Neutrinoless double beta decay with scalar bilinears

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Abstract

One possible probe to physics beyond the standard model is to look for scalar bilinears, which couple to two fermions of the standard model. We point out that the scalar bilinears allow new diagrams contributing to the neutrinoless double beta decay. The upper bound on the neutrinoless double beta decay lifetime would then give new constraints on the ratio of the masses of these scalars to their couplings to the fermions.

In the standard model both baryon B and lepton L numbers are conserved. The baryon number conservation gives stability of the proton, while the lepton number conservation does not allow any Majorana mass of the neutrino. But in recent times non-vanishing neutrino mass has been observed in the atmospheric neutrinos [1, 2]. The smallness of the observed mass is naturally explained if the neutrinos are Majorana particles. More recently a direct evidence of lepton number has been announced in the neutrinoless double beta decay ($0\nu\beta\beta$) [3]. This observation has several interesting consequences [4, 5].

The neutrinoless double beta decay constrains the neutrino mass matrices, when combined with the atmospheric, solar and laboratory neutrino results. The amount of neutrino dark matter is also limited by this observation. In addition to these direct consequences, there are also several indirect consequences of the neutrinoless double beta decay, which depend only on the upper bound of its lifetime.

An upper bound on the $0\nu\beta\beta$ decay restricts the scale of lepton number violation or the Majorana mass of a heavy right-handed neutrino [6]. In the conventional diagram, the lepton number violation is introduced through the Majorana mass of the neutrino. It is also possible to introduce a doubly charged dilepton, whose couplings break lepton number explicitly, which can then give a bound on the mass of the doubly charged dilepton (see figure 1) [7].

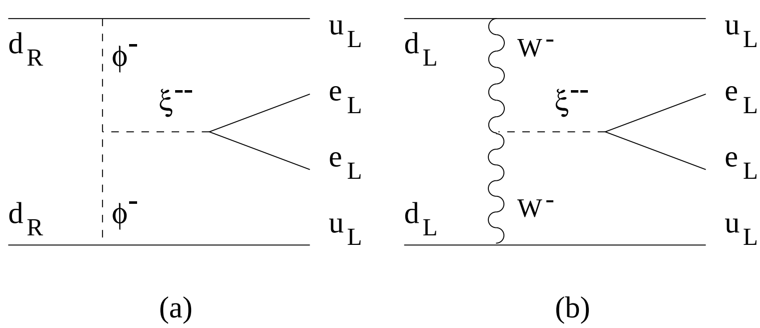

Figure 1: Diagram for neutrinoless double beta decay with dileptons.

The doubly charged component of the $SU(2)_L$ triplet Higgs scalar ξ^{--} allows the diagram of figure 1 with its couplings to the standard model $SU(2)_L$

doublet Higgs ϕ and the leptons $l_{iL} \equiv \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L$, $(i = e, \mu, \tau)$, given by

$$\mathcal{L} = \mu \phi \phi \xi + f_{ij} l_{iL} l_{jL} \xi^\dagger. \tag{1}$$

This Lagrangian can also give a neutrino mass. In this scenario the effective neutrino mass that enters into the $0\nu\beta\beta$ decay is given by

$$< m_\nu >= \mu f_{ee} \frac{v^2}{m_\xi^2} \tag{2}$$

where $< \phi >= v$ is the vacuum expectation value (vev) of the usual Higgs doublet ϕ and m_ξ is the mass of the triplet Higgs scalar ξ. Then the amplitude for the $0\nu\beta\beta$ decay is given by

$$A_{0\nu}[\beta\beta] \sim \mu \frac{m_d^2}{v^2} f_{ee}^2 \frac{1}{m_\phi^4 m_\xi^2} \sim \frac{m_d^2 m_\nu}{v^4 m_\phi^4}., \tag{3}$$

This contribution is much smaller than the usual contribution to the $0\nu\beta\beta$ decay because of the suppression due to the down quark mass. A comparison of this contribution with the present upper bound on the neutrinoless double beta decay lifetime can only give a very weak lower bound on m_ϕ of the order of a few GeV.

The diagram with the W boson can also give a bound on the mass of the dileptons to its couplings. Although the down quark mass does not enter in the expression, now the coupling of the W boson with the dilepton has a suppression proportional to the mass of the neutrino. If the Higgs doublet ϕ is replaced by the exotic scalar Σ, which transforms as an octet under the color $SU(3)_c$ and doublet under $SU(2)_L$, then this can again give a weak bound on the ratio of the mass to the couplings of this scalar Σ.

