Abstract

Several observed anomalies in neutrino oscillation data could be explained by a hypothetical fourth neutrino separated from the three standard neutrinos by a squared mass difference of a few 0.1 eV$^2$ or more. This hypothesis can be tested with MCi neutrino electron capture sources ($^{51}$Cr) or kCi antineutrino β-source ($^{144}$Ce) deployed inside or next to a large low background neutrino detector. In particular, the compact size of this source coupled with the localization of the interaction vertex lead to an oscillating pattern in event spatial (and possibly energy) distributions that would unambiguously determine neutrino mass differences and mixing angles.

Keywords: Neutrino Anomalies, Sterile Neutrinos, Neutrino Sources

1. Introduction

Over the last 20 years neutrino oscillations associated with small splittings between the $\nu$ mass states have become well established. Three $\nu$ flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are mixtures of three massive neutrinos ($\nu_1$, $\nu_2$, $\nu_3$) separated by squared mass differences of $\Delta m_{21}^2 = 8 \cdot 10^{-5}$ eV$^2$ and $\Delta m_{31}^2 = 2.4 \cdot 10^{-3}$ eV$^2$ \cite{1}. This is a minimal extension of the Standard Model that requires a lepton mixing matrix, similarly to the quark sector, and $\nu$ mass. Beyond this model indications of oscillations between active and sterile $\nu$ states have been observed in the LSND \cite{2}, MiniBooNE \cite{3}, gallium \cite{5} and reactor \cite{4} experiments. This suggests the existence of a fourth massive $\nu$ with a mass of $\gtrsim 0.1$ eV$^2$ \cite{7}. Testing $\nu$ anomalies now requires energy and baseline-dependent signatures for an unambiguous resolution. With MeV $\nu$’s very short baselines and compact sources become mandatory.

2. Gallium and Reactor Anomalies

Man-made $\nu$ sources were originally proposed and built to measure the efficiency of solar-$\nu$ detection. First Alvarez proposed a $^{65}$Zn source \cite{8} producing 1.35 MeV neutrinos. Sources of lower energy neutrinos, more appropriate for the efficiency calibration of gallium based experiments were later proposed. Performing systematic searches for candidate nuclei using as criteria the activation cross section, isotopic abundance, absence of higher energy gamma-rays, and similarity of the $\nu$ spectrum to the solar spectrum, two candidates were selected, $^{51}$Cr ($<750$ keV) proposed by Raghavan \cite{9} and $^{37}$Ar (814 keV) proposed later by Haxton \cite{10}. In the nineties two $^{51}$Cr $\nu$-sources ($A_0 \sim$ MCi) \cite{11,12} were made in the solar $\nu$ Gallex collaboration \cite{11} one in the Sage collaboration \cite{12} complemented with an $^{37}$Ar source ($A_0=0.4$ MCI) \cite{13}. Both experiments observed an average deficit of $R_G = 0.86 \pm 0.06 (1\sigma)$. Fitting the data with the hypothesis of $\nu_e$ disappearance caused by short baseline oscillations leads to $|\Delta m_{\text{new}}^2| > 0.3$ eV$^2$ (95%) and $\sin^2(2\theta_{\text{new}}) \sim 0.2$ \cite{5,4}, assuming only one additional sterile $\nu$ (the so-called 3+1 model).

Recently the hypothetical existence of a fourth $\nu$ has been revived by a new calculation \cite{6} of the rate of $\bar{\nu}_e$ production by nuclear reactors that yields a $\nu$ flux about 3.5% higher than previously predicted. Coupled with cross section reevaluations this result implies that the measured event rates for all reactor $\bar{\nu}_e$ experiments within 100 meters of the reactor are 7% too low,
with an average deficit of \( R_k = 0.927 \pm 0.023 \) (1σ) \[4\]. The deficit could also be explained by a hypothetical fourth massive \( \nu \) separated from the three others by \( |\Delta m_{\text{new}}^2| > 0.1 \text{ eV}^2 \) and \( \sin^2(2\theta_{\text{new}}) \sim 0.2 \) \[4\].

