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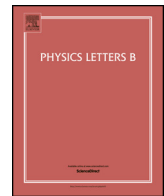
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Neutrino decay and solar neutrino seasonal effect



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ABSTRACT

We consider the possibility of solar neutrino decay as a sub-leading effect on their propagation between production and detection. Using current oscillation data, we set a new lower bound to the ν_2 neutrino lifetime at $\tau_2/m_2 \geq 7.2 \times 10^{-4} \text{ s.eV}^{-1}$ at 99% C.L. Also, we show how seasonal variations in the solar neutrino data can give interesting additional information about neutrino lifetime.

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1. Introduction

Beyond any reasonable doubt, it is now established that neutrinos have non-zero, non-degenerate masses. Thus, it would be possible – if not mandatory – for them to decay into other particles.

Although neutrino decay is now ruled out as a leading process [1] in the so-called Solar Neutrino Problem (SNP) – the difference between the expected solar neutrino flux produced in nuclear fusion processes in the Sun and the detected flux on Earth – one can investigate this phenomenon as a sub-leading effect in the propagation of solar neutrinos and set limits to their lifetime using the most recent experimental data.

Solar neutrinos are produced in the nuclear fusion processes that power the Sun. In such processes, Hydrogen nuclei are converted into Helium through several intermediate reactions, some of which produce neutrinos in very particular spectra – both continuous and monochromatic.

Over the years, several experiments were developed for the detection of solar neutrinos at different energy ranges. From the pioneer Homestake [2] chlorine experiment – which first hinted at the SNP – through the gallium experiments GALLEX [3], SAGE [4] and GNO [5] to the water Cherenkov detectors Kamiokande, SuperKamiokande [6] and SNO [7]. Most recently, the Borexino [8] experiment measured the so called ^7Be neutrino line.

The LMA-MSW solution – Large Mixing Angle flavor oscillation with Mikheyev–Smirnov–Wolfenstein (MSW) resonant flavor conversion – established the scenario of three massive light neutrinos that mix [9] in combination with the measurement of the other

oscillation parameters by experiments designed for atmospheric, reactor and long-baseline neutrinos. With such precise measurements of the standard oscillation parameters, it is possible to investigate new phenomena such as the neutrino decay scenario: $\nu' \rightarrow \nu + X$.

For solar neutrinos, the decay of the mass-eigenstate ν_2 into the lighter state ν_1 is disfavored by the data and the current bound to ν_2 lifetime for invisible non-radiative decays [1] is $\tau_2/m_2 \geq 8.7 \times 10^{-5} \text{ s.eV}^{-1}$ at 99% C.L. Most recently, Ref. [10] argues for $\tau_2/m_2 \geq 7.1 \times 10^{-4} \text{ s.eV}^{-1}$ at 2σ .

Similarly, from the combined accelerator and atmospheric neutrino data the lifetime of the ν_3 eigenstate is $\tau_3/m_3 \geq 2.9 \times 10^{-10} \text{ s.eV}^{-1}$ at 90% C.L. [11] and an analysis of the long-baseline experiments MINOS and T2K gives a combined limit of $\tau_3/m_3 \geq 2.8 \times 10^{-12} \text{ s.eV}^{-1}$ at 90% C.L. [12].

In this work, we consider the decay scenario in which all the final products are invisible. We combine the available solar neutrino data with KamLAND [13] and Daya Bay [14] data. For both experiments the effect of neutrino decay is minimum, allowing us to constrain the standard neutrino mixing parameters independently of the decay parameter τ_2/m_2 and leading us to obtain a robust bound on ν_2 lifetime. Additionally, we show how seasonal variations in the solar neutrino data, which are enhanced by neutrino decay, can give some interesting information about neutrino lifetime.

2. Formalism

After production in the solar core, neutrinos propagate outwards undergoing flavor oscillation and resonant flavor transition due to the solar matter potential. After emerging from the Sun, they travel across the interplanetary medium until they reach the

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Earth's surface where they can be detected either promptly or after traversing Earth's matter – on which they may also be subject to matter effects.

The transition amplitude for an electron neutrino produced in the Sun to be detected on Earth as a neutrino of flavor α , $\nu_e \rightarrow \nu_\alpha$, for the standard case of neutrino oscillations with MSW effect, can be written as [15]

$$A_{e\alpha} = \sum_i A_{ei}^\odot A_{ii}^{\text{vac}} A_{i\alpha}^\oplus, \quad (1)$$

where A_{ei}^\odot is the transition amplitude of an electron neutrino produced in the solar core to be in a ν_i mass-eigenstate in the solar surface, A_{ii}^{vac} is the transition amplitude for the propagation between Sun and Earth surfaces, and $A_{i\alpha}^\oplus$ is the transition amplitude of a ν_i to be in a ν_α state upon detection on Earth.

