Can Neutrinos Decay?*

Renan Picoreti,† M. M. Guzzo, and P. C. de Holanda
Instituto de Física Gleb Wataghin - UNICAMP, 13083-859, Campinas SP, Brazil.

O. L. G. Peres
Instituto de Física Gleb Wataghin - UNICAMP,
13083-859, Campinas SP, Brazil. and
The Abdus Salam International Centre for Theoretical Physics,
Strada Costiera 11, 34014 Trieste, Italy.‡

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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 ν_2 lifetime $\tau_2 \,/\, m_2 \geq 7.2 \times 10^{-4}$ 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.

INTRODUCTION

The LMA-MSW solution for the Solar Neutrino Problem, in combination with the measurement of the other oscillation parameters by experiments designed for atmospheric, reactor and long-baseline neutrinos, established the scenario of three massive light neutrinos that mix [1]. With precise measurements of the standard oscillation parameters, it is possible to investigate new phenomena such as the neutrino decay scenario, $\nu' \to \nu + X$, as a sub-leading effect in the propagation of solar neutrinos and set limits to their lifetime using the most recent experimental data. For solar neutrinos, the current bound to ν_2 lifetime for invisible non-radiative decays [2] is $\tau_2/m_2 \geq 8.7 \times 10^{-5}$ s . eV^{-1} at 99% C.L..

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 solar matter, they travel across the interplanetary medium until they reach the Earth's surface where they can be detected.

For the current limits to their lifetime, neutrinos do not decay inside the Sun and it is sufficient to only consider their decay on the way to Earth. For the scenario in which all the final products are invisible, the decay survival probability of a neutrino mass-eigenstate i, with energy E_ν, after propagating a distance L, is

$$P_{\rm i}^{\rm surv} = \exp\left[-\left(\frac{\alpha_i}{E_\nu}\right) L\right] \text{ , with } \alpha_i = \frac{m_i}{\tau_i} \, , \qquad (1)$$

where m_i is the eigenstate's mass, τ_i is the eigenstate's 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

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

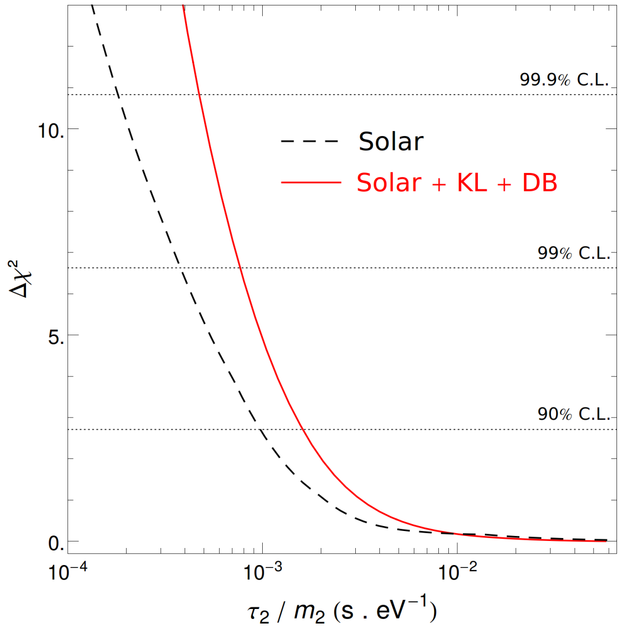

Figure 1: $\Delta\chi^2$ as a function of ν_2 lifetime τ_2/m_2. The continuous curve shows the results for the analysis using only solar data while the dashed curve shows results for the combined data analysis.

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$, $P_{\rm i}^{\rm surv}$ is given in Eq. (1), $P_{ei}^{\odot}$ is the probability of the produced ν_e to be found as a ν_i at the surface of the Sun, and $P_{i\alpha}^{\oplus}$ is the probability of a ν_i to be detected as a ν_α on Earth.

In this scenario, one interesting point is that the sum over all probabilities is not equal to 1, as explicitly we have $\sum_{\alpha=e,\mu,\tau} P(\nu_e \to \nu_\alpha) = 1 - c_{13}^2\, P_{e2}^{\odot}\, (1 - P_2^{\rm surv})$. This non-unitary evolution was discussed in Ref. [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 numerically calculate the neutrino survival probabilities under the assumption of adiabatic evolution inside the Sun [4]. Then, we compute the expected event rate for each relevant experiment and compare it to their data [5–10].

We can add complementary information from the reactor experiments KamLAND [11] and Daya Bay [12] and their detection of $\bar{\nu}_e$ oscillations. These reactor experiments give precise constraints on Δm_{21}^2 and $\sin^2\theta_{13}$ and for their typical baselines, and the currently allowed values of τ_2/m_2, decay can be neglected and their standard neutrino analysis can also be used for decay scenario.