The combination of the reactor \( \bar{\nu}_e \) anomaly with the gallium \( \nu_e \) anomaly disfavors the no-oscillation hypothesis at 99.9% C.L. \[4, 7\].

3. Searching for a \( \Delta m^2 > 0.1 \text{ eV}^2 \) new \( \nu \) state

Both reactor and gallium anomalies rely on the observation of the disappearance MeV-scale \( \bar{\nu}_e \)'s and \( \nu_e \)'s by counting experiments. Therefore the definitive test of the anomalies is not only to test the \( \nu \) disappearance at short baselines, but also to search for an oscillation pattern as a function of \( L/E \).

Probing a \( \Delta m^2 \) of \( \sim 1 \text{ eV}^2 \) implies that an oscillation search using neutrinos with energies of typical of radioactive decays, in the few MeV range, requires a baseline of several meters only. Therefore, assuming CP invariance, both anomalies could be unambiguously tested using \( \bar{\nu}_e/\nu_e \) emitters deployed at the center or next to a large detector, ~10 m-scale, such as Sage-2Z \[7\], Borexino \[16\], KamLAND \[27\], SNO+ \[18\], or Daya Bay \[22\].

4. A new (anti)neutrino source experiment

There are two suitable \( \nu \)-sources options for searching for light sterile neutrinos: monochromatic \( \nu_e \) emitters, like \( ^{51}\text{Cr} \) or \( ^{37}\text{Ar} \), or \( \bar{\nu}_e \) emitters with a continuous \( \beta^-\)spectrum, like \( ^{144}\text{Ce} \) or \( ^{106}\text{Ru} \). In both cases the source must be as compact as possible to allow the observation of the characteristic \( \nu \)-oscillation pattern of event positions, even for \( |\Delta m_{\text{new}}^2| \gg \text{few eV}^2 \).

4.1. Neutrino Emitters

Radioactive neutrino sources involve either \( \beta^-\)-decay or electron capture. Electron capture decays produce mono-energetic \( \nu_e \)'s allowing for a determination of \( L/E \) by measuring only the interaction vertex. Intense man-made \( \nu_e \) source were used for the calibration of solar-\( \nu \) experiments. In the nineties, \( ^{51}\text{Cr} \) and \( ^{37}\text{Ar} \) were used as a check of the radiochemical experiments Gallex and Sage \[23\]. Production of an \( ^{37}\text{Ar} \) source requires a large fast breeder reactor that leaves \( ^{51}\text{Cr} \) as the best current \( \nu_e \) source candidate for sterile \( \nu \) search.

\( ^{51}\text{Cr} \) has a half-life of 27.7 days. 90.1% of the time it decays to the ground state of \( ^{51}\text{V} \) and emits a 751 keV \( \nu_e \) while 9.9% of the time it decays to the first excited state of \( ^{51}\text{V} \) and emits a 413 keV \( \nu_e \) followed by 320 keV \( \gamma \). \( ^{50}\text{Cr} \) has a relatively high average thermal neutron capture cross section of 17.9 barn that makes the large scale production of \( ^{51}\text{Cr} \) possible. Natural Cr is primarily \( ^{52}\text{Cr} \) (83.8%) and contains 4.35% \( ^{50}\text{Cr} \). The isotope \( ^{53}\text{Cr} \) (9.5% of natural chromium) has an average thermal neutron cross section of 18.7 barn, so when natural chromium is irradiated, \( ^{53}\text{Cr} \) absorbs 2.5 neutrons to every one captured on \( ^{50}\text{Cr} \), reducing the \( ^{51}\text{Cr} \) yield. Therefore enriched \( ^{50}\text{Cr} \) is needed for reaching several MCI of activity. Enrichment would also play in favor of manufacturing a compact target necessary for the sterile neutrino search. The material used by Gallex was enriched to 38.6% in \( ^{50}\text{Cr} \) while the Sage target was enriched to 92%. Because many isotopes have high neutron capture cross sections great care must be taken during the production and handling of the Chromium rods to minimize the introduction of chemical impurities leading to high-energy gamma rays.