It has been argued that if there is coupling of the leptoquarks with the usual standard model higgs doublets, then the mixing between a doublet leptoquark and a singlet leptoquark is allowed [8]. This will then give an effective operator $d\bar{u}\bar{\nu}\bar{e}$, which gives a new contribution to the $0\nu\beta\beta$ decay, as shown in figure 2. From this it is then possible to obtain a bound on the ratio of mass and the coupling of the leptoquark scalar [8], using the upper bound on the lifetime of the $0\nu\beta\beta$ decay. Similarly R-parity violating couplings are also constrained by the neutrinoless double beta decay [9].

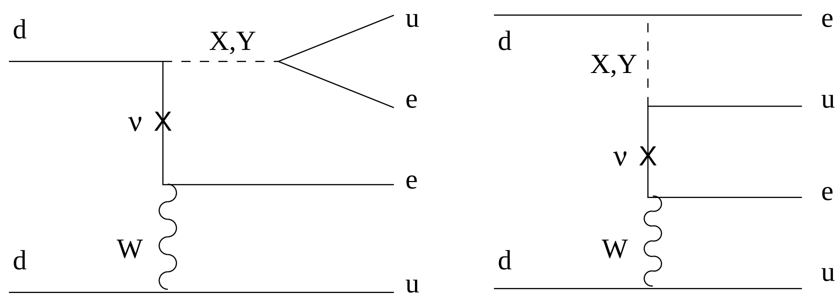

Figure 2: Diagram for neutrinoless double beta decay involving leptoquarks.

Leptoquarks are only one of the possible scalars, which can couple to a couple of fermions, In general, there are several other scalar bilinears, which can couple to two fermions. In the standard model one such scalar bilinear exists, which is the usual Higgs doublet, which couples to $\bar{q}_{iL} u_R$, $\bar{q}_{iL} d_R$ and $\bar{\ell}_{iL} e_R$ (generation indices are suppressed). Other scalar bilinears have been considered to understand the neutrino masses, the triplet Higgs scalar [10] or the doubly charged dileptons [11], which transforms under $SU(3)_c \times SU(2)_L \times U(1)_Y$ as $(1, 3, -1)$ or $(1, 1, -2)$ respectively. All possible scalar bilinears which could exist in theories beyond the standard model have been listed in table .

Phenomenological consequences of these scalars have been studied in the literature [12, 13]. The LEP constraints and the collider signals of these scalars have been extensively studied [12]. Among the various constraints, the baryon number violating constraints and the constraints from the baryon asymmetry of the universe are most severe in several cases [13]. However, none of the present constraints conclusively rule out the possibility of these scalars and hence further studies to understand their phenomenology is underway. Some of these particles are predicted to be very light in some specific theories, which make this study even more attractive [14].

In this note we point out that all these scalars and their usual couplings allow new classes of diagrams, contributing to the $0\nu\beta\beta$ decay. There are no standard model particles involved in these diagrams and the source of lepton number violation is the trilinear couplings of some of these scalar bilinears. We present these diagrams in figure 3, which will now be explained. The upper bound on the lifetime of the $0\nu\beta\beta$ decay will then be used to give a

Representation	Notation	qq	$\bar{q}l$	ql	ll
$(1,1,-1)$	χ^-				$\times$
$(1,1,-2)$	L^{--}				$\times$
$(1,3,-1)$	ξ				$\times$
$(3^*,1,1/3)$	Y_a	$\times$	$\times$		
$(3^*,3,1/3)$	Y_b	$\times$	$\times$		
$(3^*,1,4/3)$	Y_c	$\times$	$\times$		
$(3^*,1,-2/3)$	Y_d	$\times$			
$(3,2,1/6)$	X_a			$\times$	
$(3,2,7/6)$	X_b			$\times$	
$(6,1,-2/3)$	Δ_a	$\times$			
$(6,1,1/3)$	Δ_b	$\times$			
$(6,1,4/3)$	Δ_c	$\times$			
$(6,3,1/3)$	Δ_L	$\times$			
$(8,2,1/2)$	Σ				

Table 1: Exotic scalar particles beyond the standard model.

bound on the ratio of the masses and the couplings of these scalars with the usual fermions.

We start with a systematic analysis to arrive at these diagrams. In a $0\nu\beta\beta$ decay process, the effective operator is $dd\bar{u}\bar{u}\bar{e}\bar{e}$. So, we need one scalar which couples to a d quark and another d or $\bar{u}$ or $\bar{e}$. The scalars which can couple to $d\bar{u}$ are ϕ or Σ. These are the diagrams we already mentioned, in which a $\phi\phi\xi$ coupling gives $0\nu\beta\beta$ decay when ξ goes to two electrons.

Next we consider two d quarks coupling to a diquark. Since both these d quarks has to be from first generation only, only those combinations are allowed which are symmetric in generation index, these are Δ_a and Δ_L. The $Y-$type diquarks are antisymmetric in the color indices and symmetric under $SU(2)_L$, so they are always antisymmetric under the generation index.

