1 Sterile neutrinos

Neutrinos which do not participate into the Standard Model interactions are called "sterile". They arise in many extensions of the Standard Model in which singlet fermion states and the corresponding mass eigenstates are added. These new states can mix with ordinary neutrinos and generate observational effects in laboratory experiments, in cosmology and in astrophysics.

1.1 Theoretical issues

If sterile neutrinos are present, it is necessary to explain the origin of their masses and of the mixing with active neutrinos from the theoretical point of view. Small masses and large mixing can arise via higher-dimensional operators in the superpotential [1] which induce an intermediate-scale expectation value v_S (between the electroweak and a large energy scale M) of a scalar singlet field and small masses for sterile neutrinos suppressed by powers of v_S/M. Sterile neutrinos with masses from 100 MeV to few GeV are required to generate the observed light neutrino masses in theories with dynamical electroweak symmetry breaking [2]. Models with mirror matter contain mirror neutrinos [3, 4] which would be light for reasons similar to the ones for their ordinary partners. The interactions between active neutrinos and sterile neutrinos would be mediated by operators of the type $\nu\phi\nu'\phi'/M_P$, where the prime refers to the mirror world and M_P is the Planck mass. Singlet neutrinos could be the supersymmetric partners of the moduli field [5] or the singlets contained in representations of E_6 [6]. In these cases it can be argued that their mass would be of order TeV^2/M_P where the TeV mass scales arises from supersymmetry breaking. In extra-dimension models, sterile neutrinos can be easily embedded. They can be new singlet fermions propagating in the bulk of a higher dimensional theory with naturally small masses [7]. In addition, such theories predict a tower of Kaluza-Klein modes which can generate interesting observational signatures in particular in neutrino oscillations [8].

Let us stress that the discovery of the existence of sterile neutrinos would be of fundamental importance and would require a dedicated effort in understanding the origin and properties of such neutrinos.

1.2 Phenomenology of light sterile neutrinos

Here we consider sterile neutrinos with masses up to few eV and which mix with ordinary neutrinos. The main observational signatures would arise in neutrino oscillations. We do not include in the following discussion the LSND signal which will be discussed in a dedicated section. For a detailed discussion on the bounds discussed below, see Ref. [9, 10].

Reactor and accelerator neutrino experiments. In these experiments active-sterile neutrino oscillations would take place, implying a reduction of the observed flux at the far detector. Reactor neutrino experiments are sensitive to the mixing with ν_e,

U_{es}. The CHOOZ and Bugey experiments put bounds as strong as $|U_{es}|^2 \lesssim 0.01$ in various ranges of masses. The mixing with ν_μ is testable in accelerator experiments in which a beam of muon neutrinos is originally produced. The CDHS and CCFR disappearance experiments allow to put limits on $U_{\mu s}$. In addition, appearance experiments looked for $\nu_\mu \to \nu_e$ (KARMEN) and $\nu_\mu \to \nu_\tau$ (NOMAD and CHORUS) conversions. These experiments probe a combination of the mixing angles, $U_{\mu s}$, U_{es} and $U_{\mu s}$, $U_{\tau s}$, respectively. Oscillations of atmospheric neutrinos are affected by the mixing with sterile neutrinos. Combined analysis of recent atmospheric neutrino data from Super-Kamiokande, K2K, MACRO allow to constrain $|U_{\mu s}|^2 \lesssim 0.065$ at 99% C.L. [10].

Solar neutrino experiments and KamLAND. The data from these experiments put bounds on the admixture of sterile neutrinos with ν_e. MSW enhancement of electron neutrino oscillations with characteristic energy dependence allow to test small mixing angles for masses down to $\Delta m^2 \sim 10^{-8}$ eV^2, while, for large mixing angles, masses as small as $\Delta m^2 \sim 10^{-12}$ eV^2. In some cases, the effects due to sterile neutrinos can manifest themselves not at large energies, $E_\nu >$few MeV, which have been precisely tested by SNO and SK, but only at sub-MeV energies. This region was accessible only to Gallium experiments. In the future, Borexino will test part of this interesting region and might find signatures as day/night variations, seasonal dependence and a reduced total rate.

Neutrinoless double beta decay. If sterile neutrinos are Majorana particles and mix with electron neutrinos, they would have effects in neutrinoless double beta decay. They would contribute to the effective Majorana mass on which the half-life time of the process depends. In particular one would have that:

$$|<m>| = \left| \sum_{i=1,2,3} m_i \; U_{ei}^2 + m_s \; U_{es}^2 \right|, \tag{1}$$

where m_i are the masses of the light ordinary neutrinos while m_s indicates the mass of the sterile neutrino. Notice that $U_{es}^2 = |U_{es}|^2 \, e^{i\beta_s}$ where β_s is a Majorana CP–violating phase. Due to the presence of the Majorana phases the contributions in $|<m>|$ can sum up constructively as well as partially cancel [11]. A future measurement of $|<m>|$ with values outside the range predicted in the case of three light neutrinos might be a signal of the presence of sterile neutrinos. In particular, this would be the case if $|<m>|$ is larger than the predicted values, implying the presence of an additional contribution, or if it is smaller, indicating a cancellation between the different terms.

