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Neutrinos

Conveners:

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1.1 Beyond the Standard Paradigm – Anomalies and New Physics

Neutrinos moved beyond the Standard Model years ago with the discovery of neutrino oscillations which implied the existence of neutrino mass, but since neutrino masses can be accommodated with minor modifications to the Standard Model, the three neutrino mixing paradigm is no longer, or at least not widely, viewed as "new physics". Instead, when we talk about anomalies in neutrino physics we are referring to evidence that does not agree with the standard three neutrino mixing model. In particular, the marginal yet persistent evidence of oscillation phenomena around $\Delta m^2 \sim 1$ eV^2, which is not consistent with the well-established solar and atmospheric Δm^2 scales, is often interpreted as evidence for one or more additional neutrino states, known as sterile neutrinos. Beyond the sterile neutrino, new physics may appear thorough broad array of mechanisms collectively known as non-standard interactions (NSI). Typically, searches for these effects occur in experiments designed to study more standard phenomena. One type of NSI that has been the subject of dedicated searches in the past and may play a role in the future program is the neutrino magnetic moment. In the following sections we will discuss the prospects for neutrino experiments sensitive to anomalies and new physics over the next several years.

1.1.1 Sterile Neutrinos

(*Major updates to the text coming!*)

Data from a variety of short-baseline experiments as well as astrophysical observations and cosmology hint at the existence of additional neutrino mass states beyond the three active species in the Standard Model (see for example [1]). The possible implications of additional sterile neutrino states would be profound, and would change the paradigm of the Standard Model of particle physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos and providing a definitive resolution to the question: do sterile neutrinos exist?

Recently, a number of tantalizing results (anomalies) have emerged from short-baseline neutrino experiments that cannot be explained by the current three-neutrino paradigm. These anomalies are not directly ruled out by other experiments and include the excess of electron-antineutrino events (3.8σ) observed by the LSND experiment [2], the excess of electron-antineutrino events (2.3σ) observed by the MiniBooNE experiment in antineutrino mode [3], the deficit of electron-antineutrino events (0.937 ± 0.027) observed by reactor neutrino experiments [4], and the deficit of electron-neutrino events (0.86 ± 0.05) observed by the SAGE and GALLEX gallium calibration experiments [5].

How can we explain these anomalies? Although there are several possibilities (e.g., Lorentz invariance violation), one of the simplest explanations is the $3 + N$ sterile neutrino model, in which there are three light, mostly active neutrinos and N heavy, mostly sterile neutrinos. For $N > 1$, these models allow for CP violation in short-baseline experiments. These $3 + N$ models fit the world's neutrino and antineutrino data fairly well [6, 7], albeit it in a not-too-convincing fashion. One key test of these $3 + N$ models is the existence of muon-neutrino disappearance ($\sin^2 2\theta > 10\%$) at a $\Delta m^2 \sim 1$ eV^2. Several workshops have been held over the past year to critically review the evidence for and against sterile neutrinos and the need to pursue new experiments and strategies to address the experimental observations [8, 9, 1].

In order to determine whether these short-baseline anomalies are due to neutrino oscillations in a $3 + N$ sterile neutrino model and not to some other process or background, future short-baseline experiments with good electron and muon identification will need to measure (with precision) the L/E dependence of neutrino appearance and disappearance at L/E values of order 1. Various ways of measuring the L/E dependence

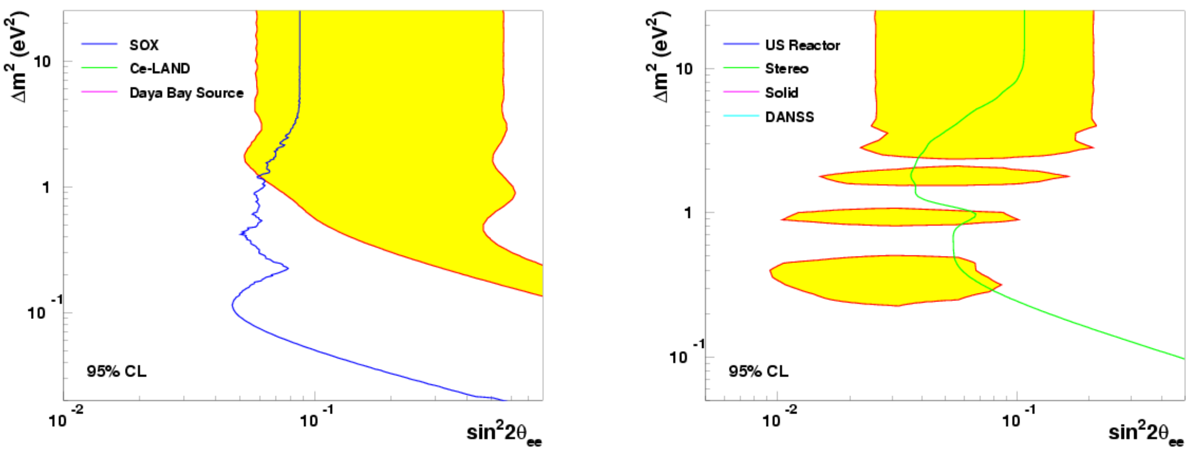

Figure 1-1. *Collaboration-reported sensitivity curves for proposed source (left) and reactor (right) experiments plotted against the global fits [13] for the gallium anomaly and reactor anomaly respectively.*