The transition probability is given as $P(\nu_e \rightarrow \nu_\alpha) = |A_{e\alpha}|^2$. In the LMA parameter region one can neglect coherence effects [16] and simply write the incoherent sum of probabilities:

$$P(\nu_e \rightarrow \nu_\alpha) = \sum_i P_{ei}^\odot P_{i\alpha}^\oplus, \quad (2)$$

where $P_{ei}^\odot = |A_{ei}^\odot|^2$ is the probability of the produced ν_e to be found as a ν_i at the surface of the Sun, and $P_{i\alpha}^\oplus = |A_{i\alpha}^\oplus|^2$ is the probability of a ν_i to be detected as a ν_α on Earth.

Considering the current limits to their lifetime, neutrinos do not decay inside the Sun and it is sufficient to consider their decay on their way to Earth. The survival probability for the invisible decay of a neutrino mass-eigenstate i , with energy E_ν , after propagating a distance L , is

$$P_i^{\text{surv}} = \exp\left[-\left(\frac{\alpha_i}{E_\nu}\right)L\right], \quad \text{with } \alpha_i = \frac{m_i}{\tau_i}, \quad (3)$$

where m_i is the eigenstate mass, τ_i is the eigenstate lifetime and L is the Sun–Earth distance.

For the assumption that only the ν_2 mass-eigenstate is unstable, the electron neutrino survival probability including decay and oscillation for three neutrino families is

$$P(\nu_e \rightarrow \nu_e) = c_{13}^4 \left[P_{e1}^\odot P_{1e}^\oplus + P_{e2}^\odot (P_2^{\text{surv}}) P_{2e}^\oplus \right] + s_{13}^4, \quad (4)$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ and P_i^{surv} is given in Eq. (3) and P_{ei}^\odot and P_{ie}^\oplus are the probabilities in Eq. (2). One interesting consequence of this scenario is that the sum over all probabilities is not equal to 1, as explicitly we have

$$\sum_{\alpha=e,\mu,\tau} P(\nu_e \rightarrow \nu_\alpha) = 1 - c_{13}^2 P_{e2}^\odot (1 - P_2^{\text{surv}}). \quad (5)$$

This non-unitary evolution was discussed in Ref. [17].

Another important consequence is that, for appreciable values of τ_2/m_2 , the solar neutrino data can be explained by a combination of standard three neutrino MSW oscillation and decay, which leads to a degenerescence between neutrino parameters, specially Δm_{21}^2 and τ_2/m_2 [1].

3. Analysis and results

For the analysis of ν_2 decay over the Earth–Sun distance and how it affects the expected rate for each solar neutrino experiment, we calculate the neutrino survival probabilities as shown in Eq. (4) and Eq. (5), numerically, under the assumption of adiabatic evolution inside the Sun [18]. Then, we compute the expected event rate for each relevant experiment and compare it to their data.

We include Homestake total rate [2], GALLEX and GNO combined total rate [19], SAGE total rate [4], SuperKamiokande I full energy and zenith spectrum [20], SNO combined analysis [7] and Borexino 192-day low-energy data [21]. Then, we build a χ^2 function as a function of the relevant parameters $\chi_\odot^2 = \chi_\odot^2(\tan^2\theta_{12}, \Delta m_{21}^2, \sin^2\theta_{13}, \tau_2/m_2)$.

We can add complementary information from the reactor experiments KamLAND [13] and Daya Bay [14] and their detection of $\bar{\nu}_e$ oscillations. One important point that led us toward this analysis is the fact that these experiments give precise constraints on Δm_{21}^2 and $\sin^2\theta_{13}$. KamLAND and Daya Bay have typical baselines of $L/E_\nu \sim 10^{-10}$ s.eV $^{-1}$ and $\sim 10^{-12}$ s.eV $^{-1}$ respectively. For the currently allowed values of τ_2/m_2 , one has that $P_i^{\text{surv}} \sim 1$, which implies that, in the context of these experiments, decay can be neglected and the relevant neutrino probability is the standard three neutrino expression

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - c_{13}^4 S_{12}^2 \sin^2 \Delta_{21} - S_{13}^2 \sin^2 \Delta_{ee}^2, \quad (6)$$

where $S_{ij} = \sin 2\theta_{ij}$, $\Delta_{ij} = \Delta m_{ij}^2/4E_\nu$ and $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$, and we define an effective mass square difference $\sin^2 \Delta_{ee}^2 \equiv c_{12}^2 \sin^2 \Delta_{31} + s_{12}^2 \sin^2 \Delta_{32}$.