In radiochemical experiments the interaction of \( ^{51}\text{Cr} \) and \( ^{37}\text{Ar} \) neutrinos induce the reaction \( ^{71}\text{Ga}(\nu_e,\gamma)^{72}\text{Ge} \). The \( ^{72}\text{Ge} \) produced is chemically extracted from the detector and converted to GeH\(_4\). Ge atoms are then placed in proportional counters and their number is determined by counting the Auger electrons released in the transition back to \( ^{71}\text{Ga} \), which occurs with a half life of 11.4 days.

In LS experiment the signature is provided by \( \nu_e \) elastic scattering off electrons (ES) in the LS molecules. The cross section is \( \sigma(E_{\nu_e}) \sim 0.95 \times 10^{-43} \times E_{\nu_e} \text{ cm}^2 \), where \( E_{\nu_e} \) is the neutrino energy in MeV. This signature can be mimicked by Compton scattering induced by radioactive and cosmogenic background, or by Solar-\( \nu \) interactions. The constraints of an experiment with \( \nu_e \) impose the use of a very high activity source, 5-10 MCi, to provide a production rate in the detector that will exceed the rate from the Sun, and to compensate the loss of solid angle due to the location of the source outside of the detector (since the ES does not provide any specific signature of \( \nu_e \) interaction).

4.2. Antineutrino Emitters

Antineutrino sources are non-monochromatic \( \bar{\nu}_e \) emitters decaying through \( \beta^-\)-decay. \( \beta^-\)-decay induced \( \bar{\nu}_e \) are detected through the inverse beta-decay (IBD) reaction \( \bar{\nu}_e + p \rightarrow e^+ + \nu \). The IBD cross section is \( \sigma(E_{\bar{\nu}_e}) \sim 0.96 \times 10^{-43} \times p_e E_{\bar{\nu}_e} \text{ cm}^2 \), where \( p_e \) and \( E_{\bar{\nu}_e} \) are the momentum and energy (MeV) of the detected \( e^+ \), neglecting recoil, weak magnetism, and radiative second order corrections. This lead to an interaction rate of an order of magnitude higher than the EC process at 1 MeV, allowing to reduce the activity to the kCi scale for the sterile neutrino search \[25\].
The \( \nu_e \) promptly deposits its kinetic energy in the LS and annihilates emitting two 511 keV \( \gamma \)-rays, yielding a prompt event, with a visible energy of \( E_\gamma = E_\nu - (m_e - m_p) \) MeV; the emitted keV neutron is captured on a free proton with a mean time of a few hundred microseconds, followed by the emission of a 2.2 MeV deexcitation \( \gamma \)-ray providing a delayed coincidence event. The delayed coincidence between detection of the positron and the neutron capture gamma rays suppressed any non-source background to a negligible level.

A suitable \( \bar{\nu}_e \) source must have \( Q_{\beta} > 1.8 \) MeV (the reaction threshold) and a lifetime that is long enough (\( \gtrsim 6 \) months) to allow for production, transportation, and deployment in the detector. For individual nuclei, these two requirements are contradictory so one expect candidate sources to involve a long-lived low-\( Q \) nucleus that decays to a short-lived high-\( Q \) nucleus. Four such pairs have been identified: \(^{144}\text{Ce} - ^{144}\text{Pr} (Q_{\beta}(\text{Pr})=2.99 \text{ MeV}), ^{106}\text{Ru} - ^{106}\text{Rh} (Q_{\beta}(\text{Rh})=3.54 \text{ MeV}), ^{90}\text{Sr} - ^{90}\text{Y} (Q_{\beta}(\text{Y})=2.28 \text{ MeV}), \) and \(^{42}\text{Ar} - ^{42}\text{K} (Q_{\beta}(\text{K})=3.52 \text{ MeV}) \). The first three are common fission products from nuclear reactors that can be extracted from spent fuel rods.

