Institute of Physics Publishing Journal of Physics: Conference Series **39** (2006) 176–178
doi:10.1088/1742-6596/39/1/043 TAUP 2005: Proc. Ninth Int. Conf. on Topics in Astroparticle and Underground Physics

The νMSM, dark matter and neutrino masses

Mikhail Shaposhnikov
Institute of Theoretical Physics
Ecole Polytechnique Fédérale de Lausanne
Lausanne CH-1015, Switzerland

E-mail: Mikhail.Shaposhnikov@epfl.ch

Abstract. An extension of the minimal standard model by three right-handed neutrinos with masses smaller than the electroweak scale (the νMSM) allows to explain simultaneously neutrino oscillations and dark matter in the universe. We show how to fix the absolute values of the active neutrino masses in this model.

Perhaps, a simplest extension of the Minimal Standard Model (MSM) which allows to explain neutrino oscillations is the one in which several right-handed SU(2) singlet fermions with zero weak hypercharges are added. These fermions can be called sterile or right-handed neutrinos. It has been demonstrated recently [1, 2] that if the number of sterile neutrinos is three[1] and their Majorana masses are smaller than the electroweak scale (for this specific choice of parameters this model was dubbed "the νMSM") this model can explain neutrino oscillations, dark matter and baryon asymmetry of the universe. Moreover it can also explain the pulsar kick velocities [3]. In this talk I will review the general motivation for the choice of scales of the νMSM and the results of [1] where it was shown that the absolute scale of *active* neutrino masses can be determined in this model as well.

The most general renormalizable Lagrangian of the νMSM has the form

$$L_{\nu MSM} = L_{MSM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c., \tag{1}$$

where L_{MSM} is the Lagrangian of the MSM, Φ and L_α ($\alpha = e, \mu, \tau$) are the Higgs and lepton doublets, respectively, and both Dirac ($M^D = f^\nu\langle\Phi\rangle$) and Majorana ($M_I$) masses for neutrinos are introduced. We have taken a basis in which mass matrices of charged leptons and right-handed neutrinos are real and diagonal. In comparison with the MSM, this model contains 18 new parameters: 3 Majorana masses of new neutral fermions N_i, and 15 new Yukawa couplings in the leptonic sector (corresponding to 3 Dirac neutrino masses, 6 mixing angles and 6 CP-violating phases).

Let us discuss in general terms what kind of scale for Majorana neutrino masses M_I one could expect. If Dirac neutrino masses $(M^D)_{\alpha I} = F_{\alpha I} v$ (where $v = 174$ GeV is the vacuum expectation value of the Higgs doublet) are much smaller than the Majorana masses M_I, the see-saw formula for active neutrino masses

$$m_\nu = -M^D \frac{1}{M_I}[M^D]^T \tag{2}$$

[1] Interestingly, in this case the leptonic sector has the same structure as the quark sector.

is valid. Though it is known that the masses of active neutrinos are smaller than $O(1)$ eV, it is clear that the scale of Majorana neutrino masses cannot be extracted out of eq.(2). This is simply because the total number of physical parameters describing m_ν is equal to 9 (three absolute values of neutrino masses, three mixing angles and three CP-violating phases), which is two times smaller than the number of new parameters in the νMSM.

A most popular proposal [4] is to say that the Yukawa couplings F in the active-sterile interactions are of the same order of magnitude as those in the quark and charged lepton sector. Then one has to introduce a new energy scale, $M_I \sim 10^{10} - 10^{15}$ GeV, which may be related to grand unification. This model has several advantages in comparison with the MSM: it can explain neutrino masses and oscillations, and give rise to baryon asymmetry of the universe through leptogenesis [5] and anomalous electroweak number non-conservation at high temperatures [6]. However, it cannot explain the dark matter as the low energy limit of this theory is simply the MSM with non-zero active neutrino masses coming from dimension five operators. On a theoretical side, as a model with two very distinct energy scale it suffers from a fine-tuning hierarchy problem $M_I \gg M_W$.

Another possibility is to say that no new energy scale is introduced, and $M_I < M_W$. In this case the Yukawa couplings must be much smaller than those in the quark sector, $F < 10^{-6}$. Clearly, no internal hierarchy problem appears for this choice. Also, the neutrino masses and mixing can be easily incorporated. In addition, all the parameters of the νMSM can be potentially determined experimentally since only accessible energy scales are present.

Let us discuss the problem of dark matter in the νMSM[2]. Though this model does not offer any stable particle besides those already present in the MSM, it contains a sterile neutrino with a life-time exceeding the age of the universe, provided the corresponding Yukawa coupling is small enough [8, 9, 10]. The decay rate of N_1 to three active neutrinos and antineutrinos (assuming that N_1 is the lightest sterile neutrino) is given by

$$\Gamma_{3\nu} = \frac{G_F^2\, M_1^3 m_0^2}{96\,\pi^3}, \quad m_0^2 = \sum_{\alpha=e,\mu,\tau} |M^D \alpha 1|^2 \ . \tag{3}$$

For example, a choice of $m_0 \sim O(1)$ eV and of $M_1 \sim O(1)$ keV leads to a sterile neutrino life-time $\sim 10^{17}$ years.

The mass of the sterile dark matter neutrino cannot be too small. An application of the Tremaine-Gunn arguments [11] to the dwarf spheroidal galaxies [12] gives the lower bound $M_1 > 0.5$ keV . Even stronger constraint (based on the assumption that the sterile neutrino was produced in active-sterile neutrino oscillations in the early universe and plays a role of the so-called warm dark matter (WDM)) comes from the analysis of the cosmic microwave background and the matter power spectrum inferred from Lyman-α forest data [13, 14]: $M_1 > 2$ keV .

