Updating ν_3 lifetime from solar antineutrino spectra

R. Picoreti[*], D. Pramanik[†], P. C. de Holanda[‡] and O. L. G. Peres[§]
Instituto de Física Gleb Wataghin—UNICAMP, Campinas SP 13083-859, Brazil

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We study the production of antineutrinos from the solar neutrinos due to Majorana neutrino decays of neutrino to antineutrino. Using the antineutrino spectra from KamLAND and Borexino, we present the newest limits on the lifetime of ν_3 in this scenario. We consider $\nu_3 \to \bar{\nu}_1 + X$ and $\nu_3 \to \bar{\nu}_2 + X$ channels assuming scalar or pseudoscalar interactions. For hierarchical mass-splittings, we obtain the limits $\tau_3/m_3 \geq 7\times 10^{-5}$ s/eV and $\tau_3/m_3 \geq 1\times 10^{-5}$ s/eV for the two channels at 90% C.L. We found that the newest bound is five orders of magnitude better than the atmospheric and long-baseline bounds.

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I. INTRODUCTION

The neutrino nature, i.e., whether it is a Dirac or Majorana particle, is currently unknown despite extensive experimental searches. The best known probe for the neutrino nature are neutrinoless double-beta decay experiments [1], which would provide a clear signature that neutrinos are Majorana particles. However, recent experimental efforts have not yet found evidence for this process and could not establish the neutrino nature [2–4], establishing instead a limit on the neutrino mass. Other possibilities, for instance, through the search of differences between the lepton-number violating decay rates of K and B mesons [5], also cannot find any clear signature of the Majorana character of the neutrino.

The transition between flavors during neutrino evolution is detected in different experiments, and there is strong evidence for neutrino masses to be a culprit of this flavor change. Pontecorvo's original idea [6] proposed neutrino to antineutrino transitions, and later it was reformulated to conversion between neutrinos. Therefore, our question is: can we have a different way to produce antineutrinos from a neutrino source that, if observable, could provide the first signal of the Majorana nature?

Recently, there is an increasing interest in the idea of neutrino decay (for an incomplete list of articles, see [7–14]). The larger the baseline, or, in other words, the longer the propagation time available for decay, the more sensitive to neutrino decay is the experiment, as shown in Fig. 1. In this scenario, a beam of muon neutrinos, that are the linear combination of mass eigenstates, $\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3$ can have their ν_3 component decay into ν_1 states in the normal ordering. These states are $\nu_1 = U^*_{1e}\nu_e + U^*_{1\mu}\nu_\mu + U^*_{1\tau}\nu_\tau$, and thus a ν_e can appear in the final states. The search for such effect was negative in long-baseline neutrino experiments, atmospheric experiments [9,15–33] where the initial state is richer in ν_μ state and the lower bound on neutrino lifetime was found as $\tau_3/m_3 \geq 2.9\times 10^{-10}$ s/eV at 90% C.L. Other bounds are possible for reactor neutrinos [34,35] where it was found that $\tau_3/m_3 \geq 1.0\times 10^{-10}$ at 90% C.L. as for in Ref. [35]. We provide a summary of these limits in the Supplemental Material [36].

If neutrinos are Dirac particles, decay can happen between (anti)neutrino to (anti)neutrino. If neutrinos are Majorana particles, it can happen through two additional channels: neutrino to antineutrino and vice-versa. In the Sun, neutrino emission is made of electron neutrinos $\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$. If neutrinos are Dirac particles, a $\nu_3 \to \nu_1$ decay would produce extra ν_e content, proportional to $U_{e3} \ll 1$. Otherwise, if neutrinos are Majorana particles, there can be a $\bar{\nu}_1$ component that produces $\bar{\nu}_e$ from the Sun. Consequently, if a search for antineutrinos from the Sun yields a positive result, the neutrino nature can be determined. In this case, the smallness of the U_{e3} is compensated by the large electron antineutrino cross-section. We show that, since standard oscillation produces no antineutrinos, we obtain robust bounds on τ_3/m_3 from the solar antineutrino data. This article is organized as follows. First, we describe our decay model. Next, we show how much antineutrino flux we can get from the Sun for a decay scenario, and then we present limits obtained in our analysis. Finally, we give our conclusions.