This implies that the standard neutrino analysis for three neutrinos of KamLAND and Daya Bay experiments can also be used for decay scenario. In other words, we can identify $\chi_{\text{decay}}^2 = \chi_{\text{no decay}}^2$ in our analysis for both experiments.

For the KamLAND experiment, a χ_{KL}^2 function for the standard three neutrino scenario used in Ref. [13] is available in table format as a function of $\tan^2\theta_{12}$, Δm_{21}^2 and $\sin^2\theta_{13}$. For the Daya Bay experiment, the χ_{DB}^2 function is available in table format provided in the supplementary material from Ref. [14] as a function of Δm_{ee}^2 and $\sin^2\theta_{13}$.

Then, we write the combined χ^2 function for solar, KamLAND and Daya Bay data as

$$\begin{aligned} \chi^2 = & \chi_\odot^2(\tan^2\theta_{12}, \Delta m_{21}^2, \sin^2\theta_{13}, \tau_2/m_2) + \\ & + \chi_{\text{KL}}^2(\tan^2\theta_{12}, \Delta m_{21}^2, \sin^2\theta_{13}) + \\ & + \chi_{\text{DB}}^2(\Delta m_{ee}^2, \sin^2\theta_{13}), \end{aligned} \quad (7)$$

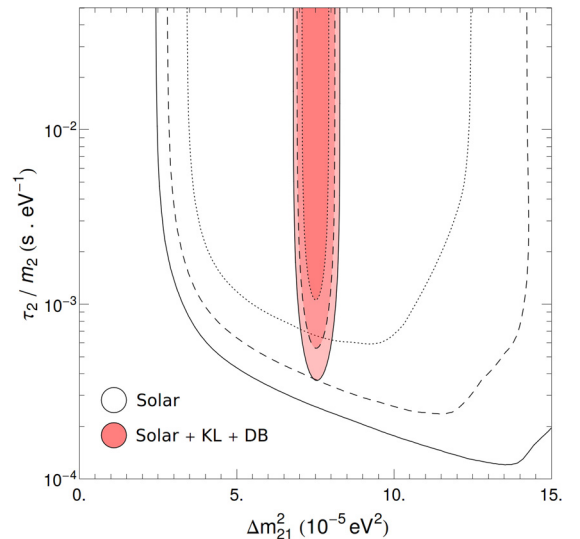


Fig. 1. Allowed regions for the decay parameter τ_2/m_2 and the mass squared difference Δm_{21}^2 . The hollow curves represent the analysis with only solar neutrino data and the filled curves represent the combined analysis of solar, KamLAND and Daya Bay data. The dotted, dashed and continuous lines represent respectively 90% C.L., 99% C.L. and 99.9% C.L.

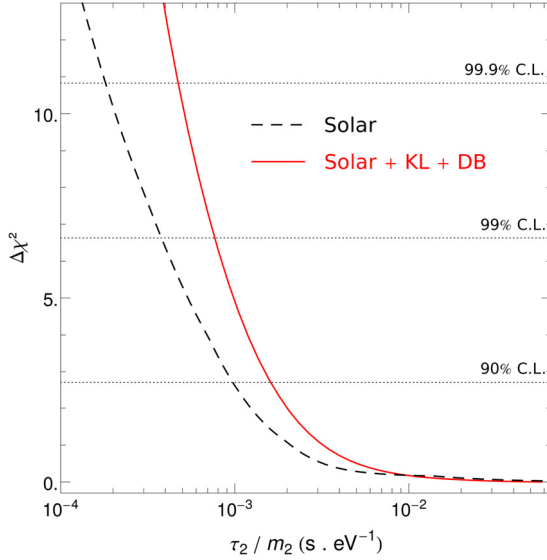


Fig. 2. $\Delta\chi^2$ for ν_2 lifetime τ_2/m_2 . The dashed (continuous) curve shows the solar (combined) neutrino data analysis.

where Δm_{ee}^2 was defined before and over which we can promptly marginalize the χ^2 . From Eq. (7), we find the allowed regions for independent parameters $\tan^2\theta_{12}$, $\sin^2\theta_{13}$, Δm_{21}^2 , and τ_2/m_2 . By marginalizing over the first two, we obtain the allowed region for the mass squared difference Δm_{21}^2 and the decay parameter τ_2/m_2 as shown in Fig. 1, where the hollow (filled) regions show the results for the solar neutrino (combined) analysis.

