PROCEEDINGS OF SCIENCE

Kaon physics within νMSM[*]

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In a search for physics beyond the Standard Model (SM) one can use different types of guidelines. A possible strategy is to attempt to explain the phenomena that cannot be fit to the SM by minimal means, that is by introducing the smallest possible number of new particles without adding any new physical principles (such as supersymmetry or extra dimensions) or new energy scales (like the Grand Unified scale). An example of such a theory is the renormalizable extension of the SM, the νMSM (neutrino Minimal Standard Model) [2, 3], where three *light* singlet right-handed fermions (sterile neutrinos) are introduced. The leptonic sector of the theory has the same structure as the quark sector, i.e. every left-handed fermion has its right-handed counterpart. This model is consistent with the data on neutrino oscillations, provides a candidate for dark matter particle – the lightest singlet fermion (sterile neutrino), and can explain the baryon asymmetry of the Universe [3]. A crucial feature of this theory is the relatively small mass scale of the new neutral leptonic states, which opens a possibility for a direct search of these particles.

We discuss here the properties of neutral leptons in this model and the ways they can be searched for in particle physics experiments. In particular, if sterile neutrinos are lighter than kaons, they can be produced in leptonic and semileptonic kaon decays with branching ratios only one-two orders of magnitude below the current experimental limits from direct searches. This gives a unique possibility to either prove or rule out νMSM with light sterile neutrinos.

KAON International Conference
May 21-25 2007
Laboratori Nazionali di Frascati dell'INFN, Rome, Italy

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[*] The main results presented in this talk are obtained in Ref. [1], where details and relevant references can be found.
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1. The description of νMSM

The Lagrangian of the model can be written as [5]:

$$\mathscr{L}_{\nu\mathrm{MSM}} = \mathscr{L}_{\mathrm{SM}} + \bar{\widetilde{N}}_I i\partial_\mu \gamma^\mu \widetilde{N}_I - F_{\alpha I}\bar{L}_\alpha \widetilde{N}_I \widetilde{\Phi} - M\bar{\widetilde{N}}_2^{\,c} \widetilde{N}_3 - \frac{\Delta M_{IJ}}{2}\bar{\widetilde{N}}_I^{\,c} \widetilde{N}_J + \mathrm{h.c.}\,,$$

where $\widetilde{N}_I$ are the right-handed singlet leptons (we keep the notation without tilde for mass eigenstates), $\widetilde{\Phi}_i = \varepsilon_{ij}\Phi_j^*$, Φ and L_α ($\alpha = e, \mu, \tau$) are the Higgs and lepton doublets, F is a matrix of Yukawa couplings, M is the common mass of two heavy neutral fermions, ΔM_{IJ} are related to the mass of the lightest sterile neutrino N_1 responsible for Dark Matter (DM) and produce the small splitting of the masses of N_2 and N_3, $\Delta M_{IJ} \ll M$.

The νMSM contains 18 new parameters: 3 Majorana masses for singlet fermions, 3 Dirac masses associated with mixing between left-handed and right-handed neutrinos, 6 mixing angles and 6 CP-violating phases. These parameters can describe any pattern (and in particular the observed one) of masses and mixings of active neutrinos, which is characterized by 9 parameters only. The choice of the small M leads to the small values of the Yukawa coupling constants, at the level $10^{-6} - 10^{-12}$, which is crucial for explanation of DM and baryon asymmetry of the Universe.

The lightest singlet fermion N_1 may have a lifetime greatly exceeding the age of the Universe and thus plays a role of a DM particle. DM sterile neutrino is likely to have a mass in the $\mathscr{O}(10)$ keV region. The arguments leading to the keV mass for DM neutrino are related to structure formation and to the problems of missing satellites and cuspy profiles in the Cold Dark Matter cosmological models; the keV scale is also favoured by the consideration of DM production via active-sterile neutrino transitions; Warm DM may help to solve the problem of galactic angular momentum.

The baryon (B) and lepton (L) numbers are not conserved in νMSM: L is violated by Majorana neutrino masses, while B + L is broken by the electroweak anomaly; the sphaleron processes with baryon number non-conservation are in thermal equilibrium for temperatures above 100 GeV. As compared to SM, νMSM contains 6 CP-violating phases in the lepton sector and extra degrees of freedom - sterile neutrinos - which may be out of thermal equilibrium exactly because their Yukawa couplings to ordinary fermions are very small. Thus all three Sakharov conditions are fulfilled.