5. Current proposals

We present here a non-comprehensive description of possible future neutrino source experiments dedicated to sterile neutrino oscillation search. The projects described below are in various stages of development from early stage to conceptual.

5.1. \(^{51}\text{Cr} \) neutrino projects

We first review projects based on \(^{51}\text{Cr} \nu_e \) emitters whose decay scheme is shown on Fig. 1.

5.1.1. Dual Metallic Gallium Target at Baksan

The goal is to place a \(^{51}\text{Cr} \) source with initial activity of 3 MCi at the center of a 50-ton target of liquid Ga metal. The target will be divided into two concentric spherical zones, an inner 8-ton zone and an outer 42-ton zone. In this two-zone experiment the source dimension will be on the scale of 10 cm and the baseline will be one the scale of a few meters, therefore the oscillation ripples won’t be averaged out for \( \Delta m^2 = 1 \) eV\(^2 \). 65 atoms of \(^{71}\text{Ge} \) are expected each day in each zone at the beginning of each run. A sequence of exposure period of a few days will be done. The extraction and the counting will be the same as for the well understood SAGE experiment. Assuming 10 extractions, each with a 9-day exposure, one expects a total uncertainty of ±4.5%. The results will partially rely on the knowledge of the activity of the source that will be measured by calorimetry (a 3 MCi source releases initially 650 W of heat). Either a significant difference between the capture rates in the two zones, or an average rate in both zones significantly below the expected rate would be an evidence of non-standard neutrino properties. The proposed experiment has the potential to test neutrino oscillation transitions with mass-squared difference \( \Delta m^2 > 0.5 \) eV\(^2 \) and mixing angle \( \theta \) such that \( \sin^2 2\theta > 0.1 \). To conclude this project relies on a proofed concept, e.g., the measurement of the solar neutrino flux by SAGE for many years, with well understood backgrounds and systematics. A relevant aspect concerns the accompanying gamma radiation related to impurities which are not able to produce the reaction \(^{71}\text{Ga} (\nu_e, e^-) \) \(^{71}\text{Ge} \). A high activity a \(^{51}\text{Cr} \) source can thus be deployed inside such a neutrino detector and the requested shield surrounding the source is mainly used to fulfill safety requirements.

5.1.2. SOX and SNO+Cr

After more than five years of data taking the solar-\( \nu \) detector Borexino is well suited to host an external neutrino source experiment [19]. A tunnel exists right below the water tank, providing a location at a distance of 8.25 m to the scintillator inner vessel center. The unique extreme radiopurity achieved in the LS medium will allows to control the irreducible contribution of \(^{7}\text{Be} \) solar neutrinos. The experiment will consist in counting the number of observed events at each detector location and to compare it to the expectation without oscillations. The position of each event can be reconstructed with a precision of \( \sim 12 \) cm at 1 MeV. In order to highlight the physics reach of a test accomplished with an external source, Fig. 5 displays the exclusion plot that might be obtained at 95% C.L., with a 10 MCI \(^{51}\text{Cr} \) source located externally. Though not conclusive, an external
test performed with a sufficiently strong neutrino source will start to address a sizable portion of the oscillation parameter region of the Gallium and reactor anomalies.

A similar program as been proposed in the SNO+ detector but deploying the source at the center of the detector [7]. Since the detection will be performed via elastic scattering on electrons, the usual Compton effect induced by gammas is a dangerous background. Feedback from Gallex experiment activity measurement performed after the preparation $^{51}$Cr source indicates a rate of 10 GBq of long lived 1.5 MeV y’s [23]. Those y’s must thus be shielded via a thick dense alloy like tungsten, that also needs to be ultrapure at the mBq level.

We mention here that the Borexino contemplates first the deployment a $^{51}$Cr $\nu_e$ external source and second the deployment of an internal $\bar{\nu}_e$ source, like the $^{144}$Ce-$^{144}$Pr material (see Section 5.2.1).

