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Title: Sterile neutrinos in the early Universe

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Summary

Although the Standard Model (SM) of elementary particles successfully describes the Universe up to the smallest known scales, we know that there exists a number of observational phenomena, which do not find explanation in the framework of this theory. Among these problems are Neutrino Oscillations, Dark Matter and the Baryon Asymmetry of the Universe.

In this thesis, we are studying the Neutrino Minimal Standard Model (νMSM), a minimalistic extension of the Standard Model, which can explain all the three above mentioned Beyond the Standard Model (BSM) phenomena simultaneously, by adding only three right-handed neutrinos N_1, N_2, and N_3, to the known three left-handed neutrinos. This way the symmetry between left and right particles, which is absent in the Standard Model, is established. At the same time, the masses of the right-handed neutrinos in the νMSM are chosen to be below 100 GeV, so that no new high energy scale is added to the Standard Model.

Although these new particles interact very weakly with ordinary matter, they nevertheless have a significant impact on the Universe today, for the following reason. Although the probability for an individual sterile neutrino to interact with any Standard-Model particle is suppressed (with respect to the interactions of the SM particles among themselves), once we go back in time to the epoch of the hot and dense early Universe, the total number of the SM particles encountered on the trajectory of the sterile neutrino is so large that the total probability of a sterile neutrino to interact becomes significant. As a result, sterile neutrinos can be produced in large numbers and affect the rest of the Universe. In particular, the two heavier particles of the νMSM, N_2 and N_3, produce the Baryon and Lepton Asymmetry of the Universe, and the remaining particle N_1 plays the role of the Dark Matter particle, and constitutes most of the gravitating matter in the present Universe.

The νMSM has a great potential for discovery, since the two heavier particles N_2 and N_3 can be produced directly in accelerator experiments, like the planned experiment SHiP (Search for Hidden Particles) at CERN. On the other hand, the Dark Matter particle N_1 decays and produces a monochromatic X-ray line in the Dark Matter dominated regions, and this specific signal can be discovered in astrophysical observations.

In this thesis, we show that sterile neutrinos N_2 and N_3 with masses below 140 MeV (mass of π-meson), which explain Neutrino Oscillations via the see-saw mechanism, could have been present in such large amounts in the early Universe that they spoil the otherwise excellent agreement between the Standard-Model prediction of light nuclei production during the Big-Bang Nucleosynthesis and the astrophysical observations. In this way, masses of sterile neutrinos are excluded from below, which reduces the potentially interesting parameter space for future accelerator searches.

Although N_2 and N_3 describe the BSM phenomena, which are apparently not related to Dark Matter, in the νMSM the properties of the Dark Matter particle N_1 *are* affected by N_2 and N_3. Namely, in order to produce the observed abundance of Dark Matter and simultaneously to satisfy the astrophysical bounds, lepton asymmetry should be present in the Universe at relatively low temperatures (below 1 GeV). The value of this asymmetry at higher temperatures is governed by the dynamics of N_2 and N_3. However, as it is argued in this thesis, this dynamics is able to trigger the production of large-scale magnetic fields due to the so-called Chiral Magnetic Effect (CME).

The CME manifests itself in two ways. First, it appears whenever left- and right-handed particles are populated asymmetrically. Fermion mass m is important for the νMSM, since we are interested in large scales of the magnetic field, $q \ll m$, where q is a typical wavenumber of the magnetic field. In this thesis, we demonstrate that CME is present in this case as well, therefore it should be included in the description of the νMSM dynamics in the early Universe. CME is essentially a non-equilibrium effect, since the state with asymmetric population relaxes to a symmetric state due to the presence of (slow) processes that change the number of left- and right-handed particles. In this relaxed state, the CME is still expected to manifest itself, provided that lepton asymmetry is present, since the numbers of left- and right-handed particles are different due to the presence of parity-violating (weak) interactions in the Standard Model. In this way, the ground state of plasma is expected to be shifted, and populated by large-scale magnetic fields. In this thesis it is shown, however, that the systematic account of different contributions of weak interactions implies that they all cancel each other, and the shift of the ground state actually does not happen.

As a conclusion, in order to understand the evolution of lepton asymmetry at lower temperatures, and predict the abundance of Dark Matter consistently, and thus to reduce the parameter space of the νMSM, the Chiral Magnetic Effect should be included in the description of the Universe, together with the Maxwell equations for the electromagnetic field and equation for chiral asymmetry. Magnetic fields and electric currents lead to the excitation of macroscopic matter flows, turbulence may appear, and this system should be considered by a set of correct magnetohydrodynamical equations, which take into account chiral asymmetry. This is the work for future studies.