Neutrino physics

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Abstract

Neutrino masses are likely to be a manifestation of the right-handed, gauge singlet fields, which correspond to new degrees of freedom. I discuss theoretical arguments in favor of the high and low scale seesaw mechanisms, review the existing experimental results, and discuss the astrophysical hints that may point to future discoveries.

1 Introduction

In reviewing the field as broad as neutrino physics at a conference, one is forced to make choices and focus on some specific areas, although some very comprehensive reviews are available [1]. I will concentrate on some new developments that stem from some fundamental ideas about the neutrino masses and which have exciting ramifications for cosmology and astrophysics.

Most discoveries in particle physics amount to either a measurement of some parameter related to a known particle, or a detection of some new degrees of freedom, new particles. The discovery of the neutrino mass[1] is both. Not only is it a measurement of the non-zero mass, but it also implies the existence of some additional, SU(2) singlet fermions, "right-handed" neutrinos. The corresponding particles can be made very heavy even for small masses of the active neutrinos (the seesaw mechanism [2]), but they can also be light, in which case they are called sterile neutrinos.

2 Sterile neutrinos in particle physics

The term *sterile neutrino* was coined by Bruno Pontecorvo, who hypothesized the existence of the right-handed neutrinos in a seminal paper [3], in which he also considered vacuum neutrino oscillations in the laboratory and in astrophysics, the lepton number violation, the neutrinoless double beta decay, some rare processes, such as $\mu \rightarrow e\gamma$, and several other questions that have dominated the neutrino physics for the next four decades. Most models of the neutrino masses introduce sterile (or right-handed) neutrinos to generate the masses of the ordinary neutrinos via the seesaw mechanism [2]. The seesaw lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\gamma^\mu \partial_\mu \right) N_a - y_{\alpha a} H \, \bar{L}_\alpha N_a - \frac{M_a}{2} \, \bar{N}_a^c N_a + h.c. \,, \qquad (1)$$

where $\mathcal{L}_{\rm SM}$ is the lagrangian of the Standard Model, includes some number n of singlet neutrinos N_a with Yukawa couplings $y_{\alpha a}$. Here H is the Higgs doublet and L_α $(\alpha = e, \mu, \tau)$ are the lepton doublets. Theoretical considerations do not constrain the number n of sterile neutrinos. In particular, there is no constraint based on the anomaly cancellation because the sterile fermions do not couple to the gauge fields. The experimental limits exist only for the larger mixing angles [4]. To explain the neutrino masses inferred from the atmospheric and solar neutrino experiments, $n = 2$ singlets are sufficient [5], but a greater number is required if the lagrangian (1) is to explain the r-process nucleosynthesis [6], the pulsar kicks [7, 8], dark matter [11, 12, 13, 14], and the formation of supermassive black holes [15].

The scale of the right-handed Majorana masses M_a is unknown; it can be much greater than the electroweak scale [2], or it may be as low as a few eV [22, 16]. The seesaw mechanism [2] can explain the smallness of the neutrino masses in the presence of the Yukawa couplings of order one if the Majorana masses M_a are much larger than the electroweak scale. Indeed, in this case the masses of the lightest neutrinos are suppressed by the ratios $\langle H \rangle / M_a$.

However, the origin of the Yukawa couplings remains unknown, and there is no experimental evidence to suggest that these couplings must be of order 1. In fact, the Yukawa couplings of the charged leptons are much smaller than 1. For example, the Yukawa coupling of the electron is as small as 10^{-6}.

One can ask whether some theoretical models are more likely to produce the numbers of order one or much smaller than one. The two possibilities are, in fact, realized in two types of theoretical models. If the Yukawa couplings arise as some topological intersection numbers in string theory, they are generally expected to be of order one [17], although very small couplings are also possible [18]. If the Yukawa couplings arise from the overlap of the wavefunctions of fermions located on different branes in extra dimensions, they can be exponentially suppressed and are expected to be very small [19].

In the absence of the fundamental theory, one may hope to gain some insight about the size of the Yukawa couplings using 't Hooft's naturalness criterion [20], which states essentially that a number can be naturally small if setting it to zero increases the symmetry of the lagrangian. A small breaking of the symmetry is then associated with the small non-zero value of the parameter. This naturalness criterion has been applied to a variety of theories; it is, for example, one of the main arguments in favor of supersymmetry. (Setting the Higgs mass to zero does not increase the symmetry of the Standard Model. Supersymmetry relates the Higgs mass to the Higgsino mass, which is protected by the chiral symmetry. Therefore, the light Higgs boson, which is not natural in the Standard Model, becomes natural in theories with softly broken supersymmetry.) In view of 't Hooft's criterion, the *small* Majorana mass is natural because setting M_a to zero increases the symmetry of the lagrangian (1) [21, 22].