The outgoing scalars should go into a leptoquark ue or a diquark uu and a dilepton ee. Since all particles should be from the same generations, these scalars should also be symmetric in the generation index. So, only the leptoquarks Y_a and Y_c can enter in the process, or diquarks Δ_a or Δ_L in combination with the dileptons ξ or L^{--}. This consideration allows only

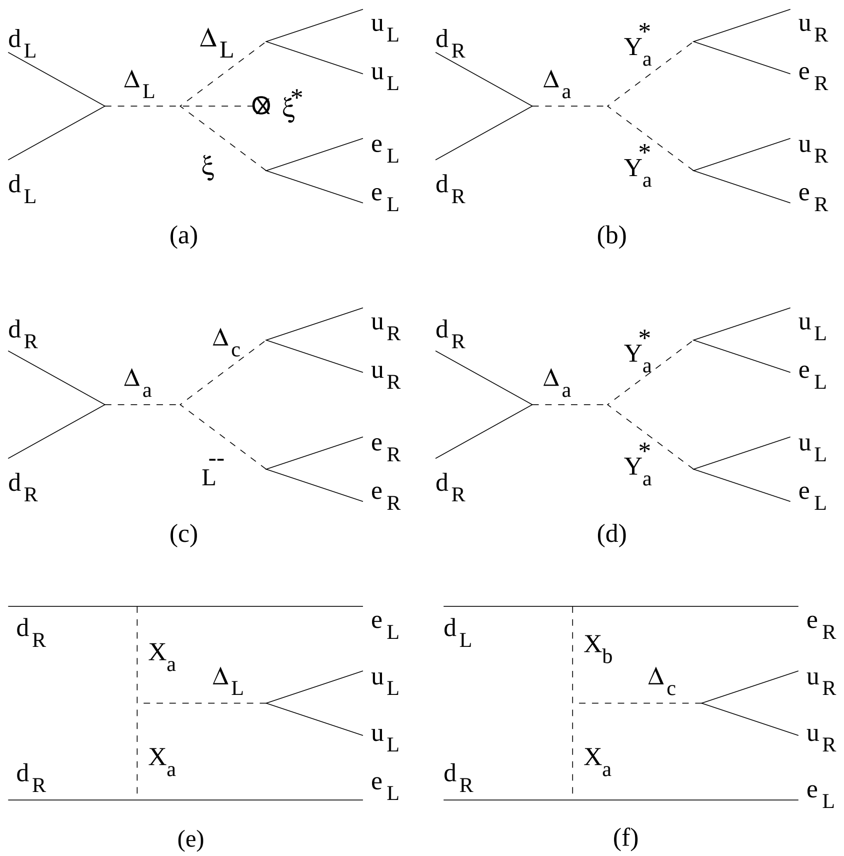

Figure 3: New diagrams for neutrinoless double beta decay with scalar bilinears.

four possible diagrams given by figures (3a - 3d).

The last possibility is when the incoming scalar is a $d\bar{e}$, which are the $X-$type leptoquarks. Since they should go into a scalar, which couples to two u quarks symmetrically, the third scalar could be either Δ_c or Δ_L. This gives two possibilities, given by figures (3e - 3f).

In all these diagrams, there is one d i m e n s i o n f u l ???????? trilinear scalar coupling constant, say μ, and six powers of heavy masses in the denominator. In figure 3a, μ is of the order of $< \xi >\sim m_\nu$, and hence the contribution of this diagram is negligible. So, this diagram may not provide us with any new constraint. In the remaining diagrams, μ is not related to the electroweak symmetry breaking scale, and hence it could be large.

Figure 3b and Figure 3d contribute to the $0\nu\beta\beta$ decay by equal amount,

$$A_{0\nu}[\beta\beta] = \frac{\mu_{\Delta YY} f_{\Delta dd} f_{Yue}^2}{M_\Delta^2 M_Y^4}. \tag{4}$$

The present lifetime of the $0\nu\beta\beta$ decay [3], $\tau_{1/2} = 1.5 \times 10^{25}$ yrs, if not fully atributed to the neutrino mass mechanism, then gives a constraint

$$\frac{\mu_{\Delta YY} f_{\Delta dd} f_{Yue}^2}{M_\Delta^2 M_Y^4} < 10^{-25}\ \mathrm{GeV}^{-5}, \tag{5}$$

considering the Fermi momentum of a nucleon inside a nucleus to be about 200-300 MeV [15].

If we assume that all the coupling constants involved in this expression are of the order of 1, and all masses are of the same order of magnitude, $\mu_{\Delta YY} \sim M_\Delta \sim M_Y \sim M_s$, then we get a bound on the mass of the exotic scalar diquarks or the leptoquarks to be

$$M_s > 10^5\ \mathrm{GeV}. \tag{6}$$

The scalar Y_a can, in general, mediate proton decay through its couplings to two quarks or a quark and a lepton, which gives the strongest bound on its mass to the coupling ratio, which is

$$\frac{M_Y}{|f_{Yud} f_{Yul}|^{1/2}} > 10^{16}\ \mathrm{GeV}. \tag{7}$$

For f_{Yud} to be very small or vanishing, this bound is trivially satisfied and there does not exist any bound on the Y_a-boson mass. In such theories, the bound from the $0\nu\beta\beta$ decay becomes the strongest bound on the mass of the Y_a and the coupling f_{Yul}.