The degenerescence between Δm_{21}^2 and τ_2/m_2 is evident in the hollow regions of Fig. 1, where higher values for Δm_{21}^2 are allowed alongside lower values for τ_2/m_2 and lower values for Δm_{21}^2 are allowed alongside higher values for τ_2/m_2 .

High values of Δm_{21}^2 are ruled out in the standard neutrino scenario because it leads to spectral distortions that are disfavored by the solar neutrino data. On the other hand, high values of Δm_{21}^2 could become a viable solution at the cost of having lower values of τ_2/m_2 . The inclusion of KamLAND and Daya Bay data breaks this degenerescence due to their precise independent measurement of Δm_{21}^2 and $\sin^2\theta_{13}$ respectively.

We can now precisely isolate the contribution of the decay parameter τ_2/m_2 . The complete marginalization over the standard parameters results in the curve shown in Fig. 2 of $\Delta\chi^2$ as a function of τ_2/m_2 . From it, we can extract a lower limit to the ν_2 eigenstate lifetime

$$\tau_2/m_2 \geq 7.7 \times 10^{-4} \text{ s} \cdot \text{eV}^{-1}, \text{ at } 99\% \text{ C.L.}, \quad (8)$$

which corresponds to an upper bound to the decay parameter $\alpha_2 \leq 8.5 \times 10^{-13} \text{ eV}^2$.

4. Seasonal effect

One interesting consequence of the decay scenario that has not been discussed recently is its effect in the seasonal variation of solar neutrino flux. In the absence of decay, the neutrino flux arriving on Earth is given by $\phi_v^\oplus = \phi_v^\odot / (4\pi r^2)$, where $r = r(t)$ is the time-dependent Earth–Sun distance. The ratio between maximum (at perihelion) and minimum (at aphelion) fluxes is $R_0 = (1 + \epsilon_0)^2 / (1 - \epsilon_0)^2$, where $\epsilon_0 = 0.0167$ is the eccentricity of Earth's orbit.

The inclusion of decay modifies the ratio between maximum and minimum neutrino fluxes and hence also the measured eccentricity ϵ as given by

Table 1

Experimental best-fit values and errors for Earth's orbital eccentricity ϵ for different solar neutrino experiments. We also show the ratio between the fitted values and Earth's eccentricity ϵ_0 .

Experiment	$\epsilon_{\text{exp}} \pm \sigma_{\text{exp}}$	$(\epsilon_{\text{exp}} \pm \sigma_{\text{exp}}) / \epsilon_0$
Borexino [8]	0.0398 ± 0.0102	2.38 ± 0.61
SK-I [22]	0.0252 ± 0.0072	1.51 ± 0.43
SNO Phase I [23]	0.0143 ± 0.0086	0.86 ± 0.51

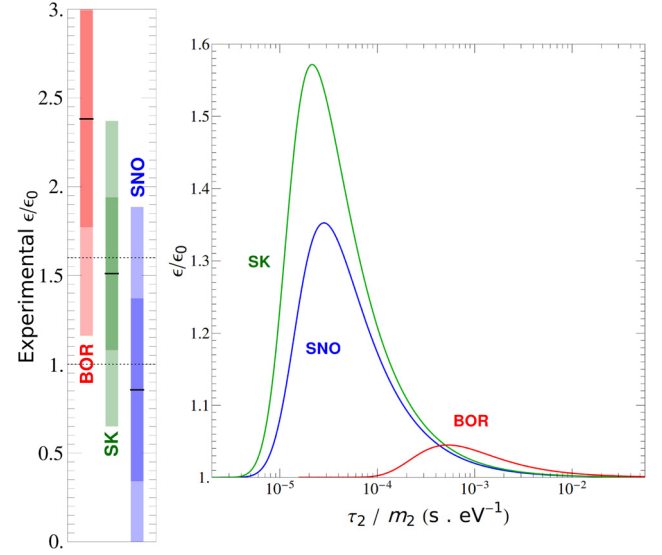


Fig. 3. Left: Experimental values for ϵ/ϵ_0 . Black lines are the best-fit values and darker (lighter) shades are the 1σ (2σ) ranges as shown in Table 1. Right: Dependence of the orbital eccentricity ϵ with the neutrino lifetime τ_2/m_2 as it would be measured by different experiments – the ^7Be line in Borexino (BOR), and the ^8B spectrum in Super-Kamiokande (SK) and SNO.