One can ask whether cosmology can provide any clues as to whether the mass scale of sterile neutrinos should be above or below the electroweak scale. It is desirable to have a theory that could generate the matter–antimatter asymmetry of the universe. In both limits of large and small M_a one can have a successful leptogenesis: in the case of the high-scale seesaw, the baryon asymmetry can be generated from the out-of-equilibrium decays of heavy neutrinos [23], while in the case of the low-energy seesaw, the matter-antimatter asymmetry can be produced by the neutrino oscillations [24]. The Big-Bang nucleosynthesis (BBN) can provide a constraint on the number of light relativistic species in equilibrium [25], but the sterile neutrinos with the small mixing angles may never be in equilibrium in the early universe, even at the highest temperatures [11]. Indeed, the effective mixing angle of neutrinos at high temperature is suppressed due to the interactions with plasma [26], and, therefore, the sterile neutrinos may never thermalize. High-precision measurements of the primordial abundances may probe the existence of sterile neutrinos and the lepton asymmetry of the universe in the future [27].

While many seesaw models assume that the sterile neutrinos have very large masses, which makes them unobservable, it is worthwhile to consider light sterile neutrinos in view of the above arguments, and also because they can explain several experimental results. In particular, sterile neutrinos can account for cosmological dark matter [11], they can explain the observed velocities of pulsars [7, 8], the x-ray photons from their decays can affect the star formation [28].

3 Experimental limits

Laboratory experiments are able to set limits or discover sterile neutrinos with a large enough mixing angle. Depending on the mass, they can be searched in different experiments.

The light sterile neutrinos, with masses below 10^2 eV, can be discovered in one of the neutrino oscillations experiments [30]. The search by MiniBooNE [31] has shown no evidence of light sterile neutrinos with a large mixing angle.

In the eV to MeV mass range, the "kinks" in the spectra of beta-decay electrons can be used to set limits on sterile neutrinos mixed with the electron neutrinos [32]. Neutrinoless double beta decays can probe the Majorana neutrino masses [33].

For masses in the MeV–GeV range, peak searches in production of neutrinos provide the limits. The massive neutrinos ν_i, if they exist, can be produced in meson decays, e.g. $\pi^\pm \to \mu^\pm \nu_i$, with probabilities that depend on the mixing in the charged current. The energy spectrum of muons in such decays should contain monochromatic lines [32] at $T_i = (m_\pi^2 + m_\mu^2 - 2m_\pi m_\mu - m_{\nu_i}^2)/2m_\pi$. Also, for the MeV–GeV masses one can set a number of constraints based on the decays of the heavy neutrinos into the "visible" particles, which would be observable by various detectors. These limits are discussed in Ref. [4].

4 Sterile neutrinos in astrophysics and cosmology

Sterile neutrinos can be produced in supernova explosions. The observations of neutrinos from SN1987A constrain the amount of energy that the sterile neutrinos can take out of the supernova, but they are still consistent with the sterile neutrinos that carry away as much as a half of the total energy of the supernova. A more detailed analysis shows that the emission of sterile neutrinos from a cooling newly born neutron star is anisotropic due to the star's magnetic field [7]. The anisotropy of this emission can result in a recoil velocity of the neutron star as high as $\sim 10^3$km/s. This mechanism can be the explanation of the observed pulsar velocities [8]. The range of masses and mixing angles required to explain the pulsar kicks is shown in Fig. 1.

The neutrino-driven kicks can increase the energy of the supernova explosion because they enhance the convection in front of the moving neutron star and increase the energy of the shock wave [9], and also because they deposit entropy ahead of the shock [10]. The increase of convection in front of the moving neutron star can produce asymmetric jets with the stronger jet pointing in the direction of the pulsar motion, in contrast with what one could expect from other kick mechanisms [9].

The sterile neutrinos could play an important role in Big-Bang nucleosynthesis [27], as well as in the synthesis of heavy elements in the supernova, by enhancing the r-process [6].

