Reviews in Physics 1 (2016) 52–59

Contents lists available at ScienceDirect

Reviews in Physics

journal homepage: www.elsevier.com/locate/revip

Experimental investigation of the thriving mystery of sterile neutrinos

A. Fava[a,b,*]

[a] Fermi National Accelerator Laboratory, Wilson Street & Kirk Road, Batavia, IL 60510, United States
[b] I.N.F.N., Via Marzolo 8, 35131 Padova, Italy

ARTICLE INFO

Article history:
Available online 7 April 2016

Keywords:
Sterile neutrinos
Neutrino oscillations
LSND anomaly
Reactor anomaly
Gallium anomaly
Short-baseline

ABSTRACT

Several “anomalies” have been reported from a variety of experiments studying neutrino oscillations over short baselines (less than 1 km) since 1998. Even though not fully compatible with each other, these results could possibly hint at the existence of at least one additional “sterile” neutrino state beyond the Standard Model picture of Particle Physics.

In recent years significant contributions to the search for sterile neutrinos have led to a narrowing of the region of the parameter space where all experimental results can be accommodated. However, the persistence of unexplained tensions together with the groundbreaking impact of the possible discovery of sterile neutrinos call for a conclusive experiment.

1. The backstory

Neutrino Physics is a lively and exciting research field that, despite its youth, has already traced a story dense with surprising discoveries continuously undermining the basis of the theoretical models aimed at a comprehensive description of the Particle Physics.

The quantum-mechanical phenomenon of neutrino oscillations, originated by flavour eigenstates (observables in the detection of ν interactions) being a superposition of mass eigenstates (driving the propagation of ν's in time and space), has catalysed the interest of the greatest part of the neutrino community in the last decades.

An intense experimental investigation, carried out with a broad variety of sources, energies, baseline lengths and detection techniques, has led to the establishment of a scenario consistent with the mixing of 3 neutrino flavours (ν_e, ν_μ, ν_τ) with 3 mass eigenstates (ν_1, ν_2, ν_3)

$$\nu_\alpha = \sum_{j=1}^{3} U_{\alpha j} \cdot \nu_j, \quad \alpha = e, \mu, \tau \tag{1}$$

---

[*] Correspondence address: Fermilab, P.O. Box 500, Batavia, IL 60510, United States.
E-mail address: angela.fava@cern.ch

http://dx.doi.org/10.1016/j.revip.2016.03.003

Table 1
Most recent values of the parameters describing the 3-flavours ν mixing.

Parameter	Best fit value	Note
$\sin^2(\theta_{12})$	$0.304^{+0.014}_{-0.013}$	
Δm^2_{12}	$(7.53 \pm 0.18) \times 10^{-5}$	
$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$	Normal mass hierarchy
	0.511 ± 0.055	Inverted mass hierarchy
Δm^2_{23}	$(2.42 \pm 0.06) \times 10^{-3}$	Normal mass hierarchy
	$(2.49 \pm 0.06) \times 10^{-3}$	Inverted mass hierarchy
$\sin^2(\theta_{13})$	$(2.19 \pm 0.12) \times 10^{-2}$	

where the mixing matrix U is parameterised in terms of three angles (θ_{12}, θ_{23}, θ_{13}), one Dirac CP-violating phase (δ) and possibly 2 Majorana CP-violating phases (α_{21}, α_{31}):

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times diag(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}}) \tag{2}$$

with $c_{jk} = \cos(\theta_{jk})$ and $s_{jk} = \sin(\theta_{jk})$.

In this framework the phenomenology of oscillations is thoroughly described by two relatively small squared mass differences ($\Delta m^2_{ij} = m^2_i - m^2_j$), the neutrino energy E [MeV] and the propagation length L [m]:

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \tag{3}$$

The most recent determination of the values of all oscillation parameters, outcome of a global fit of all experimental results, is reported in Table 1 [1].

However a series of experimental anomalies, uncorrelated with each other but all hinting at oscillation phenomena driven by values of the (Δm^2, $\sin^2(2\theta)$) parameters not compatible with the scenario depicted in Table 1, has started casting shadows over the picture of 3 generations of neutrinos since the late 90's (Section 2). The attempt to give a plausible explanation still without entering in conflict with the precision measurements of the decay width of Z_0 boson that limit the number of active light neutrinos to 3 [2], triggered the proliferation of theoretical and experimental quests for additional sterile (i.e. not weakly interacting) ν states (Section 3). Unexpectedly the results obtained so far, despite leading to sensible advances in the comprehension of the problem, have not clarified the mystery at all and have rather clouded the issue, for instance in deepening the tension between appearance and disappearance effects. Hence, a new generation of experiments is already under construction, with the specific purpose of addressing this enigma (Section 4).

2. The first clues pointing out the enigma of sterile neutrinos

The primary indications of neutrino oscillation phenomena that could not be interpreted within the three flavours scheme can be grouped into two distinct classes:

- the observation of ν_e interactions in ν_μ beams produced at accelerators and propagated over short baselines (Section 2.1), well beyond the intrinsic beam contamination (*LSND anomaly*);
- a short baseline disappearance of low energy ν_e with respect to expectations (Section 2.2), both at nuclear reactors (*reactor anomaly*) and from Mega-Curie radioactive ν sources in Gallium experiments originally designed to detect solar neutrinos (*Gallium anomaly*).

2.1. ν_e appearance: LSND anomaly

At the outset of the era of neutrino oscillation physics, in the flourishing of experiments scanning the parameter space, a dedicated search for $\overline{\nu}_\mu \to \overline{\nu}_e$ transitions was performed at the Los Alamos Neutron Science Center (LANSCE) [3].

The Los Alamos Meson Physics Facility (LAMPF) accelerator delivered a 1 mA proton beam at 798 MeV on a target/dump, producing a large number of pions decaying into muons and then neutrinos. Since π^- and μ^- were promptly absorbed by the Fe shielding and Cu beam stop, produced neutrinos came mainly from $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$ decays mostly (>95%) at rest, resulting in a pure $\overline{\nu}_\mu$ beam in the $20 < E_\nu < 60$ MeV energy range with only ~0.8‰ $\overline{\nu}_e$ contamination, whose fluxes are well under control.

The search for $\overline{\nu}_e$'s was performed ~30 m downstream of the target position, looking for inverse beta decay $\overline{\nu}_e + p \to n + e^-$ reactions in the 167 tons of liquid scintillator (mineral oil doped with 0.031 g/l of b-PBD) contained in the Liquid Scintillator Neutrino Detector (LSND), consisting of an approximately cylindrical tank 8.3 m long by 5.7 m in diameter whose internal surface was covered for the 25% by 1220 8 in. Hamamatsu phototubes (PMTs). The experimental signature