$$R = R_0 \frac{N(r_{\text{per}})}{N(r_{\text{aph}})} = \frac{(1 + \epsilon)^2}{(1 - \epsilon)^2}, \quad (9)$$

where r_{aph} (r_{per}) is the aphelion (perihelion) distance and N is the number of events calculated from the convolution of the adequate probabilities and cross sections for each experiment.

From Eq. (4) and Eq. (5), we know that $N(r_{\text{per}}) > N(r_{\text{aph}})$ holds also for the decay scenario due to P_2^{surv} dependence on the orbital distance. This implies that $R > R_0$ for all energies and thus, for any neutrino decay scenario, an enhancement in the seasonal variation of the solar neutrino flux would be expected.

Thus, the measurement of an eccentricity $\epsilon > \epsilon_0$ is a hint in the direction of the neutrino decay scenario. In fact, some experiments have measured Earth's orbital eccentricity to be different than the standard value albeit still compatible with ϵ_0 as shown in Table 1.

Fig. 3 shows the dependence of the neutrino eccentricity ϵ with the neutrino lifetime τ_2/m_2 as it would be measured by SuperKamiokande (SK), SNO and Borexino (BOR) experiments. As it can be seen, the higher energy ^8B solar neutrinos (measured by SK and SNO) would have a greater seasonal variation due to decay than the lower energy ^7Be solar neutrinos (measured by Borexino).

Due to the MSW effect, the ν_2 content in the neutrino flux leaving the Sun is energy dependent. At higher energies, there are more ν_2 neutrinos available for decay during the propagation to Earth. On the other hand, for lower energy neutrinos, there are fewer ν_2 leaving the sun and thus fewer ν_2 available for decay. For this reason, the seasonal variation for higher energy neutrinos would be bigger than for lower energy neutrinos and, consequently, also the measured eccentricity. Also from Fig. 3, it can be seen that due to the decay survival probability in Eq. (3), the lower (higher) the energy of the neutrinos, the bigger (smaller) is

the lifetime for which the enhancement in the eccentricity is maximum.

We can now include the eccentricity data in the analysis as a penalty function added to the χ^2 for each experiment: $\chi_{\text{seasonal}}^2 = (\epsilon_{\text{exp}} - \epsilon)^2 / (\sigma_{\text{exp}})^2$. The marginalization of the combined $\Delta\chi^2$ results in a slightly lower value

$$\tau_2 / m_2 \geq 7.2 \times 10^{-4} \text{ s.eV}^{-1}, \text{ at 99\% C.L.} \quad (10)$$

for the decay parameter. This is due to the fact that the seasonal variation data favor non-zero values for the lifetime while the solar data analysis favors a no-decay scenario. The combination of both samples results in the lower value for the neutrino lifetime.

5. Conclusion

We know that neutrinos oscillate with non-zero mass differences and mixing angles. *Can neutrinos decay?* The answer is negative from the combined analysis of data of solar neutrino experiments and KamLAND and Daya Bay data. From our analysis, we have obtained a new upper bound to the ν_2 eigenstate lifetime $\tau_2 / m_2 \geq 7.2 \times 10^{-4} \text{ s.eV}^{-1}$ at 99% C.L. which is almost one order higher than the previous established bound [1] at $\tau_2 / m_2 \geq 8.7 \times 10^{-5} \text{ s.eV}^{-1}$ at 99% C.L. Also, for comparison with Ref. [10], our result at 2σ is $\tau_2 / m_2 \geq 1.1 \times 10^{-3} \text{ s.eV}^{-1}$ which is a similar but more constrained result.

Also, we have shown how decay can enhance the seasonal variation of solar neutrino fluxes and how it affects the measurement of Earth's orbital eccentricity. Current data is not good enough to improve the constraints to neutrino lifetime. Although future experiments could certainly improve on the measurement of solar neutrino fluxes and thus better constrain neutrino lifetime, the analysis of existing data from later phases of, e.g., Super-Kamiokande and SNO for its seasonal variation could, in principle, already improve such constraints. We urge those experimental collaborations [22,23] to redo their analysis with more of the available data.

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