Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 908 (2016) 408–422

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

Quantum dissipation in a neutrino system propagating in vacuum and in matter

Marcelo M. Guzzo [a], Pedro C. de Holanda [a], Roberto L.N. Oliveira [a,b,*]

[a] *Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, UNICAMP 13083-970, Campinas, São Paulo, Brazil*

[b] *Northwestern University, Department of Physics & Astronomy, 2145 Sheridan Road, Evanston, IL 60208, USA*

Received 22 December 2015; received in revised form 15 April 2016; accepted 16 April 2016

Available online 22 April 2016

Editor: Tommy Ohlsson

Abstract

Considering the neutrino state like an open quantum system, we analyze its propagation in vacuum or in matter. After defining what can be called decoherence and relaxation effects, we show that in general the probabilities in vacuum and in constant matter can be written in a similar way, which is not an obvious result for such system. From this result, we analyze the situation where neutrino evolution satisfies the adiabatic limit and use this formalism to study solar neutrinos. We show that the decoherence effect may not be bounded by the solar neutrino data and review some results in the literature, in particular the current results where solar neutrinos were used to put bounds on decoherence effects through a model-dependent approach. We conclude explaining how and why these models are not general and we reinterpret these constraints.

1. Introduction

We present a study on dissipative effects on neutrino evolution, such as the decoherence and relaxation effects, and their consequences in neutrino oscillations. These effects are obtained when we consider neutrinos as an open quantum system [1–3]. In this approach, neutrinos are

* Corresponding author.
E-mail address: robertol@ifi.unicamp.br (R.L.N. Oliveira).

http://dx.doi.org/10.1016/j.nuclphysb.2016.04.030

considered as a subsystem that is free to interact with the environment that presents a reservoir behavior.[1]

The decoherence effect is the most usual dissipative effect. In the neutrino oscillation phenomenon, the decoherence effect acts only on the quantum interference, dynamically eliminating the oscillating terms in oscillation probabilities. This feature has been investigated in a number of previous studies [7–14].

The relaxation effect acts in a different way and it does not affect the oscillating terms. It changes only the pure mixing terms in the probabilities, leading all averaged conversion probabilities to $1/n$, where n is the number of neutrino families. Then, the relaxation effect can change the probability behavior even when the oscillation terms are not important, like the solar neutrino case [3]. The relaxation effect can be confused with the decoherence effect and this can occur in those particular cases where quantum coherence is averaged out in neutrino oscillations. In Ref. [11], the authors analyzed quantum decoherence effect with solar and KamLAND neutrinos. However, for solar neutrinos the decoherence effect could be investigated only using a model-dependent approach, because in general, the quantum coherence is averaged out for solar neutrinos and just relaxation effects can be investigated.

There are some experimental bounds on dissipative effects and we will compare some concrete bounds obtained from some experimental data analyses found in the literature. All these limits were obtained for neutrino propagation in vacuum and in two neutrino approximation. For example, in Ref. [14], the analysis was made considering MINOS experiment. There, the decoherence parameter has a superior limit given by $\gamma < 9.11 \times 10^{-23}$ GeV at 95% C.L. and this result agrees with the upper limit found in Ref. [8] where $\gamma < 4.10 \times 10^{-23}$ GeV at 95% C.L., which was obtained for atmospheric neutrino case.

A very interesting upper limit was introduced by Ref. [11] obtained in a model-dependent approach that constrain decoherence effect using solar neutrinos. It was obtained that decoherence parameter is limited to $\gamma < 0.64 \times 10^{-24}$ GeV at 95% C.L. As it is known, the matter effect is important in this case, and we will address this issue later on this article. In [16] an analysis using only reactor neutrinos found different bounds on the decoherence effect, $\gamma < 6.8 \times 10^{-22}$ eV at 95% at C.L. All bounds presented above can be found in Table 1.[2]

In general, bounds on dissipative parameters come from $e^{-\gamma x} \lesssim 1$ since this is the kind of damping terms which appear in the oscillation probabilities. This can be checked to work reasonably well for all the limits presented above, with terrestrial experiments with a typical baseline $x = 10^{20} \sim 10^{22}$ GeV^{-1} ($20 \sim 2000$ km).

However for the numbers presented in [11], using the bound found for $\gamma < 0.64 \times 10^{-24}$ GeV, the exponential term tends strongly to 1. As it will be clear in this work, the model-dependent approach used in Ref. [11] also constrains the relaxation effect with $\gamma_{relax.} < 10^{-25}$ GeV at 95% C.L. For solar-neutrinos $x = 10^{26}$ GeV^{-1}, and the exponential term in this case makes the sur-

[1] Some possible sources of violations of quantum mechanics fundamentals include the spontaneous evolution of pure states into mixed decoherent states [4] induced by interactions with the space–time at Planck scale [5] which unavoidly appear in any formulation of a quantum gravity theory. Such sources of decoherence was first analyzed in Ref. [6] which considered oscillating systems propagating over large distances and the corresponding damping effects in the usual interferometric pattern characterizing the oscillation phenomenon.

[2] Following the arguments of the present article, decoherence effect can be described by one parameter and relaxation effect by another parameter. However, in the case of three neutrino oscillation there are three different decoherence parameters and two different relaxation parameters. As we can see in Ref. [15], the decoherence parameters describe the quantum effect between specific families and then, the decoherence bound for accelerator or atmospheric neutrinos can be different from the one for reactor neutrinos.