[*]renanpicoreti@gmail.com
[†]dpramanik92@gmail.com
[‡]holanda@ifi.unicamp.br
[§]orlando@ifi.unicamp.br

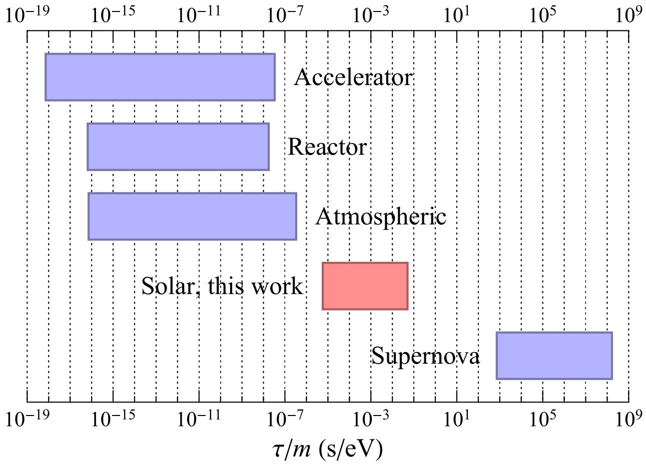

FIG. 1. Schematic diagram for the sensitivity of various neutrino sources to the lifetime τ/m between 99% and 1% neutrino survival. Typical baseline values for each source are used.

II. NEUTRINO DECAY MODEL

Neutrino masses may arise from the coupling to a scalar singlet known as Majoron [37,38]. As a consequence, it is possible for a neutrino to decay into a lighter neutrino alongside the emission of a Majoron, inducing a rich phenomenology [39,40]. For an interaction Lagrangian with Yukawa scalar and pseudoscalar couplings, this process is described by [41]

$$\mathcal{L}_{\rm int} = \sum_{i,j,i\neq j} (g_s)_{ij}\bar{\nu}_j\nu_i X + i(g_p)_{ij}\bar{\nu}_j\gamma_5\nu_i X + \text{H.c.}, \quad (1)$$

where i, j are respectively mother and daughter mass eigenstates, while $(g_s)_{ij}$ and $(g_p)_{ij}$ are respectively the scalar and pseudoscalar coupling constants.

In this work, neutrinos are assumed to be Majorana particles. Neutrinos and antineutrinos are identical and can only be distinguished by their left and right-handed helicities, respectively. Weak interactions couple chiral left-handed neutrinos and chiral right-handed antineutrinos, which, for relativistic neutrinos, are approximated as equal to left, and right helicity states up to terms of order m/E. Hence, both left-handed and right-handed Majorana neutrinos are detectable.

The decay rate Γ_{ij}^{rs} for each decay process is obtained from the appropriate Feynman diagrams and describe helicity-conserving ($\nu_i^r \to \nu_j^r$) and helicity-violating ($\nu_i^r \to \nu_j^s$) decays, where r, s denote helicity states. In the following analysis, we assume at each case that only a single heavier active mass eigenstate ν_i is unstable and decays into neutrinos and antineutrinos of a single lighter active mass eigenstate, ν_j and $\bar{\nu}_j$. As such the energy distribution of the daughter neutrinos as a function of mother and daughter neutrino energies and masses is given by

$$w_{ij}^{rs}(E_i, E_j) = \frac{1}{\Gamma_i^r}\frac{d\Gamma_{ij}^{rs}}{dE_j}(E_i, E_j), \quad (2)$$

such that

$$w_{ij}^{rs} = \begin{cases} \frac{1}{E_i}\frac{1-A^\pm}{1-\delta^2}, & \text{helicity conserving} \\ \frac{1}{E_i}\frac{A^\pm}{1-\delta^2}, & \text{helicity violating} \end{cases} \quad (3)$$

