Search for sterile neutrinos of the vMSM

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Abstract. Sterile neutrinos arise in several extensions of the Standard Model to accommodate massive neutrinos. In particular the recently proposed vMSM predicts 3 right-handed neutrinos, one of them could explain the dark matter puzzle.

1. The vMSM model [1]
Singlet (sterile) neutrino states arise in models which try to implement massive (light) neutrinos in extensions of the Standard Model. In particular the recently developed vMSM model considers 3 singlet states $N_1, N_2$ and $N_3$ associated with the 3 active neutrinos.

$N_1$ having a mass around 10 keV has a lifetime very long compared to the age of the Universe. Because of its small mass, it is essentially stable on cosmological times. It could account for the missing mass in the form of Warm Dark Matter.

The other two states, $N_2$ and $N_3$, if they are almost degenerate could solve the problem of the matter/antimatter asymmetry in the Universe. Their masses are expected to be in the range 100 MeV-few GeV. $N_2$ and $N_3$ can be searched for in the laboratory through their mixings with light neutrinos.

2. Production and decay of $N_2$ and $N_3$
If heavy neutrinos exist, they mix with active neutrinos through a unitary transformation. Any neutrino beam will contain a fraction of heavy neutrinos at the level $U_{Nl}^2$ where $U$ denotes the mixing matrix element between the heavy state $N$ and $l$, either $e$ or $\mu$ or $\tau$.

At accelerators, neutrinos are emitted in pion and kaon decays. At higher energies, charm, beauty and $W$ contribute. Kinematically the mass range allowed for a heavy $N$ depends on the emission process. In $\pi\mu$ decays, sterile neutrinos can reach a mass of 30 MeV. In $\pi e$, the range is increased to 130 MeV. Kaons allow larger potential masses of up to 450 MeV.

The flux of $N$’s accompanies the flux of known neutrinos at the level of $U_{Ni}^2$. Corrections to this straightforward result come from helicity conservation. For massless neutrinos, it suppresses $\pi e$ decays relative to $\pi \mu$ decays. This is not true anymore for $\pi \rightarrow eN$.

$N$’s will decay through weak interactions. The decay modes depend on the $N$ mass. The first channel to open is $N \rightarrow e e \nu$, as soon as the mass is greater than 1 MeV. With increasing masses, new modes open and one can obtain $e \mu \nu$, $\pi e$, $\mu \nu \nu$, $\pi \mu$…

The lifetime is given by the formula applying to weak decays, with a suppression factor coming again from the mixing $U_{Ni}^2$. Phase space factors are also to be taken into account.

The search consists in looking for a decay signature, typically two charged tracks reconstructing a vertex in an empty volume arising in a neutrino beam.
This has been attempted by the low energy experiment PS191 [2] with 5 \(10^{18}\) protons of 19 GeV on target. This put strong limits on the existence of sterile neutrinos in the mass range between 20 and 450 MeV.

For masses of a few MeV, a limit is given by the Borexino experiment in the \(N \rightarrow eee\) mode [3]. This limit could be improved with data from nuclear reactor experiments.

3. Sterile neutrinos as WDM?
From astrophysical measurements we know that the missing mass of the Universe corresponds to a local density of 300 MeV/cm\(^3\). If this is in the form of 10 keV neutrinos, here called \(N_1\), this means that we are surrounded by a density of \(3 \times 10^4 N_1/cm^3\). It has been argued that the local density of the dark halo could be much higher.

The solar system moves within this halo at a velocity of 200 km/s. This means that a detector is crossed by an average flux of \(6 \times 10^{11} N_1/cm^2s\). These particles are far from relativistic, they have an average \(\beta = 200/300000 = 0.7 \times 10^{-3}\) and \(\gamma = 1\).

The earth travels around the sun at the velocity of 30 km/s. This secondary motion gives a yearly modulation of \(\pm 15\%\) over periods of 6 months. The flux is maximum in June corresponding to \(6.9 \times 10^{11} N_1/cm^2s\), and minimum in December with a value of \(5.1 \times 10^{11} N_1/cm^2s\). The relative velocity \(\beta\) of the \(N_1\) is also modulated, the particles cross the detector faster in June.

4. Radiative decay of \(N_1\)
Neutrinos having a mass of 10 keV can decay radiatively. Their decay mode gives a \(\nu_e\) together with a monoenergetic photon carrying half of the \(N_1\) mass. The lifetime in vacuum for this process is extremely long:

\[
\tau_0 = 7 \times 10^{43} (1\text{eV/m})^5 \frac{1}{U^2} \text{(s)}
\]

It has been noticed that the radiative decay is very efficiently increased in matter(3):

\[
\frac{\tau_0}{\tau_m} \sim 9 \times 10^{21} F(\nu)(N_e/10^{24} \text{cm}^{-3})^2 (1\text{eV/m})^4
\]

This means that a 10 keV neutrino will have a lifetime in matter equal to:

\[
\tau_m = 0.8 \times 10^{16} \frac{1}{U^2} \text{(s)}
\]

5. Mixing of \(N_1\) and possible signal
If the interpretation of dark matter as composed of 10 keV sterile neutrinos is correct, it is possible to extract the mixing parameter from cosmological considerations.

Within this scenario, the number of \(N_1\) in the Universe is \(U^2\) times the number of \(\nu_e\). Furthermore the sum of all \(N_1\) constitutes 25\% of the total content of the Universe. We also know that ordinary matter composed of nucleons constitute 4\% of the total content of the Universe. The mass of nucleons being 1 GeV, this means that there are \((25/4) \times 10^5 N_1\) for 1 nucleon.

We know that the ratio between nucleons and photons in the Universe is \(3 \times 10^{10}\). The density of photons is 400/cm\(^3\) while for \(\nu_e\) it is 100/cm\(^3\). We can then derive the number of \(N_1\) per \(\nu_e\). This directly gives \(U^2 = 7 \times 10^{-4}\).

The problem is then entirely soluble. Let us consider a sensitive detector having a volume of \(10 \times 10 \times 10\) m\(^3\). It is traversed all the time by a flux of \(6 \times 10^{17} N_1/s\) (slightly modulated over the year). With a 10 m long decay path, the number of expected decays is \(4 \times 10^{3} \text{U}_2/s\). With the \(U^2\) extracted from cosmology this gives a total of \(3 \times 10^{16}\) photons of 5 keV or 100 per year.

One can solve the same exercise for 1 keV and 100 keV sterile neutrinos. One finds respectively 1000 and 10 events per year.
6. Conclusion
The vMSM model is a natural and attractive extension of the Standard Model. It predicts new states which can be searched for in forthcoming experiments. The fascinating possibility of the existence of warm dark matter as sterile neutrinos of keV mass is a challenging idea. The search is difficult but could be made easier if the dark matter is locally strongly amplified. Existing data obtained with germanium crystals could be analysed to put limits on local density of such candidates for the dark matter puzzle.

References
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