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Neutrinoless double-beta decay with massive scalar emission

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ABSTRACT

Searches for neutrino-less double-beta decay ($0\nu 2\beta$) place an important constraint on models where light fields beyond the Standard Model participate in the neutrino mass mechanism. While $0\nu 2\beta$ experimental collaborations often consider various massless majoron models, including various forms of majoron couplings and multi-majoron final-state processes, none of these searches considered the scenario where the "majoron" ϕ is not massless, $m_\phi \sim$ MeV, of the same order as the Q-value of the $0\nu 2\beta$ reaction. We consider this parameter region and estimate $0\nu 2\beta\phi$ constraints for m_ϕ of order MeV. The constraints are affected not only by kinematical phase space suppression but also by a change in the signal to background ratio charachterizing the search. As a result, $0\nu 2\beta\phi$ constraints for $m_\phi > 0$ diminish significantly below the reaction threshold. This has phenomenological implications, which we illustrate focusing on high-energy neutrino telescopes. The spectral shape of high-energy astrophysical neutrinos could exhibit features due to resonant $\nu\nu \to \phi \to \nu\nu$ scattering. Such features fall within the sensitivity range of IceCube-like experiments, if m_ϕ is of order MeV, making $0\nu 2\beta\phi$ a key complimentary laboratory constraint on the scenario. Our results motivate a dedicated analysis by $0\nu 2\beta$ collaborations, analogous to the dedicated analyses targeting massless majoron models.

1. Introduction

Neutrinoless double beta ($0\nu 2\beta$) decay [1–4],

$$(A, Z) \to (A, Z+2) + 2e^-, \tag{1}$$

is a lepton number violating process. It is sensitive to the neutrino mass parameter

$$m_{ee} = \left| \sum_i m_{\nu_i} U_{ei}^2 \right|, \tag{2}$$

where m_{ν_i} $(i = 1, 2, 3)$ are the neutrino masses and U is the lepton mixing matrix [5]. While the renormalizable Standard Model (SM) has lepton number as an accidental symmetry and, consequently, predicts that the neutrinos are massless, adding dimension-five terms [6][1,2]

$$\mathcal{L}_{d=5} = -\frac{\mathcal{Z}_{\alpha\beta}}{\Lambda}(HL_\alpha)(HL_\beta), \tag{3}$$

where H is the Higgs doublet field and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublet fields, leads to neutrino masses,

$$m_\nu = \frac{v^2 \mathcal{Z}}{\Lambda}, \tag{4}$$

with $v = 246$ GeV.

We do not know the beyond-SM origin of the dimension-five terms in Eq. (3). It is possible that additional light particles accompany the neutrino mass mechanism and interact with SM fields in various ways. If there exists a light gauge-singlet scalar ϕ, then the dimension-six terms

$$\mathcal{L}_{d=6} = -\frac{\mathcal{Y}_{\alpha\beta}}{\Lambda^2}\phi(HL_\alpha)(HL_\beta) \tag{5}$$

are possible. The dimension-six terms lead to Yukawa couplings of ϕ to neutrinos,

$$\mathcal{L} \supset -\frac{1}{2}\mathcal{G}_{\alpha\beta}\,\phi\,\nu_\alpha\nu_\beta + \text{h.c.}, \tag{6}$$

$$\mathcal{G} = \frac{v^2}{\Lambda^2}\mathcal{Y}. \tag{7}$$

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[1] Repeated flavour indices are summed-over, and the bracket (HL) denotes contraction to an SU(2) singlet.

[2] See Ref. [7] for a recent discussion of $0\nu 2\beta$ in the SM effective field theory.

