νMSM and its experimental tests

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Abstract. νMSM is a minimal renormalizable extension of the Standard Model by right handed neutrinos. This model explains the neutrino oscillations and provides a candidate for the Dark Matter and a mechanism of baryon number generation in the Early Universe. We discuss here existing constraints on the model and possible consequences for astrophysical and laboratory experiments.

Introduction. Extension of the Standard Model (SM) is inevitable. Current evidences include neutrino oscillations and existence of large amount of the Dark Matter in the Universe.

Here we shall describe a minimal extension of the SM which explains these effects. This extension is not addressing the hierarchy problem or other naturalness issues. Let us note, that aside from a certain amount of fine tuning, the SM is logically consistent [1], so it is really needed only to explain these new experimental facts.

The model we adopt was introduced in [2, 3]. It adds the singlet leptons to the SM with the mass scale below the electroweak scale (O(1) keV − O(1) GeV), so one may expect that experimental investigation is viable. We will discuss possible astrophysical and laboratory experimental checks of the model.

The νMSM model and its predictions. The νMSM adds three singlet right-handed neutrinos $N_I$ to the SM in the most general renormalizable way

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{SM}} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \overline{L}_\alpha N_I \overline{\Phi} - \frac{M_I}{2} \overline{N}_I^2 N_I + \text{h.c. },$$

where $\overline{\Phi} = \epsilon^{ab} \Phi^*_b$ is the Higgs doublet, $L_\alpha$ are the left-handed lepton doublets ($\alpha = e, \mu, \tau$). New coupling constants present in this Lagrangian are the Yukawa couplings $F_{\alpha I}$ (giving rise to the Dirac masses for the neutrinos $M^D = F(\Phi)$) and the Majorana masses $M_I$. This gives 18 new parameters, which are 3 Majorana masses, 3 Dirac masses, 6 mixing angles and 6 CP-violating phases.

This Lagrangian is the same that is used in the ordinary seesaw models to explain small neutrino masses [4, 5] and leads to the active neutrino mass matrix of the form $m^\nu = (M^D)^T M_I^{-1} M^D$ and active-sterile neutrino mixing angles $\theta = (M^D)^T M_I^{-1} \ll 1$. However, it is not supposed that the Majorana mass scale coincides with the grand unification scale [1]. The typical mass spectrum of the νMSM is given in the Fig. 1. It is important to note, that while any mixing angles and mass splittings observed in the active neutrino sector can be
reproduced, the cosmological requirements together with astrophysical constraints and observed neutrino oscillation pattern fixes the absolute scale of the active neutrino masses, predicting the hierarchical spectrum.

Dark matter and astrophysical constraints. The sterile neutrino $N_1$ with the mass $M_1 < 1$ MeV decays mainly into three active neutrinos ($2\nu\bar{\nu}$ or $2\bar{\nu}\nu$) by Z boson exchange, with the life time $\tau_{N_1} = 5 \times 10^{26} \left(\frac{1\text{keV}}{M_1}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)$. For mixing angle $\theta^2 \simeq 10^{-8}$ and $M_1 \simeq 1 \div 10$ keV we get the life time much larger than the age of the Universe. Such neutrino may play a role of the Warm Dark Matter (WDM) particle.

The mass of the WDM particle is natural to choose of the order of $O(10)$ keV. This range is favourable to solve the problem of missing satellite galaxies and cuspy profiles in the Cold Dark Matter scenarios [6, 7, 8, 9]. Low mass is also favoured by the thermal production mechanism via active-sterile oscillations [10]. However, there is really no upper bound if the DM neutrino mass is produced by other mechanisms [11, 12, 13]. There is an astrophysical lower bound of 0.3 keV [14, 15, 16] and a stronger (but model dependent) bound from Lyman-$\alpha$ observations $M_1 > 10 \div 14$ keV $\left(\frac{\langle p_s\rangle}{\langle p_a\rangle}\right)$, where $\langle p_s\rangle$ and $\langle p_a\rangle$ are the average momenta of the sterile and active neutrinos [17, 18, 19, 20].

Another major constraint [21] is provided by the observation of the photons from the radiative decay $N_1 \to \nu\gamma$ with the width $\Gamma(N_1 \to \nu + \gamma) = 1.38 \times 10^{-22} \sin^2(2\theta) \left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$. Thus, the dark matter halos should emit the gamma rays with the energy $E = M_1/2$. The resulting constraint is presented in Fig. 2. This constraint, immediately leads to the conclusion that the lightest active neutrino mass is extremely small, about $10^{-5}$ eV or smaller.