have been proposed. These include: (1) positioning two or more detectors at different distances in an accelerator-induced neutrino beam to reduce systematic errors, (2) placing a large detector close to a source of low-energy neutrinos from a reactor or intense radioactive source and measuring the L/E distribution of neutrino events in the single detector, and (3) measuring the L/E distribution of high energy (TeV) atmospheric-induced neutrinos, where strong matter effects are expected at particular values of L/E.

Diverse experiments, spanning vastly different energy scales, have been proposed or are being built to test the $3 + N$ models and resolve the present anomalies. The MicroBooNE collaboration is building a liquid-argon (LAr) TPC just upstream of the MiniBooNE detector that will be able to determine whether the event excesses observed by MiniBooNE are due to electron events, as expected from $3+N$ models, or are simply due to unmodeled photon backgrounds. Another LAr TPC proposal is to move the ICARUS detector, now taking data in the Gran Sasso National Laboratory, to the PS neutrino beamline at CERN and to build a second, smaller LAr TPC [10]. Similar options also exist in the Booster neutrino beamline at Fermilab. With two detectors at different distances, many of the associated systematic errors cancel, which will allow a definitive test of the LSND neutrino oscillation signal. Other accelerator neutrino experiments at Fermilab include the MINOS+ experiment [11], which will search with high sensitivity for muon neutrino to sterile disappearance, and the BooNE experiment [12], which proposes the construction of a second MiniBooNE-like detector at a different distance (200 m) than the original MiniBooNE detector (541m). BooNE would have the potential to measure electron neutrino and electron antineutrino appearance, muon neutrino and muon antineutrino disappearance, and CP violation in the lepton sector, as well as demonstrate the existence of sterile neutrinos by comparing neutral current π^0 scattering at different distances. Fermilab already has world-class neutrino beams (the Booster neutrino beamline and NuMI); however, future facilities could significantly enhance these capabilities. These future facilities include Project-X, which would increase present proton intensities by an order of magnitude or more, and a muon storage ring, which would enable an extremely precise search for electron neutrino and electron antineutrino disappearance.

Besides those at Fermilab and CERN, there are also several other opportunities for pursuing short-baseline neutrino physics. The Spallation Neutron Source (SNS) facility at Oak Ridge National Laboratory produces an intense and well-understood flux of neutrinos from π^+ and μ^+ decay at rest. An idea has been put forward, OscSNS [14], for building a MiniBooNE-like detector approximately 60m from the SNS beam dump. OscSNS would be capable of making precision measurements of electron antineutrino appearance and muon neutrino

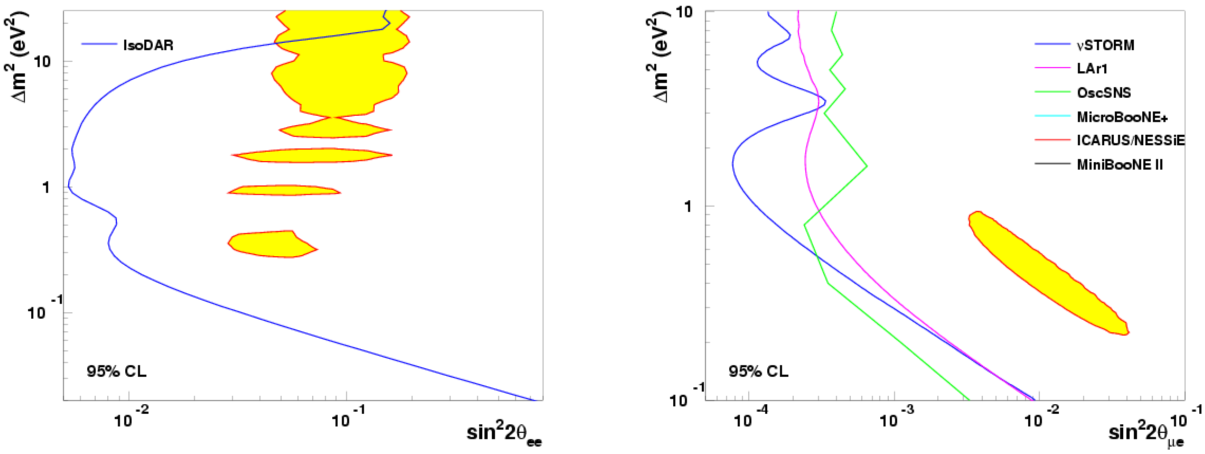

Figure 1-2. *Collaboration-reported sensitivity curves for proposed accelerator-based experiments sensitive to ν_e and $\bar{\nu}_e$ disappearance and appearance ($\nu_e \to \nu_\mu$, $\bar{\nu}_e \to \bar{\nu}_\mu$ or $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$) plotted against the global fits [13].*