The baryon asymmetry within νMSM can be generated through CP-violating sterile neutrino oscillations in the Early Universe. The kinetics of these oscillations and the transfers of L between active and sterile neutrino sectors has been worked out in [3]. For masses of sterile neutrinos exceeding ~ 20 GeV the mechanism does not work as the sterile neutrinos equilibrate. The temperature of baryogenesis is right above the electroweak scale.

2. Constraints on the model parameters

The Yukawa coupling constants of DM neutrino $|F_{\alpha 1}| \lesssim 10^{-12}$ are strongly bounded by cosmological considerations [2] and by the X-ray observations [4] and for the present discussion field N_1 can be omitted from the Lagrangian. So, with definition $f_\alpha \equiv |F_{\alpha 2}|$, we arrive at

$$\mathscr{L}_N \simeq -\frac{1}{\sqrt{2}} f_\alpha \bar{L}_\alpha (N_2 + N_3)\tilde{\Phi} - \frac{M_1}{2}\bar{N_2}^c N_2 - \frac{M_2}{2}\bar{N_3}^c N_3 + \mathrm{h.c.}$$

where masses M_2 and M_3 must be almost the same (baryogenesis constraint), $|M_2^2 - M_3^2| \lesssim 10^{-5} M^2$.

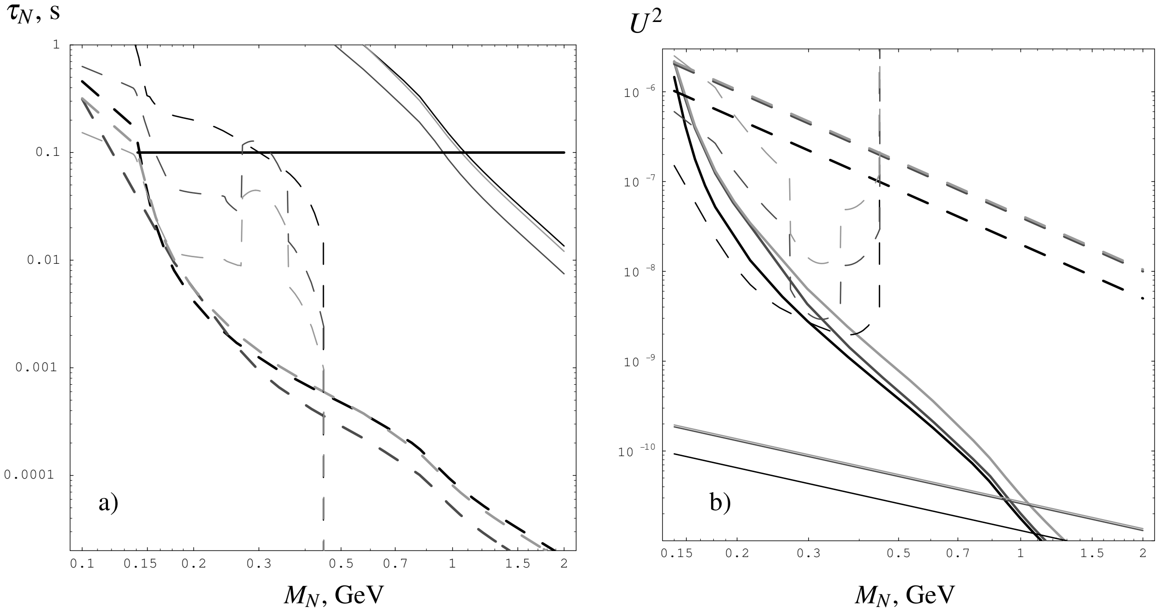

Figure 1: a) Upper (solid lines) and lower limits (dashed lines) on neutrino lifetime in models I (black), II (dark gray) and III (light gray); a horizontal thick solid black line indicates the order-of-magnitude upper limit from BBN, $\tau_N < 0.1$ s, thin solid lines are limits from eq. (2.2), thick dashed lines refer to eq. (2.1), thin dashed lines correspond to limits from direct searches for sterile neutrinos discussed in Sec. 2; charge-conjugated modes are accounted. b) Lower (solid lines) and upper limits (dashed lines) on overall mixing U^2 in models I (black), II (dark gray) and III (light gray). Thin solid lines and thick dashed lines depict limits from eqs. (2.2) and (2.1), respectively. Thick solid lines indicate lower limits from the BBN bound ($\tau_N < 0.1$ s), thin dashed lines refer to limits from direct searches discussed in Sec. 2.