1.3 Signatures of heavy sterile neutrinos

We review in this section briefly the observational signatures of heavy sterile neutrinos with masses $m_s \gg 100$ eV. They depend strongly on the flavour with which the sterile neutrino mixes and on the mass range. For a detailed review see [12].

For masses 30 eV $\simeq m_N \simeq$ 1 MeV, the most sensitive probe is the search for kinks in the β-decay spectra [13] at the end point electron energy E_e. The bounds are typically in the $|U_{es}|^2 \sim 10^{-2}$–10^{-3} range.

For heavier masses a very powerful probe of the mixing of a heavy neutrino with both ν_e and ν_μ are peak searches in leptonic decays of pions and kaons [13, 14]. A heavy neutrino can be produced in such decays and the lepton spectrum would show a monochromatic line at

$$E_l = \frac{m_M^2 + m_l^2 - m_s^2}{2m_M}, \tag{2}$$

where E_l and m_l are respectively the lepton energy and mass, m_M is the meson mass. The mixing angle controls the branching ratio of this process and can be constrained by the height of the peak. Let us notice that these bounds are very robust because they rely only on the assumption that a heavy neutrino exists and mixes with ν_e and/or ν_μ. The limits for $|U_{es}|^2$ are as strong as 10^{-8}–few 10^{-7} for masses around 100 MeV. For masses up to 34 MeV, the most stringent constraints on the mixing with muon neutrinos come from pion decays with $|U_{\mu s}|^2 \lesssim$ few 10^{-5}, while for higher masses kaon decays are used and lead to limits as strong as $|U_{\mu s}|^2 \lesssim 10^{-6}$. A detailed review is given in Figs. 1 and 2 in Ref. [15].

Another strategy to constrain the heavy neutrinos mixed with ν_e, ν_μ and ν_τ, is via searches of the products of their decays. Neutrinos ν_s, if existing and kinematically allowed, are produced in every process in which active neutrinos are emitted, with a branching ratio which depends on the mixing $|U_{ls}|^2$. They would subsequently decay via CC and NC interactions into neutrinos and other "visible" particles, as electrons, muons, pions. Searches for the "visible" products were performed and were used to constrain the mixing parameters. These bounds are less robust than the ones previously discussed. In fact, if the heavy neutrinos have other dominant decay modes into invisible particles, these bounds would be weakened, if not completely evaded. In reactors and in the Sun only low mass, $m_N <$ few MeV, heavy sterile neutrinos mixed with ν_e can be produced. The bounds, obtained by looking for decays into electron-positron pairs read typically $|U_{es}|^2 \lesssim 10^{-4}$. For higher masses, heavy sterile neutrinos mixed with $\nu_{e,\mu,\tau}$ can be produced in meson and vector bosons decays. There are two different type of experiments. In beam dump experiments, ν_s are usually produced by the decay of mesons, π, K and D, and the detector is located far away from the production site. Otherwise, the production can happen in the detector itself via interactions with the nucleons. The limits depend strongly on the mass range. We have typically if $m_s \sim 0.02$ GeV – 0.4 GeV $|U_{es}|^2 \lesssim 10^{-9}$–$10^{-4}$, for $m_s \sim 0.4$ GeV – 2 GeV $|U_{es}|^2 \lesssim 10^{-7}$–$10^{-6}$ and if $m_s \sim 2$ GeV – 80 GeV, $|U_{es}|^2 \lesssim$ few 10^{-5}. Similar bounds hold for the mixing with ν_μ while $|U_{\tau s}|^2$ is constrained at most to be smaller than 10^{-5}. For a detailed review see Ref. [15, 12].

If heavy sterile neutrinos are of Majorana type, they would mediate $\Delta L = 2$ processes as neutrinoless double beta decay. New processes would be allowed and could also be resonantly enhanced for some mass ranges. A very sensitive probe of mixing with muon neutrinos is given by the rare kaon decay $K^+ \to \pi^- \mu^+ \mu^+$ [16] as well as the nuclear transition $\mu^- + (A, Z) \to \mu^+ + (A, Z-2)$ [17]. Heavy-quark meson decays were also searched for, as $D^+ \to K^-(\pi^-)\mu^+\mu^+$ [18]. Recently, bounds were obtained from the search of $\Xi^- \to p\mu^-\mu^-$ [19].

1.4 Cosmology and astrophysics of sterile neutrinos

Sterile neutrinos, if mixed with the active ones, would be copiously produced in the Early Universe and in astrophysical objects as supernovae. As they would affect sensibly their evolution, it is possible to constrain their parameters from astrophysical and cosmological observations (see, e.g. [20]).