with the kinematics condition $E_i\delta^2 \leq E_j < E_i$, where $\delta = m_j/m_i$ is the ratio between daughter and mother neutrino masses, in general, $0 \leq \delta < 1$. The function $A^\pm = A^\pm(E_i, E_j)$ is given by

$$A^\pm = \frac{1}{(1\pm\delta)^2}\left(1 + \delta^2 - \frac{E_j}{E_i} - \delta^2\frac{E_i}{E_j}\right), \quad (4)$$

where the plus (minus) sign denotes a scalar (pseudo-scalar) interaction, with $g_s \neq 0$ and $g_p = 0$ (with $g_s = 0$ and $g_p \neq 0$). We have given a full derivation of the probability in the Supplemental Material [36].

In Fig. 2, as $\delta \to 0$, that is, if neutrino masses are hierarchical, the decays become independent of the coupling constants, and both scalar and pseudoscalar will produce comparable daughter fluxes. On the other hand, as $\delta \to 1$, if the neutrino masses are quasidegenerate, the helicity-violating decays are suppressed for the scalar interaction. At the same time, that is not the case for the pseudoscalar interaction where helicity-conserving and violating decays will produce comparable daughter fluxes.

III. ANTINEUTRINO FLUX FROM DECAY

A model-independent combined formalism for obtaining survival and transition probabilities, including neutrino oscillations and decay, is presented in [41].

Current limits on their lifetime imply that solar neutrinos do not substantially decay either inside the Sun or Earth. As such, assuming solar neutrinos decay only in vacuum on their way from Sun to Earth, the neutrino and antineutrino fluxes arriving at the detector are given by

$$\phi_\beta^s(E_j) = \phi_\alpha^r(E_j)\delta_{rs}\sum_k P_{\alpha k}^\odot\left[\exp\left(-\frac{m_k}{\tau_k}\frac{L}{E_k}\right)\right]P_{k\beta}^\oplus + \int dE_i\phi_\alpha^r(E_i)P_{\alpha i}^\odot\left[1-\exp\left(-\frac{m_i}{\tau_i}\frac{L}{E_i}\right)\right]w_{ij}^{rs}(\delta)P_{j\beta}^{\oplus s} \quad (5)$$

with the integration limits $E_j \leq E_i < E_j/\delta^2$, where $P_{\alpha i}^\odot$ is the probability of the produced ν_e be found as a ν_i at the surface of the Sun, $P_{i\beta}^\oplus$ is the probability of a ν_i be detected as a ν_β on Earth. As such, in Eq. (5), the first term describes the oscillation and decay of the parent neutrinos, while the second term describes the production of daughter neutrinos from the decay of parent neutrinos.