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If the mass of the ϕ particle is less than the Q-value of the $(A, Z) \to (A, Z+2)$ transition, $m_\phi < Q$, then the $\mathcal{G}_{ee}$ coupling leads to a decay where $0\nu2\beta$ is accompanied by on-shell ϕ emission ($0\nu2\beta\phi$),

$$(A, Z) \to (A, Z+2) + 2e^- + \phi. \tag{8}$$

A well known framework that leads to Eq. (5) and to the decay mode $0\nu2\beta\phi$ is that of majoron models [8–13], where ϕ is the Goldstone boson related to the spontaneous breaking of the lepton number symmetry. Many variants of the majoron model have been studied in the literature. In the simplest realisations, the seesaw scale Λ appearing in Eq. (3) is promoted to a dynamical field, and the phase of this field is associated with ϕ. In such models, (i) the ϕ particle is massless, and (ii) the terms of Eq. (3) and Eq. (5) are related, leading to $\mathcal{G} = m_\nu/\Lambda$. For high-scale seesaw models, with $\mathcal{Z} = \mathcal{O}(1)$, the seesaw scale is $\Lambda \sim 10^{14}$ GeV, leading to $\mathcal{G} \sim 10^{-24}$. As we review in Sec. 2, such tiny coupling is some 20 orders of magnitude below the reach of $0\nu2\beta\phi$ searches.

In other scenarios, like the inverse-seesaw models of Ref. [14–16] (see Ref. [17] for a review), neutrino masses arise from effective dimension six terms. Namely, instead of $1/\Lambda$ in Eq. (3) we have μ/Λ^2, where a technically natural hierarchy $\mu \ll \Lambda$ is responsible, at least in part, for the smallness of the neutrino mass. In such case, a light scalar field could arise if we promote the inverse-seesaw parameter μ to a field ϕ with $\mu = \langle\phi\rangle$. In this case, $\mathcal{G} = m_\nu/\mu$ and if μ is small enough, $0\nu2\beta\phi$ could be observable. If lepton number is broken spontaneously by $\langle\phi\rangle$, then the ϕ particle is still massless.

Global symmetries, however, are not expected to be exact. If lepton number is broken not only spontaneously but also explicitly, by some small parameter, then ϕ could be light but not massless [18,19]. In addition, if the explicit lepton number violation (LNV) dominates the neutrino mass, then also the relation between $\mathcal{G}$ and m_ν is modified. Yet another framework that can accommodate this situation is if neutrinos are Dirac particles, in which case lepton number (more precisely some non-anomalous symmetry group containing it, e.g. $B - L$) may be exact; see [20] for a recent study. While $0\nu2\beta$ experimental collaborations often consider various massless majoron models, such as different forms of the majoron-neutrino couplings and multi-majoron final-state processes, none of these searches considered the scenario of a massive majoron, $m_\phi \sim$ MeV, of the same order as the Q-value of the $0\nu2\beta$ reaction. In this paper we consider this parameter region[3] and estimate $0\nu2\beta\phi$ constraints for the case of m_ϕ of order MeV. As we show, the constraints are affected not only by kinematical phase space suppression near $m_\phi \sim Q$, but also by a change in the signal to background ratio characterising the search. As a result, $0\nu2\beta\phi$ constraints for $m_\phi > 0$ diminish significantly below the reaction threshold. Our results motivate a dedicated analysis by $0\nu2\beta$ collaborations, analogous to the dedicated analyses targeting different massless majoron models.

The constraint on massive ϕ emission in $0\nu2\beta\phi$ has phenomenological implications, which we illustrate focusing on high-energy neutrino telescopes. Light scalar fields coupled to neutrinos were considered as mediators of anomalous neutrino self-interactions in many other works. Refs. [22,23] studied the effect of light scalar exchange on the energy spectrum of ∼10 MeV neutrinos from core-collapse supernovae (see also [24] where supernovae neutrinos scatter on dark matter). Vector boson or massless majoron exchange were considered in [25–27]. Refs. [28–31] discussed the relation of anomalous neutrino interactions to low-scale neutrino mass generation, focusing on spontaneously broken global and gauged lepton number. Ref. [32] extended the discussion to the technically natural possibility of small explicit LNV, and made a connection to phenomenology at high-energy neutrino telescopes. Recently, Ref. [33] considered light scalar exchange in coherent neutrino-nucleus scattering.

