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Light sterile neutrinos: Status and perspectives ☆

Carlo Giunti

INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

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Abstract

The indications in favor of the existence of light sterile neutrinos at the eV scale found in short-baseline neutrino oscillation experiments is reviewed. The future perspectives of short-baseline neutrino oscillation experiments and the connections with β-decay measurements of the neutrino masses and with neutrinoless double-β decay experiments are discussed.

1. Introduction

The 2015 Nobel Prizes in Physics is a great acknowledgment of the fundamental importance of the model-independent discoveries of neutrino oscillations in the Super-Kamiokande atmospheric neutrino experiment [1] and in the SNO solar neutrino experiment [2]. These discoveries, which proved that neutrinos are massive and mixed particles, led to the standard three-neutrino mixing paradigm (3ν), in which the three active neutrinos ν_e, ν_μ, ν_τ are superpositions of three massive neutrinos ν_1, ν_2, ν_3 with respective masses m_1, m_2, m_3 (see Ref. [3]). There are two independent squared-mass differences, the small solar $\Delta m^2_{\text{SOL}} \simeq 7.5 \times 10^{-5}\ \text{eV}^2$ and the larger atmospheric $\Delta m^2_{\text{ATM}} \simeq 2.3 \times 10^{-3}\ \text{eV}^2$, which can be interpreted as $\Delta m^2_{\text{SOL}} = \Delta m^2_{21}$ and $\Delta m^2_{\text{ATM}} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$, with $\Delta m^2_{kj} = m^2_k - m^2_j$ (see Refs. [4–6]).

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The completeness of the 3ν mixing paradigm has been challenged by the following indications in favor of short-baseline neutrino oscillations, which require the existence of at least one additional squared-mass difference, $\Delta m^2_{\text{SBL}} \gg \Delta m^2_{\text{ATM}}$ (see the review in Ref. [7]):

1. The reactor antineutrino anomaly [8], which is an about 2.8σ deficit of the rate of $\bar{\nu}_e$ observed in several short-baseline reactor neutrino experiments in comparison with that expected from the calculation of the reactor neutrino fluxes [9,10].
2. The Gallium neutrino anomaly [11–15], consisting in a short-baseline disappearance of ν_e measured in the Gallium radioactive source experiments GALLEX [16] and SAGE [17] with a statistical significance of about 2.9σ.
3. The LSND experiment, in which a signal of short-baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations has been observed with a statistical significance of about 3.8σ [18,19].

The additional squared-mass difference Δm^2_{SBL} requires the existence of at least one massive neutrino ν_4 in addition to the three standard massive neutrinos ν_1, ν_2, ν_3. Since from the LEP measurement of the invisible width of the Z boson we know that there are only three active neutrinos (see Ref. [3]), in the flavor basis the additional massive neutrinos correspond to sterile neutrinos [20], which do not have standard weak interactions.

Sterile neutrinos are singlets of the Standard Model gauge symmetries which can couple to the active neutrinos through the Lagrangian mass term. In practice there are bounds on the active-sterile mixing, but there is no bound on the number of sterile neutrinos and on their mass scales. Therefore the existence of sterile neutrinos is investigated at different mass scales. This review is devoted to the discussion of sterile neutrinos at the eV scale, which can explain the indications in favor of short-baseline neutrino oscillations listed above. However, there are other very interesting possibilities which are under study: very light sterile neutrinos at a mass scale smaller than 0.1 eV, which could affect the oscillations of solar [21–23] and reactor [24–30] neutrinos; sterile neutrinos at the keV scale, which could constitute warm dark matter according to the Neutrino Minimal Standard Model (νMSM) [31–35] (see also the reviews in Refs. [36–39]); sterile neutrinos at the MeV scale [40–43]; sterile neutrinos at the electroweak scale [44,45] or above it [45,46], whose effects may be seen at LHC and other high-energy colliders. Let us also note that there are several interesting models with sterile neutrinos at different mass scales [47–63].

The possible existence of sterile neutrinos is very interesting, because they are new particles which could give us precious information on the physics beyond the Standard Model (see Refs. [64,65]). The existence of light sterile neutrinos is also very important for astrophysics (see Ref. [66]) and cosmology (see Refs. [7,67–70]).

In this review, we consider $3+1$ [71–74] and $3+2$ [75–79], neutrino mixing schemes in which there are one or two additional massive neutrinos at the eV scale[1] and the masses of the three standard massive neutrinos are much smaller. We do not consider schemes in which Δm^2_{SBL} is obtained with one or more very light (or massless) non-standard massive neutrinos and the three standard massive neutrinos have almost degenerate masses at the eV scale (e.g., the $1+3$, $1+3+1$ and $2+3$ schemes), because this possibility is strongly disfavored by cosmological measurements [88] and by the experimental bound on neutrinoless double-β decay (assuming that massive neutrinos are Majorana particles; see Ref. [89]).

[1] In the literature one can also find studies of the $3+3$ [77,80], $3+1+1$ [81–85], and $1+3+1$ [86,87] schemes.