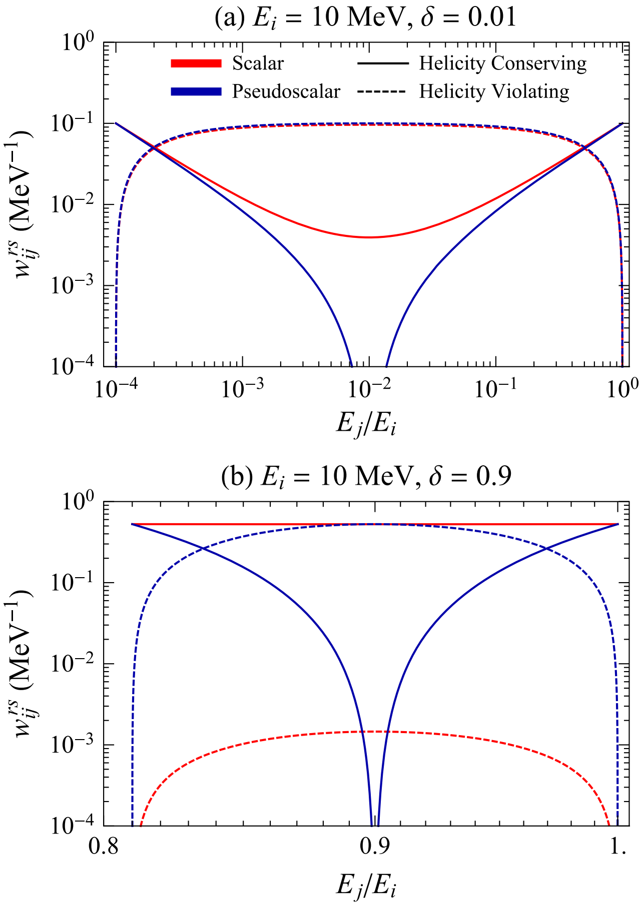

FIG. 2. Energy distribution w_{ij}^{rs} of the daughter neutrino or antineutrino ν_j^s produced in the decay of a 10 MeV mother neutrino or antineutrino ν_i^r for both helicity conserving (solid line) and violating (dashed line) decays as functions of the ratio between daughter and mother neutrino energies E_j/E_i as defined in Eq. (3) for a scalar (red) and pseudoscalar (blue) interaction.

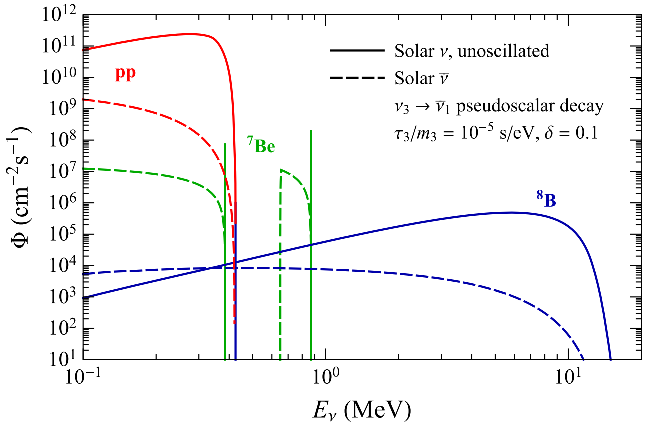

FIG. 3. Solar antineutrino $\bar{\nu}_e$ flux at Earth due to decay for pseudoscalar interactions for a $\tau_3/m_3 = 1 \times 10^{-5}$ s/eV assuming $\nu_3 \to \bar{\nu}_1$ decay. The red, green, and blue curves represent pp, ^{7}Be, and ^{8}B neutrinos respectively. The solid and dashed curves are for the original unoscillated flux, and $\delta = 0.1$ respectively.

We show the expected $\bar{\nu}_e$ flux from the decay channel $\nu_3 \to \bar{\nu}_1$ for $\tau_3/m_3 = 10^{-5}$ s/eV as a benchmark value in Fig. 3. The first thing to notice here is that the decay distorts the shape of the flux and pushes the energy of the daughter neutrino toward lower values. As a result, the ^{7}Be lines become wider. The broadening of the mono-energetic lines happens because, in two-body decays, the parent's energy is carried by both daughter particles. The kinematic factors determine the width of the line. The daughter energy E_j satisfies the conditions $E_j \leq E_i$ and $E_j \geq E_i\delta^2$ with E_i being the parent neutrino energy. We also see that, for the hierarchical scenario, at ultralow energies, the expected antineutrino flux can even be larger than the unoscillated flux at those energies, as seen in the ^{8}B flux.

IV. LIMITS FROM THE ANTINEUTRINO DATA

We present limits on the neutrino decay from the solar antineutrino data in Fig. 4 for the two channels for ν_3 decay

