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Nuclear Physics B 908 (2016) 382–407

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

Another look at synchronized neutrino oscillations

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Received 31 January 2016; received in revised form 10 February 2016; accepted 11 February 2016

Available online 17 February 2016

Editor: Tommy Ohlsson

Abstract

In dense neutrino backgrounds present in supernovae and in the early Universe neutrino oscillations may exhibit complex collective phenomena, such as synchronized oscillations, bipolar oscillations and spectral splits and swaps. We consider in detail possible decoherence effects on the simplest of these phenomena – synchronized neutrino oscillations that can occur in a uniform and isotropic neutrino gas. We develop an exact formalism of spectral moments of the flavour spin vectors describing such a system and then apply it to find analytical approaches that allow one to study decoherence effects on its late-time evolution. This turns out to be possible in part due to the existence of the (previously unknown) exact conservation law satisfied by the quantities describing the considered neutrino system. Interpretation of the decoherence effects in terms of neutrino wave packet separation is also given, both in the adiabatic and non-adiabatic regimes of neutrino flavour evolution.

1. Introduction

It is well known that neutrino oscillations in dense neutrino backgrounds existing at certain stages of supernova explosion and in the early Universe may differ drastically from the

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http://dx.doi.org/10.1016/j.nuclphysb.2016.02.011

oscillations in ordinary matter or in vacuum. In particular, synchronized oscillations [1–8], bipolar oscillations [5,9–14], spectral splits and swaps [11,15–17] and multiple spectral splits [18] are possible. These phenomena have attracted a great deal of attention recently, see Refs. [19,20] for reviews and extensive lists of literature.

The simplest system that exhibits collective neutrino oscillations is a dense uniform and isotropic gas consisting of only neutrinos (or only antineutrinos). In such a system, for sufficiently large neutrino density, neutrinos of different energies oscillate with the same frequency (i.e. undergo synchronized oscillations), and therefore even for wide neutrino spectra the oscillations do not average out with time. This is in sharp contrast with what is expected in the case of neutrino oscillations in vacuum, in usual matter or in low-density neutrino backgrounds. In particular, in vacuum neutrinos of different energies oscillate with different frequencies and over the time develop large phase differences, leading to decoherence and averaging out of the oscillations. On the other hand, synchronized neutrino oscillations in a dense neutrino gas mean that no decoherence occurs (or at least that some degree of coherence is maintained) in such a system, since complete decoherence would destroy the synchronization.

In this paper we explore late-time decoherence effects on collective neutrino oscillations. To this end, we concentrate on the simplest possible system where collective oscillations can take place – a uniform and isotropic neutrino gas. Decoherence of neutrino oscillations can be described either in momentum space or in coordinate space. In the momentum space it comes from the dephasing of different neutrino modes at late times and is related to the integration over the neutrino spectrum. In the coordinate space decoherence is related to the spatial separation of the wave packets of different neutrino propagation eigenstates after they have traveled long enough distance. The momentum-space and coordinate-space descriptions are equivalent (see, e.g., [21]).

Since in supernovae and in the early Universe neutrinos are produced at very high densities, their production processes are well localized in space and time and therefore their wave packets are very short in coordinate space [22–24]. As a result, one could expect decoherence by wave packet separation to occur rather quickly and to affect significantly collective neutrino oscillations. In particular, this would destroy synchronized neutrino oscillations at sufficiently late times. Numerical calculations show, however, no trace of such decoherence when the density of the neutrino gas is high enough. One of the main goals of the present study was therefore to understand why no decoherence (and therefore no de-synchronization) occurs in high-density neutrino gases, and how in general coherence and decoherence are related to the synchronization of neutrino oscillations or lack thereof. Our study is in a sense complementary to that in [4] where the possibility for a neutrino system to develop a spontaneous synchronization starting with a completely incoherent initial state was considered.

The paper is organized as follows. In Section 2 we review the standard flavour spin formalism which is especially well suited for describing neutrino oscillations and flavour conversions in dense neutrino backgrounds. We also discuss the conservation law for a quantity $\mathcal{E}$ which can be interpreted as the total energy of self-interacting magnetic moments in an external magnetic field. This section mainly serves to introduce our framework and notation. Sections 3–5 contain our new results. In Section 3 we develop a formalism of spectral moments $\vec{K}_n$ describing a homogeneous and isotropic gas of neutrinos or neutrinos and antineutrinos. We derive equations of motion for these quantities and relations between the time derivatives of $\vec{K}_n$ and $\vec{K}_{n+1}$. We also establish a new conservation law for this neutrino system, not previously known in the literature. In Section 4 we develop two approximate analytical approaches for describing decoherence effects on synchronized neutrino oscillations. They are based on the formalism of Section 3 aug-