The sterile neutrinos can be the cosmological dark matter [11, 12, 13, 14]. The interactions already present in the lagrangian (1) allow for the production of relic sterile neutrinos via the Dodelson-Widrow (DW) mechanism [11] in the right amount to account for all dark matter, i.e. $\Omega_s \approx 0.2$. The x-ray limits on the photons from the decays of the relic sterile neutrinos [38] forces them to have mass of at least a few keV if they are produced a la DW. However, these neutrinos appear to be too warm to agree with the Lyman-α bound [39, 40, 42], which is $m_s > 10$ keV in this scenario (see Fig. 1).

If the lepton asymmetry of the universe is relatively large, the resonant oscillations can produce the requisite amount of dark matter even for smaller mixing angles, for which there are no x-ray limits. (The x-ray flux is proportional to the square of the mixing angle.)

It is also possible that some additional interactions, not present in eq. (1) can be responsible for the production of dark-matter sterile neutrinos [46, 35]. For example, if the mass $M \sim$ keV is not a fundamental constant of nature, but is the result of some symmetry breaking via the Higgs mechanism, the Lyman-α bound can be relaxed to well below the current x-ray limits [35]. In this case the same sterile neutrino can simultaneously explain the pulsar kicks and dark matter (Fig. 1). The Higgs field giving the sterile neutrinos their Majorana mass [47], can be discovered at the Large Hadron Collider (LHC)

As was mentioned above, the relic sterile neutrinos can decay into the lighter neutrinos and an the x-ray photons [43], which can be detected by the x-ray telescopes [38]. The flux of x-rays depends on the sterile neutrino abundance. If all the dark matter is made up of sterile neutrinos, $\Omega_s \approx 0.2$, then the limit on the mass and the mixing angle is given by the dashed line in Fig. 1. However, the interactions in the lagrangian (1) cannot produce such an $\Omega_s = 0.2$ population of sterile neutrinos for the masses and mixing