At present X-ray observations provide the strongest constraint on the $\nu$MSM. The discussion of the sensitivity of the future Space missions can be found in [22].

**Neutrinoless double beta decay.** As far as the $\nu$MSM provides neutrinos with Majorana masses, the neutrinoless double beta decay is possible. The contribution of the DM neutrino $N_1$ to the rate of the decay is negligible [23], so the prediction for the effective Majorana mass $m_{\beta\beta}$ for neutrinoless double beta decay coincides with the usual 3 neutrino analysis [24] with strictly
Figure 3. Limits on the mixing angles $U_\alpha = M_{\alpha}^{D2}/M_{2,3}$ for the sterile neutrinos $N_{2,3}$ from the BBN and direct experimental search. The currently allowed region is white [30].

Hierarchical spectrum, i.e. $1.3 \text{ meV} < m_{N^{NH}} < 3.4 \text{ meV}$ in normal neutrino mass hierarchy and $13 \text{ meV} < m_{N^{IH}} < 50 \text{ meV}$ in inverted hierarchy. In particular, this means that discovery of the double beta decay at the rate corresponding to $m_{\beta\beta} > 50 \text{ meV}$ would definitely contradict the $\nu$MSM model.

One should note, however, that $m_{\beta\beta} < 13 \text{ meV}$ or $< 1.3 \text{ meV}$ can be explained in the framework of some modifications of the $\nu$MSM, that is the model with large entropy release [25] or with relatively light $N_{1,2} \lesssim 100 \text{ MeV}$ [26].

**Kinematic study of beta decays.** Previous two methods provide only indirect clues for the $\nu$MSM. It is hard to overestimate the importance of a direct experimental evidence for the sterile neutrinos. However, experiments with creation and subsequent detection of the DM neutrino in $\nu$MSM are rendered impossible by extremely low allowed values of the mixing angle, see Fig. 2. The only possibility left for laboratory experiments is detailed kinematic study of the processes creating $N_1$. Measuring the momenta of all initial and final particles in nuclear beta decay, except neutrino, allows to determine the neutrino mass in each single event [27]. Experimental techniques based on time of flight measurements that allow to determine recoil energy of the ion are being currently used in experiments in atomic physics [28, 29]. In such experiments the precision of momenta measurements reaches 0.2 keV, which is sufficient to distinguish between sterile and active neutrinos.

Detailed study of such experiments is needed, which addresses the problem of density of the source of the cold atoms (extremely high statistics is needed) and the background from bremsstrahlung emission of keV photons.

**Heavy sterile neutrinos in the long base line experiments.** Other two sterile neutrinos $N_{1,2}$ can be used to generate the baryon asymmetry of the universe [3]. It proceeds via resonant generation of the lepton number in the sterile neutrino sector which is then transferred to active neutrino sector and converted to baryon asymmetry via B+L violating electroweak sphaleron transitions.

This mechanism requires that $N_{1,2}$ are very degenerate in mass and that their Yukawa couplings are small enough so that they do not thermalize before freeze-out of the sphaleron transitions (otherwise the generated asymmetry is washed out). Certain amount of CP violation in the mixing matrix of the sterile neutrinos is also required, but it seems to have no sizable
observational effect for laboratory experiments.

The mixing angles for $N_{1,2}$ have also the lower bound from the requirement that they decay before the Big Bang nucleosynthesis (BBN), otherwise they would change the abundances of light elements in the Universe. This bound is quite close to the direct experimental limits on sterile neutrinos with masses below the kaon mass. And sterile neutrinos $N_{1,2}$ with masses below the pion mass are already excluded. The experimental signature in such experiments is appearance of $e^+e^-$ or $\mu^+\mu^-$ pairs from the decay of the heavy sterile neutrino which is created in the decay of a charged kaon in a beam dump. Existing limits from CERN PS191 experiment are given in Fig. 3. Further searches look promising and can be performed together with long baseline neutrino oscillation experiments [30].

As a summary, the $\nu$MSM model provides explanation to neutrino oscillations, DM and baryon asymmetry of the Universe. At the same time it has nontrivial experimental consequences, which can be checked in future astrophysical and laboratory accelerator experiments.

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