Before we turn into concrete calculations, let us emphasize that while $0\nu2\beta$ is a LNV process, $0\nu2\beta\phi$ could be lepton number conserving (LNC). It could be therefore that the latter is strongly enhanced compared to the former. Explicitly, for $m_\phi \ll Q$, we have

$$\frac{\Gamma_{0\nu2\beta\phi}}{\Gamma_{0\nu2\beta}} \sim \frac{|\mathcal{G}_{ee}|^2}{(4\pi)^2} \frac{Q^2}{m_{ee}^2} \gtrsim 60 \left(\frac{|\mathcal{G}_{ee}|}{10^{-5}}\right)^2, \tag{9}$$

where we used the fact that $m_{ee} \lesssim 0.1$ eV [34], with $Q \sim$ MeV. As we review in the next section, $0\nu2\beta\phi$ searches have reached a limit $|\mathcal{G}_{ee}| \lesssim 10^{-5}$ (for massless ϕ). The reason that $\Gamma_{0\nu\beta\beta\phi} \gg \Gamma_{0\nu\beta\beta}$, as shown by Eq. (9), is consistent with these limits, is related to the difference in the visible electron energy spectrum between these decay modes, which reduces the signal to background ratio for $0\nu2\beta\phi$ compared with $0\nu2\beta$. In what follows we will see an analogous effect deteriorating the sensitivity to $m_\phi > 0$ compared to the $m_\phi = 0$ case.

Finally, note that when $m_\phi > Q$, the on-shell process $0\nu2\beta\phi$ is kinematically blocked, but the off-shell process $0\nu2\beta(\phi^* \to 2\nu)$, where a virtual ϕ is emitted and decays to two neutrinos, is always allowed. However, compared to the on-shell process $0\nu2\beta\phi$ (when allowed), the off-shell ϕ process is strongly suppressed by a factor $\sim \frac{2|\mathcal{G}|^2}{15(4\pi)^2} \frac{Q^4}{m_\phi^4} \lesssim 10^{-7} \left(\frac{\mathcal{G}}{10^{-2}}\right)^2$. In addition, the spectral shape with respect to the outgoing electron energy is similar to that of the standard background process $2\nu2\beta$. These features are explained in App. A. As a result of these features, the virtual ϕ decay mode $0\nu2\beta(\phi* \to 2\nu)$ cannot be constrained with current experiments, and we limit our attention to on-shell $0\nu2\beta\phi$.

2. Neutrinoless double-beta decay with massive scalar emission

From the list of $0\nu2\beta$ experiments surveyed in [34], NEMO-3 [35] using ^{100}Mo has the highest Q-value, $Q \approx 3.03$ MeV. Recent work by NEMO-3 allowed them to surpass this record using ^{150}Nd [36], with $Q \approx 3.37$ MeV, albeit with lower exposure. Thus in principle ^{100}Mo and ^{150}Nd experiments probe the highest scalar mass. The strongest constraint on the massless majoron case is from KamLAND-Zen [37] using ^{136}Xe, which has a somewhat lower value of $Q \approx 2.5$ MeV. For these reasons – sensitivity to the highest m_ϕ, and current best sensitivity to massless ϕ – we focus on ^{100}Mo, ^{150}Nd, and ^{136}Xe in our numerical analysis below. It is straightforward to extend our analysis to other isotopes of common use, like ^{76}Ge [38,39], ^{82}Se [40], and ^{130}Te [41,42]. These isotopes yield comparable, although (currently) somewhat weaker constraints.

Refs. [35], [36], and [37] provide 90%CL bounds on the massless majoron scenario, equivalent to $|\mathcal{G}_{ee}| < (1.6 - 4.1) \times 10^{-5}$, $|\mathcal{G}_{ee}| < (3.8 - 14.4) \times 10^{-5}$, and $|\mathcal{G}_{ee}| < (0.4 - 1.0) \times 10^{-5}$, respectively. These bounds are stronger than other constraints in the literature such as those arising from light meson decay (see, e.g. [43–45]) and from cosmological and astrophysical considerations [32]. While the massless majoron bounds [46–50] coincide with our model for $m_\phi \ll Q$, to our knowledge a study of the kinematical region $m_\phi \sim Q \sim$ MeV has not been done and we consider this region in what follows.

[3] We note that Ref. [21] considered neutrino-less double-beta decay with emission of a massive vector boson.