For successful baryogenesis the active-sterile mixing must be small enough [5], otherwise N_2 and N_3 come to thermal equilibrium above the electroweak scale and the baryon asymmetry is erased. This leads to the upper bound

$$\frac{f_\alpha^2 v^2}{2M^2} \equiv U^2 < 2\kappa \cdot 10^{-8} \left(\frac{\text{GeV}}{M}\right)^2 \tag{2.1}$$

with $\kappa = 1(2)$ for the case of normal(inverted) hierarchy in active neutrino sector. The lower bound on U can be derived as well from required mass-mixing pattern in active neutrino sector:

$$U^2 > 1.3\kappa \cdot 10^{-11} \left(\frac{\text{GeV}}{M}\right) . \tag{2.2}$$

The requirement of reproducing mass-mixing pattern in active neutrino sector still allows a lot of freedom in relations between Yukawa couplings to different leptonic flavours, since CP-violating phases in the active neutrino mass matrix are not known. To present quantitative predictions we consider three sets of Yukawa couplings corresponding to three "extreme hierarchies": f_α, f_β are taken to be as small as possible compared to another one f_γ, $\alpha \neq \beta \neq \gamma$, which thus mostly determines the overall strength of mixing U^2. In what follows we will refer to these sets as benchmark models I, II and III with ratios of coupling constants given by (see Ref. [1] for details)

$$\begin{aligned} \text{model I}: &\quad f_e^2 : f_\mu^2 : f_\tau^2 \approx 52:1:1\,, \quad \kappa = 1\,, \\ \text{model II}: &\quad f_e^2 : f_\mu^2 : f_\tau^2 \approx 1:16:3.8\,, \quad \kappa = 2\,, \\ \text{model III}: &\quad f_e^2 : f_\mu^2 : f_\tau^2 \approx 0.061:1:4.3\,, \quad \kappa = 2\,. \end{aligned}$$

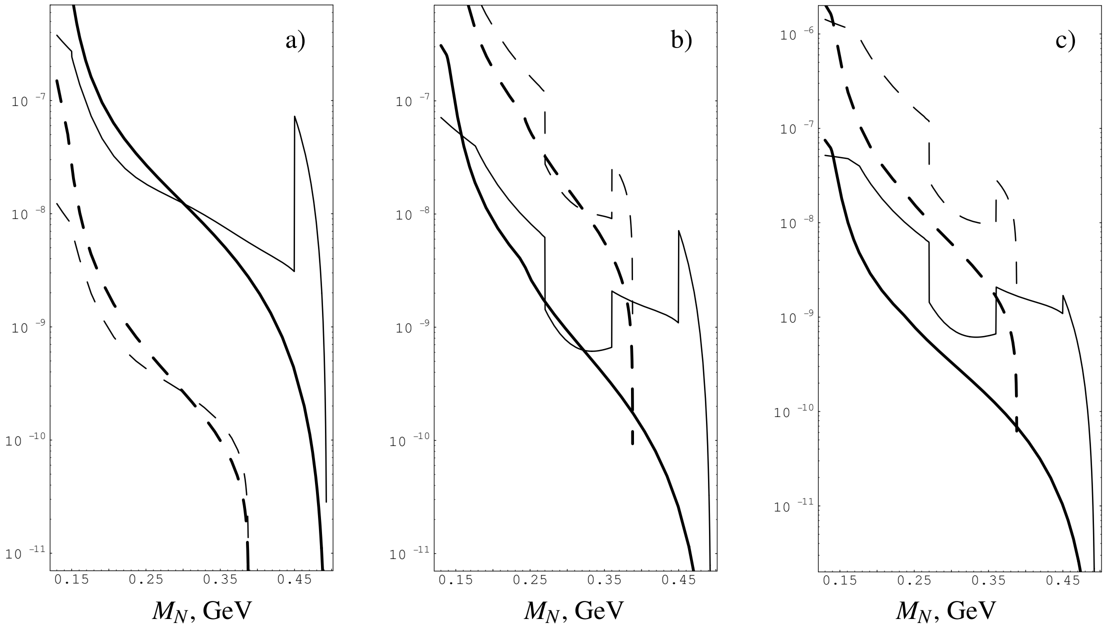

Figure 2: Branching ratios of decays $K \to eN_I$ (solid lines) and $K \to \mu N_I$ (dashed lines) at varios heavy neutrino masses M_N in models: a) I, b) II, c) III. In a phenomenologically viable model the branching ratios are confined between corresponding thin and thick lines which show upper and lower limits on U^2 from Fig. 1b, respectively.

For the mass of the neutral lepton $M > 450$ MeV none of the past or existing experiments enter into interesting for νMSM region. In the region $M < 450$ MeV the non-trivial limits on the parameters of the νMSM come from the CERN PS191 experiment [7], giving roughly $|U_{e,\mu}|^2 \lesssim 10^{-9}$ in the region 250 MeV $< M <$ 450 MeV.