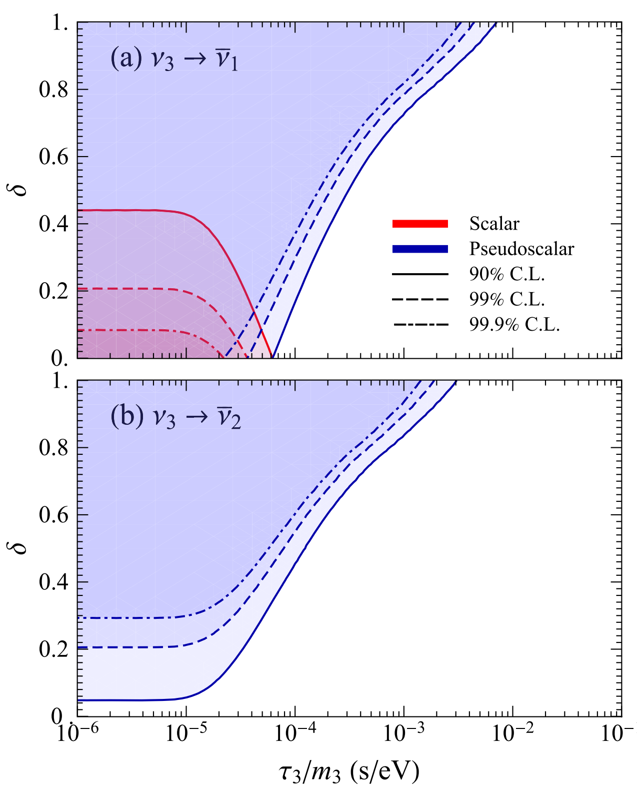

FIG. 4. Limits on the δ vs τ_3/m_3 plane from the antineutrino data. The shaded regions are disallowed. The red and blue are for scalar and pseudo-scalar interactions respectively with solid, dashed and dashed-dotted lines for 90%, 99%, and 99.9% confidence levels respectively. The top (bottom) panels are for $\nu_3 \to \bar{\nu}_1$ ($\nu_3 \to \bar{\nu}_2$) decay channel.

to antineutrinos, $\bar{\nu}_1$ or $\bar{\nu}_2$ for the antineutrino data from KamLAND[1] [43] and Borexino [44]. While Borexino is an experiment mainly dedicated to solar neutrinos, the main goal of KamLAND was to detect the large flux of reactor anti-neutrinos produced in the vicinity of the detector. However, for neutrino energies larger then ~ 8 MeV, reactor neutrinos are absent, and KamLAND becomes very sensitive to a nonstandard antineutrinos flux from other sources, e.g., the Sun.

We present here only the limits for the decay of ν_3, because getting limits on ν_3 lifetime from the solar experiments is a completely novel idea. For other possible channels we have shown the results in the Supplemental Material [36]. Both KamLAND and Borexino use inverse-beta decay to detect the antineutrinos, and thus are limited by its threshold. Therefore, we only use the ^{8}B neutrinos for our analysis as the hep neutrino flux is much smaller than the ^{8}B.

To simulate the antineutrino spectra of KamLAND, we have matched the 90% upper limit of the total number of events given in Ref. [43] assuming the model of antineutrino conversion probability as given in Ref. [43]. We assumed a fiducial mass of 1 kt. The data corresponds to 23445 days of exposure. We also ignored the systematic uncertainties and the effect of the finite resolution. To simulate Borexino, similar to the KamLAND analysis, we again matched their 90% C.L. results from Ref. [44] which corresponds to 2485 days of exposure to a total 1.32×10^{31} number of target nuclei. Again we have ignored the systematic uncertainties and the effect of the finite resolution. To obtain the limits, we have assumed that θ_{12}, θ_{13}, and Δm^2_{21} are unknown. So, we have varied these parameters with prior terms according to [45]. We see in Fig. 4 that the behaviors of the scalar and the pseudoscalar cases are different. The scalar hypothesis is ruled out only for the $\nu_3 \to \bar{\nu}_1$ channel for the hierarchical neutrino masses and very fast decay, but for the pseudoscalar interactions, the limit is increased with δ, i.e., with reducing the mass-splitting between the parent and daughter states. Another interesting thing to note is that both scalar and pseudoscalar interactions give similar bounds for the hierarchical limit. In the $\delta \to 0$ limit, the decay rates become independent of the nature of the interactions as can be seen in Eqs. (3) and (4). A bound on τ_3/m_3 is estimated in Ref. [46] for degenerate (hierarchical) case based on scaling a limit obtained for τ_2/m_2 to account for a small U_{e3} to be $1.3 \times 10^{-4} (2.2 \times 10^{-5})$ s/eV.

