Searching for dark matter sterile neutrino in laboratory

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Abstract
If the dark matter of the Universe is made of sterile neutrinos with the mass in keV region they can be searched for with the help of X-ray satellites. We discuss the prospects of laboratory experiments that can be competitive and complimentary to Space missions. We argue that the detailed study of β decays of tritium and other nuclides with the help of Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) can potentially enter into interesting parameter range and even exceed the current astrophysical bounds on the properties of dark matter sterile neutrinos.

1 Astrophysics, Cosmology, and Sterile Neutrino
The nature of Dark Matter (DM) in the Universe is a puzzle. Many different hypothetical particles coming from physics beyond the Standard Model (SM) were proposed to play a role of dark matter particle; none of them have been discovered yet. Here we consider the for a search of one of the dark matter candidates: sterile neutrino with the mass in keV region. How would it be in the case of sterile neutrino as the dark matter particle? There are not many experimental facts in particle physics which cannot be described by the Standard Model. These are neutrino oscillations (neutrinos of the SM are exactly massless and do not oscillate), dark matter (the SM does not have any stable neutral massive particle) and baryon asymmetry of the Universe (substantial deviations from thermal equilibrium, needed for baryogenesis, are absent for experimentally allowed mass of the Higgs boson). This calls for an extension of the SM. The most economic one, that can describe all these phenomena in a unified way is the vSM. In the model (see insert) leptonic singlets (other names for them are right-handed, Majorana or sterile neutrinos) are added, making the structure of quark and lepton sectors of the theory similar. The Majorana nature of singlet fermions leads to non-zero mass for active neutrinos and, therefore, to neutrino oscillations, solving in this way the SM problems. The lightest of these new particles with the mass in keV region can have a lifetime greater than that of the Universe and thus can play a role of (warm) dark matter. The preferred for keV mass scale is coming from the cosmological structure formation arguments related to the missing satellite problems (see Fig. 1) and to cuppy DM distributions in cold dark matter cosmologies. The presence of two other heavier fermions with the mass in TeV/1 GeV region leads to generation of baryon asymmetry of the Universe via resonant sterile neutrino oscillations and electroweak sphalerons. These fermions can also be searched for in particle physics experiments with high intensity proton beams, and, possibly, rare meson decays.

2 Search for sterile neutrino
Creation and Detection
Suppressed by θ2, therefore most probably impossible.

Detection only
Sterile neutrinos are created somewhere else in large amounts and then detected in the laboratory. The X-Ray Space experiments are exactly of this type: the number density of sterile neutrinos is fixed by the DM mass density, and the limits on the X-Ray flux give directly the limit on θ2 rather than θ in the previous case. Knowing decay width for the N → ν + γ channel,

\[ \Gamma_N(\nu \rightarrow \gamma) = 1.38 \times 10^{-22} (\frac{m_N}{100 \text{eV}})^2 \text{ cm}^3/\text{s} \]

and sterile neutrino density from DM density one can deduce the limit on the mixing angle from the flux X-Ray observations. The searched signal here is the X-Ray line with energy E = M/2. Existing constraints are presented in Fig. 1.

Creation only
It is possible to analyze kinematics in the beta decay to register creation of keV neutrinos. Simplest thing would be to use just the beta spectrum, but due to very small mixing angle distinguishing the kink in the signal from the physical background is impossible (c.f. limits from kink searches in Fig. 2 and about 17 keV neutrino discovery).

vSM Model Summary
Standard Model with addition of 3 right-handed SU(2) L (U(1)) singlet neutrinos

\[ \mathcal{L} = \mathcal{L}_\text{SM} + f \bar{H} N \tau \frac{M}{\Sigma} (N_1 + N_2) + h.c. \]

Dirac mass term: \[ M^2 = f^2 H M \]

Majurana mass term: \[ M_D \]

H → Higgs doublet \[ f = \text{ left lepton doublet, } \alpha = e, \mu, \tau \]

Analogous to the masses in the quark sector

SU(3) Gauge-invariant and renormalizable extension

See-saw mechanism leads to admixture of sterile neutrinos in flavour states \( \nu_\alpha \rightarrow \nu_\alpha N \), where \( \alpha = e, \mu, \tau \), \( \theta^2 = \Sigma v_i^2 = (M_0/M)^2 \). There are also additional terms for \( \nu_\alpha N \) mixing which are also present.

Typical parameters:

\( M > 0.3 \text{ keV} \) is the Warm Dark Matter neutrino.

\( \theta^2 > 10^{-2} \) depending on mass (see X-ray constraints in Fig. 1).

VSM Predictions

\[ M_N \gg 1 \text{ keV} \]

\[ \theta^2 > 10^{-2} \]

\[ \Sigma v^2 > 0.01 \text{ eV} \]

\[ \text{Both normal and inverted hierarchies are possible} \]

For normal active neutrino mass hierarchy:

\[ 1.3 \text{ meV} < m^2 < 3.4 \text{ meV} \]

for inverted hierarchy:

\[ 13 \text{ meV} < m^2 < 50 \text{ meV} \]

(Stronger for light M.)

Limits on active neutrino events:

\[ T \lesssim 10^{-3} \text{ s} \]

Specifically:

\[ 1.5 \text{ keV} < \text{MeV} \]

Number of decays with kinematic cut on the momenta is much smaller then \( Q^2 \) and the number of sterile neutrino events can be estimated as \( N_{\text{events}} = N_{\text{beam}} \cdot \frac{Q^2}{M^2} \).

Estimates shown in Fig. 1 demonstrates that the proposed experiment is very challenging compared to existing kink search experiments, but can reach into the interesting parameter region!

Of course, the X-Ray bounds presented here is a rather challenging goal, but not impossible, and in case if not all the Dark Matter is composed of sterile neutrinos, larger values of mixing angle are also interesting.

Figure 2: Cold-Target Recoil-Ion-Momentum Spectroscopy

Figure 3: Constraints on the mixing angle θ of sterile neutrino with active neutrino from X-ray observations of Large Magellanic Clouds and Milky Way by XMM-Newton and Milky Way by HEAO-1 satellites. Two nearly vertical lines correspond to the bound on the mass from the thermal background with \( T = 0.01 \text{ K} \) and 1 K. Two horizontal lines are limits from the total number of registered decays, corresponding to \( N = 10^{18} \) and \( N = 10^{19} \). A kinematic cut on reconstructed neutrino momenta \( \theta^2 < 3\text{ MeV} \) was used. β decay kink search bounds from PDG-06 are shown for reference.