The considerations coming from Big Bang Nucleosynthesis (BBN) allow to establish a number of *lower* bounds on the couplings of neutral leptons which decrease considerably the admitted window for the couplings and masses of the neutral leptons. The successful predictions of BBN are not spoiled provided the life-time of sterile neutrinos is short enough, so neutrinos decay before the onset of the BBN and the products of their decays thermalize. It was argued in Ref. [6] that the life-time τ_N of the sterile neutrino heavier than pion must be smaller than 0.1 s and we use this limit for the Models I-III.

Above pion mass, the BBN limits are down to two order of magnitude below the direct limits form CERN PS191 experiment, thus one-two orders of magnitude improvement is required to either confirm or disprove the νMSM with sterile neutrinos lighter than 450 MeV. For the three benchmark models we transfered these limits to the upper limits on overall mixing U^2 and neutrino lifetime and plotted them in Fig. 1.

3. Phenomenology of heavy neutrinos

Sterile neutrinos can be searched for in two- and three-body kaon decays due to mixing with active neutrinos. The predictions for the branching ratios are presented in Figs. 2 and 3. Similar searches can be performed with charmed and beauty mesons, see Ref. [1] for predictions.

The improvement required to test the νMSM with sterile neutrinos lighter than 450 MeV can be done with either new kaon experiments, such as one planned in JPARC, or special analysis of

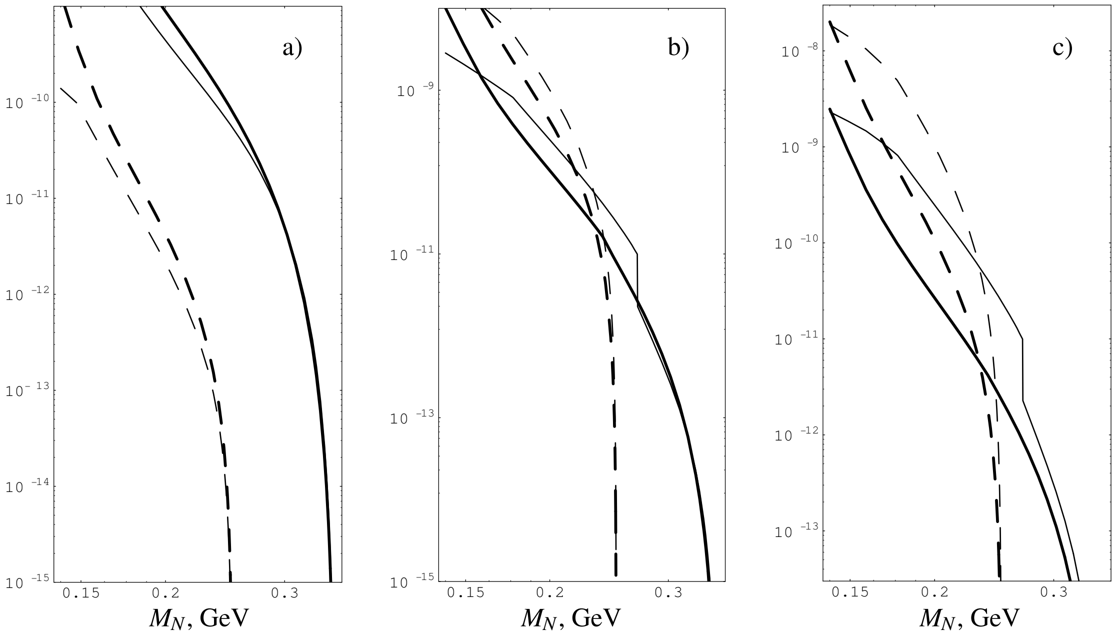

Figure 3: Branching ratios of decays $K \to \pi e N_I$ (solid lines) and $K \to \pi \mu N_I$ (dashed lines) as functions of heavy neutrino mass M_N in models: a) I, b) II, c) III. In a phenomenologically viable model the branching ratios are confined between corresponding thin and thick lines which show upper and lower limits on U^2 from Fig. 1b, respectively; form factors are taken from Ref. [8].

the available data on kaon decays collected in Brookhaven and Frascati. In particular, E787/E949 Collaboration reported limit on $K^+ \to \pi^+ X$ decay with X being hypothetical long-lived neutral particle [9]. With statistics of thousand of billions charged kaons, available in this experiment, one can expect to either prove or completely rule out νMSM with sterile neutrinos lighter than 450 MeV. The same conclusion is true for the third stage of CERN NA48 experiment.

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