We write a combined χ^2 function for solar, KamLAND and Daya Bay data and from the complete marginalization over the standard parameters, we can extract a lower limit to the ν_2 eigenstate lifetime $\tau_2\,/\,m_2 \geq 7.7 \times 10^{-4}$ s . eV^{-1}, at 99% C.L., as shown in Fig. 1 for $\Delta\chi^2$ as a function of τ_2/m_2.

Experiment	$(\epsilon_{\rm exp} \pm \sigma_{exp})/\epsilon_0$
Borexino [13]	2.38 ± 0.61
SuperK-I [14]	1.51 ± 0.43
SNO Phase I [15]	0.86 ± 0.51

Table I: 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 the Earth's eccentricity ϵ_0.

SEASONAL EFFECT

In the absence of decay, the neutrino flux arriving on Earth is given by $\phi_\nu^\oplus = \phi_\nu^\odot/(4\pi r^2)$, where r is the time-dependent Earth-Sun distance. The ratio between maximum (perihelion) and minimum (aphelion) fluxes is $R_0 = (1+\epsilon_0)^2/(1-\epsilon_0)^2$, where $\epsilon_0 = 0.0167$ is Earth's orbital eccentricity. Decay modifies the ratio between maximum and minimum neutrino fluxes and hence also the eccentricity ϵ measured from the neutrino data as given by

$$R = R_0 \frac{N(r_{\rm min})}{N(r_{\rm max})} = \frac{(1+\epsilon)^2}{(1-\epsilon)^2}\,, \tag{3}$$

where $r_{\rm max}(r_{\rm min})$ is the aphelion (perihelion) distance and N is the number of events calculated from the adequate probabilities and cross sections for each experiment. Since $N(r_{\rm min}) > N(r_{\rm max})$ due to $P_2^{\rm surv}$ dependence on the orbital distance, $R > R_0$ for any neutrino energy and thus, for any neutrino decay scenario, an enhancement in the seasonal variation of the solar neutrino flux is to be expected, which in turn would lead to $\epsilon > \epsilon_0$.

In fact, some experiments have measured an eccentricity different from the standard value, albeit still compatible with ϵ_0, as shown in Table (I). The eccentricity measured with neutrinos ϵ as it would be measured by different experiments as a function of the neutrino

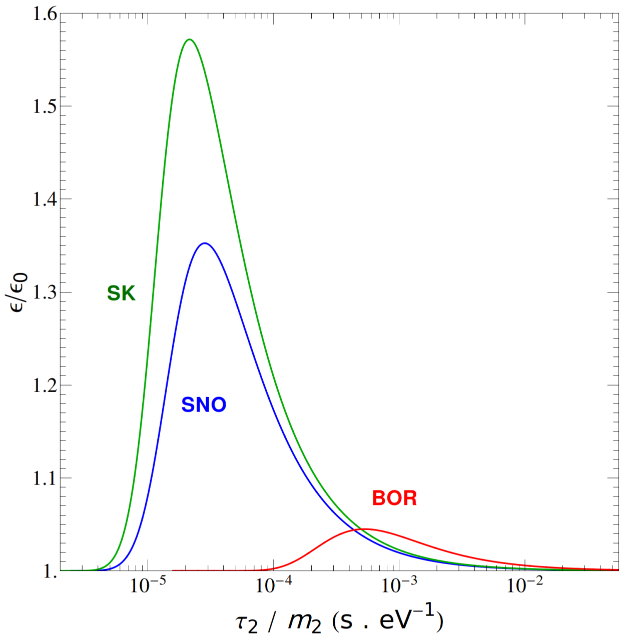

Figure 2: Dependence of the orbital eccentricity ϵ with the neutrino lifetime τ_2/m_2 as it would be measured by different experiments — the ^{7}Be line in Borexino (BOR), Super-Kamiokande (SK), and Sudbury Neutrino Observatory (SNO).

lifetime τ_2/m_2 is shown in Fig. 2.

Including the eccentricity data in the analysis with a penalty function added to the χ^2 for each experiment $\chi^2_{\text{seasonal}} = (\epsilon_{\text{exp}} - \epsilon)^2/(\sigma_{\text{exp}})^2$ results in a slightly lower value

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

due to the fact that the current eccentricity measurements and errors will favor lower, already excluded, lifetimes, for which the enhancement in the seasonal variation (and hence measured eccentricity) is higher.

CONCLUSION

From our analysis, we have obtained a new upper bound to the ν_2 eigenstate lifetime $\tau_2 \,/\, m_2 \geq 7.2 \times 10^{-4}\ \text{s}\,.\,\text{eV}^{-1}$ at 99% C.L.. which is almost one order higher than the previous established bound [2] at $\tau_2/m_2 \geq 8.7 \times 10^{-5}\ \text{s}\,.\,\text{eV}^{-1}$ at 99% C.L..

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† `picoreti@ifi.unicamp.br`

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