We can understand the behavior of the scalar and pseudoscalar cases from Fig. 2. We notice that the weighted differential rates are more significant for the pseudoscalar interactions than the scalar interactions for the helicity-violating decays, which are responsible for the antineutrino appearances. Thus we find weaker limits for the scalar scenario than for the pseudoscalar scenario. By comparing two panels of Fig. 2, it becomes clear that a higher decay rate for the scalar case happens for lower values of δ. The decay largely diminishes as the δ increases, and there are no limits for the quasidegenerate region in the case of scalar interactions. However, the weighted differential decay rate for the pseudoscalar case increases as we go from the hierarchical to the quasidegenerate region. As a result, we observe the limits getting stronger as we increase δ for the pseudoscalar case.

We also see that $\nu_3 \to \bar{\nu}_1$ decay gives better bounds than $\nu_3 \to \bar{\nu}_2$ decay. In fact the limit is so poor for latter case, that we do not see any limit for the scalar case and for hierarchical scenario for the pseudoscalar case. From the second term of the Eq. (5), we note that the probability depends on the $P^{\oplus}_{ie}$, where i is the daughter neutrino mass-eigenstate. Now, $P^{\oplus}_{1e} = c^2_{13} c^2_{12}$ and $P^{\oplus}_{2e} = c^2_{13} s^2_{12}$, so $\theta_{12} \sim 33.5°$ makes $P^{\oplus}_{1e} \simeq 0.67$ and $P^{\oplus}_{2e} \simeq 0.33$. Hence, $\nu_3 \to \bar{\nu}_1$ gives more antineutrinos compared to $\nu_3 \to \bar{\nu}_2$ decay and thus stronger limits for the first channel.

V. CONCLUSION

In this paper we present an analysis of solar-antineutrino spectra at KamLAND and Borexino through the decay of a heavier neutrino state into a lighter antineutrino and a Majoron. Previously, neutrino data from the Sun could only constrain ν_2 decay, but searches for the solar antineutrino spectra by experiments like KamLAND and Borexino, together with a positive measurement of θ_{13}, has enabled us to look for ν_3 decay. We consider two channels $\nu_3 \to \bar{\nu}_1 + X$ and $\nu_3 \to \bar{\nu}_2 + X$, both with purely scalar interactions and purely pseudoscalar interactions. We study them as a function of the mass-splitting δ between the parent and daughter neutrino states. To put our main results in a nutshell we present here limits at 90% C.L. for two benchmark values of δ, $\delta = 0.2$ and $\delta = 0.8$. For the $\nu_3 \to \bar{\nu}_1 + X$ decay channel with a pseudoscalar interaction, we obtain the limits $\tau_3/m_3 \geq 10^{-4}$ s/eV and $\tau_3/m_3 \geq 2 \times 10^{-3}$ s/eV for the two benchmark δ values, respectively. For scalar antineutrino interaction, data does not put limits on the larger values of δ. For $\delta = 0.2$ the limit is $\tau_3/m_3 \geq 3 \times 10^{-5}$ s/eV. For $\nu_3 \to \bar{\nu}_2 + X$ decay channel, we do not get any limit for the scalar case however the limits for the pseudo-scalar case for the two benchmark δ values are $\tau_3/m_3 \geq 3 \times 10^{-5}$ s/eV and $\tau_3/m_3 \geq 10^{-3}$ s/eV respectively.

To conclude, a positive measurement of solar antineutrino spectra would open up a new window of possibilities. As standard neutrino physics predicts no solar antineutrino, any observation of antineutrino from the Sun will be a new physics signal. There can be a plethora of novel ideas that can be tested using the solar antineutrino data which we leave for future work.

[1]As we were finalizing this manuscript, KamLAND collaboration has published a new result [42].

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