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Neutrinoless double-β decay with quasi-Dirac neutrinos

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A mechanism to generate the neutrinoless double-β decay process with quasi-Dirac neutrinos and no right-handed currents is described. Relatively heavy neutrinos can easily be made consistent with the constraints on the $(\beta\beta)_{0\nu}$ rate. The proposed scheme for the violation of lepton number can in principle be distinguished from a Majorana mass in $\Delta l=2$ oscillation phenomena.

Historically the first scheme proposed by Primakoff and Rosen[1] to generate the $(\beta\beta)_{0\nu}$ process was based on the existence of a right-handed charged leptonic current (RHC mechanism). More recently[2] a new scheme was found based on a nonvanishing Majorana neutrino mass (mass mechanism). The common denominator of both of these schemes is the assumption that the neutrino is described by a Majorana field operator.[3] In this Communication we stress that such an assumption is not necessary in general to generate the $(\beta\beta)_{0\nu}$ process.

Within a gauge framework both current and mass mechanisms naturally arise. For example, the standard SU(2) $\times$ U(1) theory with massive neutrinos naturally gives Majorana neutrinos so that the mass mechanism is operative. Left-right-symmetric extensions of the standard model can accomodate both mechanisms.[4] While Majorana neutrinos do naturally arise in many gauge models, their mixing pattern is exceedingly complex.[5] From this point of view it is desirable to seek models which use Dirac neutrinos, at least as an approximation, while incorporating the possibility of lepton-number violation.[6]

First we describe the mechanism to generate a $(\beta\beta)_{0\nu}$ transition mediated by a quasi-Dirac neutrino. We take the simplest $V-A$ effective charged-current weak Hamiltonian

$$H=\sqrt{2}G_F j_L \cdot J_L^\dagger + \text{H.c.} \ , \tag{1}$$

in which J_L is an hadronic current and j_L is the leptonic current,

$$j_{L\mu}=\bar{e}\gamma_\mu \frac{(1+\gamma_5)}{2}\left[\frac{\nu+\epsilon\nu^c}{(1+\epsilon^2)^{1/2}}\right] \ . \tag{2}$$

Here ν is a four-component massive Dirac field and $\nu^c \equiv C\bar{\nu}^T$. The presence of the second term, proportional to a small parameter ϵ, breaks lepton-number conservation by two units. In terms of SL$(2,C)$ mass-eigenstate neutrinos ν_1 and ν_2,

$$\nu_L \cong \frac{\nu_2+i\nu_1}{\sqrt{2}} \ , \quad (\nu^c)_L \cong \frac{\nu_2-i\nu_1}{\sqrt{2}} \ , \tag{3}$$

one rewrites the leptonic current as

$$j_{L\mu}=\sum_{\alpha=1}^{2} \bar{e}_L\gamma_\mu K_\alpha \nu_\alpha \ , \quad K_2 \cong \frac{1+\epsilon}{\sqrt{2}}, \quad K_1 \cong i\frac{1-\epsilon}{\sqrt{2}} \ , \tag{4}$$

where ν_1 and ν_2 are characterized by a *common* mass so as to make up jointly a Dirac spinor ν. Equations (1) and (2) imply, in addition to the lepton-number-conserving β-decay process of Fig. 1(a), the lepton-number-violating process depicted in 1(b). It is then possible to Wick-contract the neutrino field operators and obtain Fig. 1(c) by joining the neutrino lines of 1(a) and 1(b). The $(\beta\beta)_{0\nu}$ amplitude will be proportional to

$$m_\nu \sum_{\alpha=1}^{2} K_\alpha{}^2 = \frac{2m_\nu\epsilon}{1+\epsilon^2} \simeq 2m_\nu\epsilon \ , \tag{5}$$

so that a complete cancellation[7] of the ν_1 and ν_2 contributions is avoided even when $m_1=m_2=m_\nu$ (Dirac limit). We call ν a quasi-Dirac neutrino because, in a gauge framework, it will naturally develop a Majorana mass from radiative corrections.[8,9] One therefore sees from Eq. (5) that the present scheme requires not only an explicit $\Delta l=2$ interaction ($\epsilon \neq 0$) but

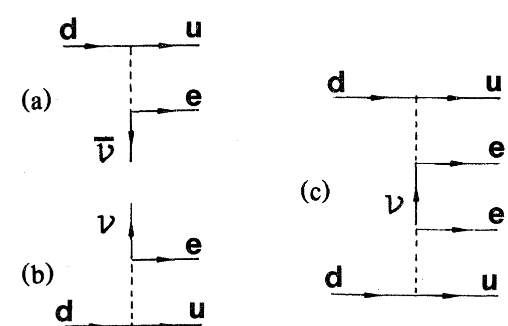

FIG. 1. (a) Ordinary β-decay process ($\Delta l=0$). (b) "Wrong" β decay ($\Delta l=2$). (c) Dirac-neutrino-mediated $(\beta\beta)_{0\nu}$ decay.