Yet another constraints on the parameters of dark matter sterile neutrino come from the observation that a radiative decay $N_1 \to \nu\gamma$, suppressed in comparison with $N_1 \to 3\nu$ by a factor $O(\alpha)$ (α is a fine structure constant), leads to diffuse X-ray background [9] and to emission of X-rays from clusters of galaxies [15]. The corresponding analysis can be found in [9, 15, 16].

Sterile neutrinos can be produced in the early universe by the processes which correspond to the physics beyond the νMSM, for example in inflaton oscillations or anything else one can imagine. Then the computation of their cosmic abundance Ω_N requires the knowledge of the physics at high energy scale. Under the assumption that they were not produced in this way and that the physics of the MSM (without ν in the name of the model!) correctly describes the universe at temperatures below 1 GeV, the concentration of sterile neutrinos, produced in

[2] The problem of the baryon asymmetry in this model is discussed in [7].

active-sterile neutrino oscillations, can be computed and expressed through the parameters m_0 and M_1 (the traditional parametrisation is M_1 and $\theta = \frac{m_0}{M_1}$) [8, 9, 10]:

$$\Omega_N \sim 0.2 \left(\frac{\theta^2}{10^{-8}}\right)\left(\frac{M_1}{1 \text{ keV}}\right)^2,$$

which leads to determination of the parameter m_0 related to Dirac neutrino masses [1],

$$m_0 \sim O(0.1) \text{ eV}. \tag{4}$$

The analysis of eqs. (2,4) together with experimental input from the neutrino oscillation experiments, and the lower bound on the dark matter sterile neutrino mass, carried out in [1], reveals that the minimal number of sterile neutrinos, which can explain the dark matter in the universe, is $\mathcal{N} = 3$. In addition, only one sterile neutrino can be the dark matter. Moreover, there is an upper bound on the lightest neutrino mass, $m_\nu < m_0^2/M_1 \simeq \mathcal{O}(10^{-5})$ eV. Since this bound is much smaller than $\sqrt{\Delta m^2_{\rm sol}} \simeq 10^{-2}$ eV, where $\Delta m^2_{\rm sol}$ is the solar mass square difference, the masses of other two active neutrinos should be given by

$$m_2 = \sqrt{\Delta m^2_{\rm sol}}, \quad m_3 = \sqrt{\Delta m^2_{\rm atm}} \tag{5}$$

or by

$$m_1 \approx m_2 = \sqrt{\Delta m^2_{\rm atm}}, \quad m_1^2 - m_2^2 = \Delta m^2_{\rm sol} \;, \tag{6}$$

if the hierarchy is inverted. The experimental numbers are [17]: $\Delta m^2_{\rm sol} = (7.2 - 8.9) \cdot 10^{-5}$ eV^2, $\Delta m^2_{\rm atm} = (1.7 - 3.3) \cdot 10^{-3}$ eV^2 . The errors correspond to 99% confidence level range of 2.58σ.

In fact, the assumptions leading to (4) are not true if the reheating temperature of the Universe is just above the nucleosynthesis scale [18]. However, it has been shown in [19] on the basis of X-ray constraints discussed above, that the predictions (5,6) remain in force provided $M_1 > 1.8$ KeV, if the diffused X-ray background constraint [16] is taken , and even for $M_1 > 0.8$ KeV if the Virgo cluster constraint [15] is incorporated.

References

[1] Asaka T, Blanchet S and Shaposhnikov M 2005 *Phys. Lett.* B **631** 151
[2] Asaka T and Shaposhnikov M 2005 *Phys. Lett.* B **620** 17
[3] Kusenko A and Segre G 1997 *Phys. Lett.* B **396** 197
[4] Minkowski P 1997 *Phys. Lett.* B **67** 421
Yanagida T 1980 *Progr. Theor. Phys.* **64** 1103
Gell-Mann M, Ramond P and Slansky R 1980 *Supergravity* (Amsterdam: North Holland)
[5] Fukugita M and Yanagida T 1986 *Phys. Lett.* B **174** 45
[6] Kuzmin V A, Rubakov V A and Shaposhnikov M E 1985 *Phys. Lett.* B **155** 36
[7] Shaposhnikov M 2006 The νMSM, dark matter and baryon asymmetry of the Universe *these proceedings*
[8] Dodelson S and Widrow L M 1994 *Phys. Rev. Lett.* **72** 17
[9] Dolgov A D and Hansen S H 2002 *Astropart. Phys.* **16** 339
[10] Abazajian K, Fuller G M and Patel M 2001 *Phys. Rev.* D **64** 023501
[11] Tremaine S and Gunn J E 1979 *Phys. Rev. Lett.* **42** 407
[12] Lin D N C and Faber S M 1983 *Astrophys. J.* **266** L21
[13] Hansen S H, Lesgourgues J, Pastor S and Silk J 2002 *Mon. Not. Roy. Astron. Soc.* **333** 544
[14] Viel M, Lesgourgues J, Haehnelt M G, Matarrese S and Riotto A 2005 *Phys. Rev.* D **71** 063534
[15] Abazajian K, Fuller G M and Tucker W H 2001 *Astrophys. J.* **562** 593
[16] Boyarsky A, Neronov A, Ruchayskiy O and Shaposhnikov M 2005 *Preprint* astro-ph/0512509
[17] Strumia A and Vissani F 2005 *Nucl. Phys.* B **726** 294
[18] Gelmini G, Palomares-Ruiz S and Pascoli S 2004 *Phys. Rev. Lett.* **93** 081302
[19] Boyarsky A, Neronov A, Ruchayskiy O and Shaposhnikov M 2006 *Preprint* hep-ph/0601098