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Effects of non-standard neutrino–electron interactions on relic neutrino decoupling

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Abstract

We consider the decoupling of neutrinos in the early Universe in presence of non-standard neutral current neutrino–electron interactions (NSI). We first discuss a semi-analytical approach to solve the relevant kinetic equations and then present the results of fully numerical and momentum-dependent calculations, including flavor neutrino oscillations. We present our results in terms of both the effective number of neutrino species (N_{eff}) and the impact on the abundance of ^{4}He produced during big bang nucleosynthesis. We find that the presence of neutrino–electron NSI may enhance the entropy transfer from electron–positron pairs into neutrinos instead of photons, up to a value of $N_{\mathrm{eff}} \simeq 3.12$ for NSI parameters within the ranges allowed by present laboratory data, which is almost three times the effect that appears for standard weak interactions. Thus non-standard neutrino–electron interactions do not essentially modify the density of relic neutrinos nor the bounds on neutrino properties from cosmological observables, such as their mass.

Keywords: Early Universe; Neutrinos; Non-equilibrium kinetics

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1. Introduction

In the early Universe, neutrinos were kept in thermal contact with the electromagnetic primordial plasma by rapid weak interactions with electrons and positrons. When the temperature dropped below a few MeV, these weak processes became ineffective and the process of neutrino decoupling took place, while shortly after the $e^{\pm}$ pairs began to annihilate almost entirely into photons thus producing a difference between the temperatures of the relic photons and neutrinos. This difference can be easily calculated if we assume that neutrinos were completely decoupled when the $e^{\pm}$ pairs transferred their entropy to photons, leading to the well-known temperature ratio $T_\gamma/T_\nu = (11/4)^{1/3} \simeq 1.40102$. Indeed, this simplified picture should be improved since some relic interactions between $e^{\pm}$ and neutrinos exist all along the $e^{\pm}$ annihilation stage, leading to a slightly smaller increase of the comoving photon temperature and to small distortions (at the percent level) of the neutrino momentum distributions.

Presently, there exist compelling evidences for flavor neutrino oscillations from a variety of experimental data on solar, atmospheric, reactor and accelerator neutrinos (see e.g. [1,2]). These results are well understood by assuming that neutrinos have masses and mix, which in turn seems to point out the necessity of some new physics beyond the Standard Model (SM) of fundamental interactions. Interestingly, non-zero neutrino masses usually come with non-standard interactions (NSI) that might violate leptonic flavor and/or break weak universality. Recent analyses [3–6] have considered the neutral current NSI in a phenomenological way, showing that they can be bound using measurements of neutrino–electron scattering, as well as data from LEP and from related charged lepton processes.

The aim of this paper is to study the neutrino decoupling process in presence of additional interactions between neutrinos and electrons, a possibility already noted in [3,5]. In this case, neutrinos could be kept in longer contact with $e^{\pm}$ and thus share a larger amount of the total entropy transfer than in the SM. Actually, if the non-standard neutrino–electron interactions were large enough, the neutrino momentum distribution would be significantly different from the standard case. In turn, this would modify the final yield of light nuclei during the epoch of big bang nucleosynthesis (BBN), as well as the radiation content of the Universe, affecting the anisotropies of the cosmic microwave background (CMB) and the power spectrum of large scale structures (LSS). Our goal is to calculate how the decoupling is modified taking into account NSI with couplings which are still allowed by present laboratory data, and to discuss the possibility that cosmological observations can be used as a complementary way to bound these exotic scenarios.

The paper is organized as follows. We begin in Section 2 by describing the formalism adopted for the non-standard electron–neutrino interactions and summarize the current bounds from a variety of experimental data. We then consider the process of relic neutrino decoupling in the presence of non-standard electron–neutrino interactions, giving first an estimate by using a semi-analytical approach in Section 3. Finally, in Section 4 we report the results of the full momentum-dependent numerical calculations for the neutrino spectra and the effect on the primordial ^{4}He yield and other cosmological observables. We present our conclusions in Section 5.

2. Non-standard neutrino–electron interactions

The long-standing evidence of flavor change in atmospheric and solar neutrino experiments represents a strong indication of some new physics beyond the SM of fundamental interactions. For several years these experimental results have been interpreted in terms of neutrino masses