For the scalar Δ_a, the strongest bound comes from radiative proton decay, which depends on its couplings $|f_{\Delta dd} f_{\Delta ud} f_{\Delta d\nu}|^{1/2}$. So, if $f_{\Delta ud}$ or $f_{\Delta d\nu}$ are small, or if the trilinear coupling $\Delta_a \Delta_b^2$ vanishes, then this bound goes away. In that case the strongest bound on Δ_a mass comes from the $K^\circ - \overline{K^\circ}$ or $B_d^\circ - \overline{B_d^\circ}$ oscillations. The bounds on the mass of Δ_a over the couplings $|f_{\Delta dd} f_{\Delta ss}|^{1/2}$ or $|f_{\Delta dd} f_{\Delta bb}|^{1/2}$, as obtained from the upper bound on the lifetime of the neutrinoless double beta decay, comes out to be 1.5×10^6 GeV and 4.6×10^5 GeV, respectively. In case $f_{\Delta ss}$ and $f_{\Delta bb}$ are small, the strongest bound would come from the present analysis of the $0\nu\beta\beta$ decay.

The constraint from figure 3c comes out to be

$$\frac{\mu_{\Delta_a \Delta_c L} f_{\Delta_a dd} f_{\Delta_c uu} f_{Lee}}{M^2_{\Delta_a} M^2_{\Delta_c} M^2_L} < 10^{-25}\ \mathrm{GeV}^{-5}. \tag{8}$$

The present bound on Δ_c is much weaker, coming from $n-\bar{n}$ oscillation, which depends on both $f_{\Delta_c dd}$ and $f_{\Delta_c uu}$. A slightly stronger bound $M_{\Delta_c}/|f_{\Delta_c uu} f_{\Delta_c cc}|^{1/2} > 10^5$ GeV comes from $D^\circ - \overline{D^\circ}$ oscillation. But both these bounds disappear, if the coupling of the Δ_c with d and c quarks are negligible. Again in this case the strongest bound would come from the $0\nu\beta\beta$ decay. The present bounds on L^{--} comes from lepton flavor changing processes, and hence involves couplings of second and third generations of charged leptons. Only for the first generation, the present bound from the $0\nu\beta\beta$ decay becomes the strongest bound.

Figure 3e and 3f give bounds

$$\frac{\mu_{\Delta_L X_a X_a} f^2_{X_a de} f_{\Delta_L uu}}{M^2_{\Delta_L} M^4_{X_a}} < 10^{-25}\ \mathrm{GeV}^{-5} \tag{9}$$

and

$$\frac{\mu_{\Delta_c X_a X_b} f_{X_a de} f_{X_b de} f_{\Delta_c uu}}{M^2_{\Delta_L} M^2_{X_a} M^2_{X_b}} < 10^{-25}\ \mathrm{GeV}^{-5}, \tag{10}$$

respectively. The bounds on Δ_L are similar to that of Δ_c and depends on its couplings to d and c quarks. The present bounds on X_a and X_b are most stringent from the lepton flavor changing processes such as $K^\circ \to e^+\mu^-$, which is greater than 2.4×10^5 GeV. But these bounds involve couplings $f_{X_a s\mu}$ and $f_{X_b s\mu}$. But the present bound is only for the first generation, which is otherwise not constrained.

The new contributions to the neutrinoless double beta decay in the presence of the scalar bilinears considered here may have other interesting consequences. The observed neutrinoless double beta decay [3] is usually translated into a Majorana mass of the neutrino. In [16], a specific model has been considered, where the observed neutrinoless double beta decay has been explained with an almost massless neutrinos. They considered our figure 3c to explain the observed neutrinoless double beta decay with suitable choice of parameters. There is no other source of lepton number violation in the model, so the neutrinos remain massless at the tree level. A tiny Majorana mass is then generated radiatively. Similar models may be constructed with other diagrams of figure 3.

To summarize, we have shown that there are new contributions to the neutrinoless double beta decay if there are scalar bilinears in theories beyond the standard model. The present lifetime of the neutrinoless double beta decay gives bounds on the ratio of the masses to some of the couplings of the new scalars entering in these diagrams. We discuss under which condition the new bounds on these diquarks, leptoquarks and dileptons are stronger than all available constraints.

Acknowledgement

One of us (US) thanks Max-Planck-Institut für Kernphysik for hospitality.

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