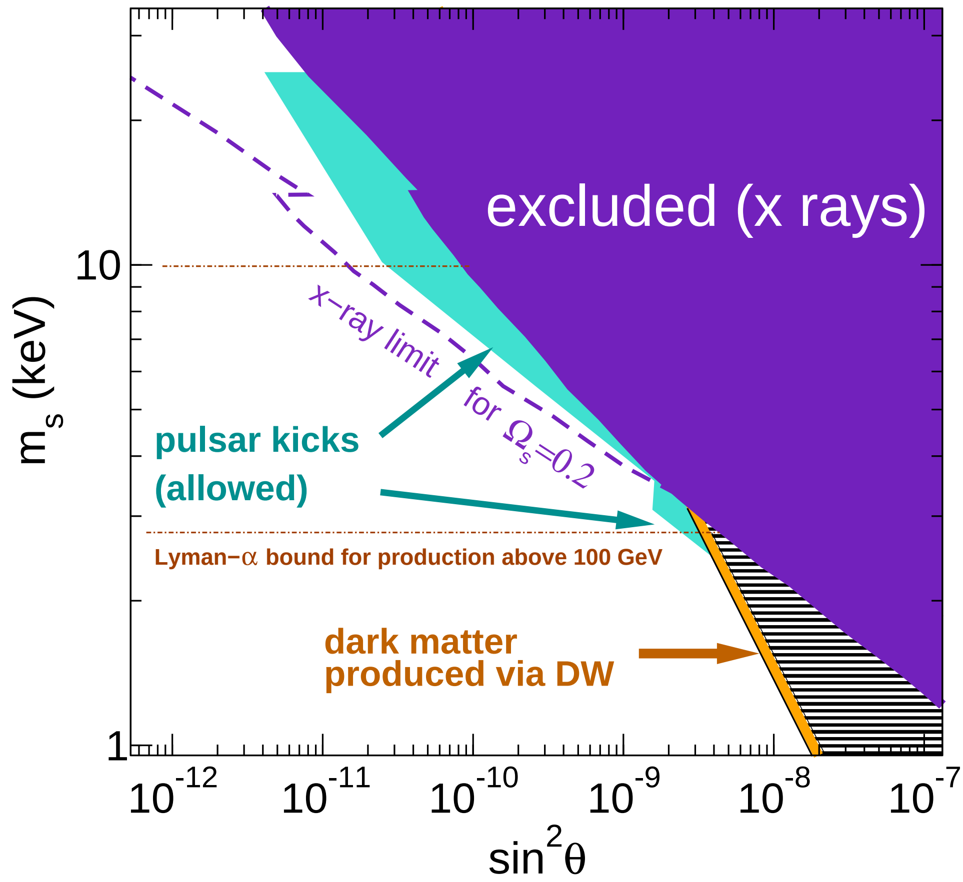

Figure 1: Sterile neutrinos in the keV mass range can be dark matter; their emission from a supernova can explain the observed velocities of pulsars. If the sterile neutrinos account for all dark matter, they must be sufficiently cold to satisfy the cosmological bounds on the mass. The limit depends on the production mechanism in the early universe. The lower bound of 2.7 keV corresponds to production at the electroweak scale [35].

angles along this dashed line, unless the universe has a relatively large lepton asymmetry [13]. If the lepton asymmetry is small, the interactions in eq. (1) can produce the relic sterile only via the neutrino oscillations off-resonance at some sub-GeV temperature [11]. This mechanism provides the lowest possible abundance (except for the low-temperature cosmologies, in which the universe is never reheated above a few MeV after inflation [34]). The model-independent bound [35] based on this scenario is shown as a solid (purple) region in Fig. 1. It is based on the flux limit from Ref. [38] and the analytical fit to the numerical calculation of sterile neutrino production [44]. This calculation may have some hadronic uncertainties [45].

Of course, the sterile neutrinos can have some additional couplings [46, 35], and the additional production can take place at higher temperatures. In particular, if the relic sterile neutrinos are produced above the electroweak scale, the Lyman-α bound is relaxed from 10 keV to 2.7 keV [35]. Of course, if the sterile neutrinos constitute only a small part of dark matter, the X-ray and Lyman-α bounds are substantially weaker[35, 40].

The x-ray photons from sterile neutrino decays in the early universe could have affected the star formation. Although these x-rays alone are not sufficient to reionize the universe, they can catalyze the production of molecular hydrogen and speed up the star formation [28], which, in turn, could cause the reionization. Molecular hydrogen is a very important cooling agent necessary for the collapse of primordial gas clouds that gave birth to the first stars. The fraction of molecular hydrogen must exceed a certain minimal value for the star formation to begin [49]. The reaction $H+H \rightarrow H_2 + \gamma$ is very slow in comparison with the combination of reactions $H^+ + H \rightarrow H_2^+ + \gamma$ and $H_2^+ + H \rightarrow H_2 + H^+$, which are possible if the hydrogen is ionized. Therefore, the ionization fraction determines the rate of molecular hydrogen production. If dark matter is made up of sterile neutrinos, their decays produce a sufficient flux of photons to increase the ionization fraction by as much as two orders of magnitude [28]. This has a dramatic effect on the production of molecular hydrogen and the subsequent star formation.

For smaller masses (the relation of free-streaming to mass depends on the production mechanism), the sterile neutrinos represent “warm” dark matter, which may be in good agreements with observational inferences regarding the small-scale structure [36, 37, 41].

5 Conclusions

The underlying physics responsible for the neutrino masses is likely to involve right-handed, or sterile neutrinos. The Majorana masses of these states can range from a few eV to values well above the electroweak scale. Theoretical arguments have been made in favor of both the high-scale and low-scale seesaw mechanisms: the high-scale seesaw may be favored by the connection with the Grand Unified Theories, while the low-scale seesaw is favored by 't Hooft's naturalness criterion. Cosmological considerations are consistent with a vast range of mass scales. The laboratory bounds do not provide significant constraints on the sterile neutrinos, unless they have a large mixing with the active neutrinos.

There are several indirect astrophysical hints in favor of sterile neutrinos at the keV scale. Such neutrinos can explain the observed velocities of pulsars, they can be the dark matter, and they can play a role in star formation and reionization of the universe.

The preponderance of indirect astrophysical hints may be a precursor of a major discovery, although it may also be a coincidence. One can hope to discover the sterile neutrinos in the x-ray observations. The mass around 3 keV and the mixing angle $\sin^2\theta \sim 3 \times 10^{-9}$ appear to be particularly interesting because the sterile neutrino with such parameters could simultaneously explain the pulsar kicks and dark matter (assuming the sterile neutrinos are produced at the electroweak scale). However, it is worthwhile to search for the signal from sterile dark matter in other parts of the allowed parameter space shown in Fig. 1.

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