Light sterile neutrinos. If light sterile neutrinos, with masses $m_s < 10$ eV, were produced in the Early Universe, they would generate various effects. At Big Bang Nucleosynthesis (BBN) they would contribute to the energy density in relativistic particles, modifying the expansion rate of the Universe and consequently the n/p ratio. Different analysis have been performed and provide bounds on the number of neutrinos, typically $N_\nu \lesssim 3.24 \pm 1.2$ at 95% C.L. [21] (see also Ref. [9]). The presence of a neutrino asymmetry affects the reactions in which neutrinos are involved and could weaken the bounds previously mentioned. For a recent detailed analysis see, e.g. Ref. [22]. The number of relativistic degrees of freedom at photon decoupling can be probed by CMB observations and is constrained to be $N_\nu = 3 \pm 2$ [23]. Finally, light sterile neutrinos affect large scale structure formation, making structures less clustered due to the free-streaming of these particles. Two parameters are relevant for these studies, namely the temperature at which these particles become non-relativistic, $T \sim m_s/3$, and the energy density $\Omega_s h^2$. As the total energy density in light degrees of freedom is constrained to be less than 1%, it is possible to put strong bounds on the mass of light sterile neutrinos. Supernovae are also sensitive probes of the existence of sterile neutrinos [24, 25]. The data from SN1987A allow to strongly constrain the mixing angles and future experiments might allow to strengthen these bounds even further. Sterile neutrinos would be produced in the core of supernovae and escape carrying away a sizable fraction of the energy. This allows to put limits as strong as $|U_{ls}|^2 \lesssim 10^{-10}$, while for large values of the mixing, $|U_{ls}|^2 \gtrsim 10^{-2}$, the sterile neutrinos would be effectively trapped and no bound applies. In addition, MSW oscillation in sterile neutrinos can take place for specific ranges of parameters and can modify the flux of electron antineutrinos. These bounds should be used with care as there is not yet a full understanding of the evolution of supernovae and of the mechanisms which lead to their explosion.

KeV sterile neutrinos. Sterile neutrinos with masses in the few KeV range have been advocated as one of the possible dark matter candidates [26, 25, 27]. They could have been produced via scattering-induced conversion of active neutrinos [26, 25]. In this case they would constitute a warm dark matter candidate with interesting features for structure formation. A bound of $m_s > 10$ KeV applies in this case [28] from Lyman-α observations. In presence of a large lepton asymmetry, the conversion can be resonantly enhanced and the resulting spectrum would be non-thermal, allowing for cool and cold dark matter as well [29]. Other mechanisms of production in which sterile neutrinos are colder than in the case of a thermal spectrum at structure formation allow to relax the 10 KeV limit reported above down to masses as small as few KeV [30]. These massive neutrinos would decay into a neutrino and a photon, contributing to the diffuse extragalactic background radiation [31]. The observations typically exclude a large fraction of the parameter space required for dark matter. Future observations and in particular the Chandra X-ray observatory have the potential of strengthening these bounds or to detect x-ray fluxes from cluster of galaxies. Weaker bounds on the mixing angles and the masses can also be obtained from the contribution of these neutrinos to BBN and to the CMB. These bounds are not competitive with the ones from x-ray observations and structure formation. The decays of sterile neutrinos into photons could have affected star formation, as they can catalyze the production of molecular hydrogen and favour star formation [32]. Sterile neutrinos in the same mass and mixing ranges can explain the very high velocities of pulsars. In presence of the strong magnetic fields of newly born neutron stars, they can be emitted asymmetrically generating a strong kick which boosts the star. The required values of the mixing angle are in the range 10^{-5}–10^{-4}, depending on the mass and on the type of conversion (resonant or non-resonant) of active-sterile neutrinos in the star core [33]. Larger values of the mixing angles are excluded by considerations similar to the case of light neutrinos in supernovae.

MeV-GeV mass sterile neutrinos. Heavy sterile neutrinos, once produced in the Early Universe, would decay rapidly into light particles, mainly neutrinos, electrons, pions, depending on the branching ratios. They would affect the predictions of BBN for the abundance of light elements and in particular of ^{4}He (see, e.g., Ref. [34]). The main effect would be to increase the energy density, leading to a faster expansion of the Universe and to an ealier freeze out of the n/p-ratio. In addition, the decay of ν_s into light neutrinos, in particular, ν_e, would modify their spectrum and the equilibrium of the $n-p$ reactions. In principle, SN1987A could also be used to exclude sterile neutrinos with mixing angles $10^{-7} \lesssim |U_{ls}|^2 \lesssim 10^{-2}$ and masses $m_s \lesssim T_{\rm core}$, where $T_{\rm core} = 30-80$ MeV is the temperature of the neutron star core. For masses larger than $T_{\rm core}$, the production of sterile neutrinos is suppressed by the Boltzmann factor. The emission of sterile neutrinos from the core depends on the mixing with active neutrinos, and the emission history might be very complicated [25]. More detailed analysis should be performed to have reliable bounds.

Notice that all the cosmological bounds above depend on the density of sterile neutrinos in the Early Universe. If they were not efficiently produced, these limits would be weakened or not apply at all. This is the case in presence of mirror neutrinos with very small mass splittings or if there is a very late phase transition such that sterile and active neutrinos are unmixed at higher temperatures, or if the reheating temperature is as low as few MeV [35].

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