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also a nonzero neutrino mass. Since the relevant combination is the product $m_\nu \epsilon$ the present mechanism can tolerate a wide range of neutrino masses even for a small $(\beta\beta)_{0\nu}$ rate. This sharply contrasts with the RHC mechanism. Taking over the recent experimental bound[3] one would expect, roughly,

$$\frac{m_\nu}{m_e}\epsilon \lesssim 10^{-5} \ . \qquad (6)$$

For $\epsilon \simeq 10^{-2}$, a neutrino mass as large as $m_\nu \simeq 1$ keV would be allowed on the basis of this mechanism alone. The general predictions of this scheme regarding the angular correlation of electrons emitted in a $0^+ \rightarrow 0^+$ neutrinoless transition are indistinguishable from those of the mass mechanism but distinct from those of the RHC mechanism. Similarly $0^+ \rightarrow 2^+$ transitions would be forbidden both here and in the mass mechanism, in contrast with the RHC mechanism.

While the present mechanism avoids completely a RHC, notice that the $(\beta\beta)_{0\nu}$ decay mode will also be generated if the lepton number is broken minimally by means of an explicit RHC.[10]

The present scheme (lepton number broken minimally by a left-handed interaction) can in principle be distinguished from the usual mass mechanism (lepton number broken by Majorana masses) in $\Delta l = 2$ oscillations. The process is depicted in Figs. 2(a) and 2(b). If the present scheme holds, the neutrino produced in 2(a) from a charged lepton e_a propagates as a neutrino and instigates in 2(b) a charged-current reaction that produces an antilepton $\bar{e}_b$. The overall amplitude factor for the combined process is

$$\text{amp}(e_a \rightarrow \bar{e}_b, t) = \epsilon \frac{1}{E} \sum_c K_{ac} e^{-iE_c t} m_c K'_{bc} \ , \qquad (7)$$

where K and K' are appropriate mixing matrices and m_c/E accounts for a helicity suppression, E is the neutrino energy, and $t \cong$ distance from the neutrino source at 2(a). Consider now the case in which lepton number is broken by Majorana neutrino masses. Then the neutrinos emitted in 2(a) would oscillate during their flight to 2(b) into antineutrinos so as to trigger, at the position of the second target, an inverse-β-decay reaction. Clearly this process will depend on the fraction of neutrinos emitted in 2(a) which have oscillated into antineutrinos by the time they reach 2(b). Then, via the usual $(\epsilon = 0)$ weak interactions they would produce antileptons $\bar{e}_b$. The overall amplitude factor is

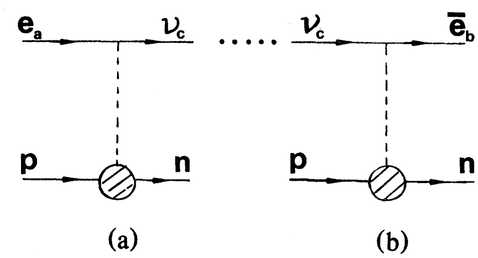

FIG. 2. (a) Ordinary charged-current reaction, in which a charged lepton e_a produces a mass-eigenstate Dirac neutrino ν_c. (b) After time evolution, ν_c triggers a $\Delta l = 2$ charged-current interaction, producting an antilepton $\bar{e}_b$.

$$\text{amp}(e_a \rightarrow \bar{e}_b, t) = \frac{1}{E} \sum_c K_{ac} e^{-iE_c t} m_c K_{bc} \ . \qquad (8)$$

Comparing these two situations one sees that they are qualitatively distinct: In the first case the process is distance independent (lepton number broken in the weak-interaction vertex), while in the case of pure mass mechanism it is distance dependent.[11]

Finally we note that the interaction (1) and (2) can be derived from a gauge-theory framework. It suffices that the fields e_L, ν_L, and ν_L^c are assigned to the fundamental representation of the gauge group. It is not always true, however, that the two-component spinors ν_L and ν_L^c will amalgamate into a Dirac neutrino. A model that accomplishes this to lowest order in perturbation theory is discussed in Ref. 6. It is an extension of the standard model in which the new energy scale is associated with the *local* breakdown of lepton number.[12] The lepton-number-violating parameter ϵ is then essentially given by the ratio of the appropriate energy scales.

To conclude, we note that the ongoing analysis of the neutrinoless nuclear double-β decay should be sharpened by taking into account the possible existence of the mechanism described here.

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[9]One can also talk of quasi-Dirac neutrinos in the context of a model with $\epsilon=0$ and 2 nearly degenerate Majorana neutrinos: In this case the interaction (1) and (2) with $\epsilon=0$ gives a $(\beta\beta)_{0\nu}$ amplitude proportional to their mass difference. This should be contrasted with the situation described in the text.

[10]See S. P. Rosen, in *Particles and Fields—1971*, proceedings of the Annual Meeting of Division of Particles and Fields of the APS, Rochester, New York, edited by A. Melissinos and P. Slattery (AIP, New York, 1971), p. 226.

[11]One can also contemplate a general situation in which "neutrino-antineutrino" oscillations also occur while the "neutrino" travels towards the second target. For that it would suffice to break lepton-number conservation by Majorana masses in addition to the present scheme.

[12]The possibility of spontaneous breakdown of *global* lepton number leads to the so-called Majoron schemes, analyzed in J. Schechter and J. W. F. Valle, Phys. Rev. D 25, 774 (1982) and references therein.