disappearance. Also, the Southern California Reactor Antineutrino Anomaly Monitor (SCRAAM) [15] experiment could be built at the San Onofre nuclear generating station in California or at the Advanced Test Reactor, a research reactor at the Idaho National Laboratory. SCRAAM would have less baseline spread than previous reactor neutrino experiments and would be able to measure oscillations by looking for a spectral distortion in the reactor neutrino energy spectrum. In addition, neutrino radioactive source experiments could be mounted in either the Borexino, Daya Bay, KamLAND, or SNO+ detectors [16, 17]. The advantage of radioactive source experiments is that due to the low neutrino energies, oscillations could be observed in a single detector or in several closely separated detectors. There are also possibilities for performing sterile neutrino measurements in neutral current coherent neutrino-nucleon scattering using cryogenic solid state bolometers [18]. A final opportunity for measuring short-baseline oscillations is to search for atmospheric muon antineutrino disappearance with the IceCube experiment at the South Pole [19]. With a typical atmospheric neutrino energy of a few TeV and a typical distance of a few thousand kilometer, IceCube is very sensitive to oscillations at the roughly 1 eV mass scale, especially because these oscillations would be matter-enhanced via the MSW mechanism.

Finally, we emphasize that satisfactorily resolving these short-baseline anomalies is very important for carrying out the neutrino oscillation program described earlier. The two to three sigma effects reported, even if unrelated to sterile neutrinos, are at the sub-percent to the several-percent level, similar to, for example, the $|U_{e3}|$ and CP-violating signals being pursued in long-baseline experiments.

1.1.2 Non-Standard Interactions

(*Needs to be updated!*)

Neutrino experiments in general, and neutrino oscillation experiments in particular, are also very sensitive to new, heavy degrees of freedom that mediate new "weaker-than-weak" neutral current interactions. These so-called non-standard interactions (NSI) between neutrinos and charged fermions modify not only neutrino production and detection, but also neutrino propagation through matter effects. In a little more detail, NSI

Table 1-1. *Proposed sterile neutrino searches. Rough recost categories: small: <$5M, medium: $5M-$50M, large: $50M-$300M.*

Experiment	ν Source	ν Type	Channel	Host	Cost Catagory
Ce-LAND [20]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[1]
SOX [21]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[1]
US Reactor [22]	Reactor	$\bar{\nu}_e$	disapp.	US[2]	
Stereo	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[3]
Solid	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	NA[3]
DANSS [23]	Reactor	$\bar{\nu}_e$	disapp.	Russia	NA[3]
MircoBooNE+ [24]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab, US	
OscSNS [25]	π-DAR	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	ORNL, US	medium
LAr1 [26]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab, US	medium
MiniBooNE II [27]	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	Fermilab, US	
ICARUS/NESSiE	π-DIF	$\overset{(-)}{\nu}_\mu$	$\overset{(-)}{\nu}_e$ app.	CERN	NA[3]
IsoDAR [28]	^{8}Li	$\bar{\nu}_e$	disapp.	Kamioka, Japan	medium
νSTORM [29]	μ Storage Ring	$\overset{(-)}{\nu}_e$	$\overset{(-)}{\nu}_\mu$ app.	Fermilab, US	large

[1] US scope only.
[2] Multiple sites are under consideration [30].
[3] No US participation proposed.

are described by effective operators proportional to, for example, $G_F\epsilon^f_{\alpha\beta}\nu_\alpha\gamma_\mu\nu_\beta\bar{f}\gamma^\mu f$, where $\nu_{\alpha,\beta}=\nu_{e,\mu,\tau}$, f are charged fermions $(e,u,d,\mu,s,\ldots)$, G_F is the Fermi constant, and ϵ are dimensionless couplings.[1] When f is a first-generation fermion, the NSI contribute to neutrino detection and production at order ϵ^2 (ignoring potential interference effects between the Standard Model and the NSI). On the other hand, the NSI also contribute to the forward-scattering amplitude for neutrinos propagating in matter, modifying the neutrino dispersion relation and hence its oscillation length and mixing parameters. These modified matter effects are of order ϵ^1 and potentially more important than the NSI effects at production or detection. Furthermore, for $\alpha\neq\beta$, the NSI-related matter effects lead to $P_{\alpha\beta}\neq\delta_{\alpha\beta}$ in the very short baseline limit $(L\to 0)$, which are not present in the Standard Model case. More information – including relations to charged-lepton processes – current bounds, and prospects are discussed in detail in, for example, [31, 32], and references therein.

1.1.3 Neutrino Magnetic Moment

(*Text will be added here*)

[1] $\epsilon\sim 1$ ($\ll 1$) implies that the new physics effects are on the order of (much weaker than) those of the weak interactions.

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