag{28}$$

As mentioned above, usually it is supposed that Majorana neutrino is produced in the first reaction and then it is absorbed in the second reaction and then the neutrinoless double beta decay arises. But in this considered case two Majorana neutrinos are produced in state $(\Psi_{eL})^c$ (weak interactions are chiral symmetric interactions and neutrino at production has definite spirality (helicity) and after production this spirality (helicity) cannot change without an external interaction), then here the capture of neutrino produced in the first reaction cannot take place the second reaction since to realize this possibility in the first reaction Ψ_{eL} (Majorana) neutrino must be emitted and then it can be absorbed in the second reaction (or reverse process can be realized). So we see that for unsuitable spirality (helicity) the neutrinoless double β decay is not possible even if neutrino is a Majorana particle.

3. HOW TO PROVE THAT NEUTRINO IS A MAJORANA PARTICLE

So, if neutrino is a Dirac particle, then ν_L and $\bar{\nu}_L$ neutrino states are produced, but if neutrino is a Majorana particle, the ν_L and $(\nu_L)^c$ neutrino states are produced (since weak interactions are chiral-invariant, neutrino at production has definite (helicity) spirality); therefore, the Majorana neutrino eigenstate $\chi = \nu_L + (\nu_L)^c$ cannot be realized, i. e., ν_L and $(\nu_L)^c$ neutrinos are separately produced. As shown above, in this case the neutrinoless double beta decay is forbidden. Then the question arises: how to prove that neutrino is a Majorana particle.

If neutrino is a Majorana particle there is no conserved lepton number, then mixing and oscillations between neutrino states will arise,

$$\begin{aligned} \nu_e &= \cos\theta \nu_1 + \sin\theta \nu_2, \\ (\nu_e)^c &= -\sin\theta \nu_1 + \cos\theta \nu_2, \end{aligned} \tag{29}$$

i.e., the ν_L and $(\nu_L)^c$ neutrino states are transformed into superpositions of the ν_1 and ν_2 neutrino states. Then oscillations between ν_L and $(\nu_L)^c$ neutrino will take place and a probability of $P(\nu_e \to \nu_e)$ transitions is

$$P(\nu_e \to \nu_e, t) = \sin^2 2\theta \sin^2(t\pi(m_2^2 - m_1^2)/2p), \tag{30}$$

where it is supposed that $p \gg m_1, m_2; E_k \simeq p + m_k^2/2p$ and m_1, m_2 are masses of ν_1, ν_2 neutrinos.

In this case at neutrino oscillations the neutrinos can be transformed into antineutrinos and vice versa. Since neutrinos ν_L and $(\nu_L)^c$ are produced separately and they have opposite spiralities (heliscities), such transitions at neutrino oscillations in vacuum must be absent. Then the only possibility to prove that neutrino is a Dirac but not Majorana particle is detection of transition of ν_L neutrino into (sterile) antineutrino $\bar{\nu}_R$ (i. e., $\nu_L \to \bar{\nu}_R$) at neutrino oscillations (lepton number changes by two units). Transition of Majorana neutrino ν_L into $(\nu_R)^c$ (i. e., $\nu_L \to (\nu_R)^c$) at oscillations is unobserved since it is supposed that the mass of $(\nu_R)^c$ is very big.

CONCLUSION

Usually it is supposed that Majorana neutrino is produced in the superposition state $\chi_L = \nu_L + (\nu_L)^c$ and then follows the neutrinoless double beta decay. But since weak interactions are chiral invariant, the neutrino at production has definite helicity (i. e., ν_L and $(\nu_L)^c$ neutrinos are separately produced and then neutrino is not in the superposition state). This helicity cannot change after production without any external interactions. Thus, we see that for unsuitable helicity the neutrinoless double β decay is not possible even if neutrino is a Majorana particle. Also, transition of Majorana neutrino into antineutrino at their oscillations is forbidden since helicity in vacuum holds. Then the only possibility to prove that neutrino is a Dirac but not Majorana particle is detection of transition of ν_L neutrino into (sterile) antineutrino $\bar{\nu}_R$ (i. e., $\nu_L \to \bar{\nu}_R$) at neutrino oscillations. Transition of the Majorana neutrino ν_L into $(\nu_R)^c$ (i. e., $\nu_L \to (\nu_R)^c$) at oscillations is unobserved since it is supposed that the mass of $(\nu_R)^c$ is very big.

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