5.1.3. LENS-Sterile

The LENS (for Low Energy Neutrino Spectroscopy) project is first intended to measure solar neutrinos in real time [20]. The LENS-Sterile concept consist in placing a 10 MCi neutrino source at the center of detector, and counting the $\nu_e$ interactions as a function of distance from the source [21]. The detection will be done through a low threshold charged current process, $^{115}$In + $\nu_e \rightarrow ^{115}$Sn + e$, followed by gamma ray’s de-exitation allowing to reject backgrounds. Beyond the very high activity source production the first challenge consist in the realization of a low background segmented neutrino detector doped with natural indium.

5.2. $^{144}$Ce-$^{144}$Pr projects

We now review projects based on $^{144}$Ce-$^{144}$Pr $\bar{\nu}_e$ emitters whose decay scheme is shown on Fig. [2].

5.2.1. CeLAND

CeLAND is a project based on 50 kCi of $^{144}$Ce [25]. Cerium was chosen because of its high $Q_f$, its ∼4% abundance in fission products of uranium and plutonium, and finally for engineering considerations related to its possible extraction of rare earth from regular spent nuclear fuel reprocessing followed by a customized column chromatography. While not minimizing the difficulty of doing this, the nuclear industry does have the technology to produce sources of the appropriate intensity, at the ppm purity level and first samples are in the processed of being delivered in 2013. The goal of CeLAND is to deploy the $^{144}$Ce radioisotope at the center or next to a large LS detector, like KamLAND, Borexino, or SNO+, and to search for an oscillating pattern in both event spatial and energy distributions that would determine neutrino mass differences and mixing angles through an unambiguously L/E signature. We now focus on the unique oscillation signature induced by an eV-scale sterile $\nu$ at the center of a large neutrino detector. For $^{144}$Ce-$^{144}$Pr, 1.85 PBq (50 kCi) source lead to 40,000 interactions in one year in a KamLAND-like detector, between 1.5 and 6 m away from the source. This is realized with ∼15 g of $^{144}$Ce, whereas the total mass of all cerium isotopes is a few kg, for an extraction from selected fission products, as fresh as possible (e.g. 2 to 3 years after the last irradiation). Thanks to cold-pressing technics the source fits inside a <5 cm-scale capsule, small enough to consider the Cerium ball as a point-like source. For comparison the vertex reconstruction is <15 cm. $^{144}$Ce has a low production rate of high-energy $\gamma$ rays (> 1MeV) from which the $\bar{\nu}_e$ detector must be shielded to limit background events. This source initially releases ~300 W, but it will be self-cooled through convective exchanges with the LS without increasing the detector temperature by more than a few degrees. The expected oscillation signal for $\Delta m^2_{new} = 2$ eV$^2$ and sin$^2(2\theta_{new}) = 0.1$, is shown on Fig. [3]. The space-time coincidence signature of IBD events ensure an almost background-free detection. Backgrounds are of two types, those induced by the environment or detector, and those due to the source and its shielding. The main concern is accidental coincidences between a prompt (E>0.9 MeV) and a delayed energy depositions (E=2.2 MeV) occurring within a time window taken as three neutron capture lifetimes.
on hydrogen (~600μsec), and within a volume of 20 m³. The main source of detector backgrounds originates from accidental coincidences, fast neutrons, and the long-lived muon induced isotopes $^3\text{Li}^\beta\text{He}$ and scales with $R^2$ when using concentric $R$-bins. These components are routinely being measured in situ in Borexino and KamLAND. Geologic $\bar{\nu}_e$ arising from the decay of radioactive isotopes of Uranium/Thorium in the Earth have been measured in KamLAND [25] and Borexino [26]. Reactor $\bar{\nu}_e$ emitted by the $\beta$-decays of the fission products in the nuclear cores have been measured in KamLAND [28] and Borexino [27]. The sum of all these backgrounds is quite small with respect to the $\bar{\nu}_e$ rate from a kCi source. Note that non-source backgrounds can be measured in situ during a blank run with an empty shielding. The most dangerous source background originates from the energetic 2.185 MeV $\gamma$ produced by the decay through excited states of $^{144}\text{Pr}$. We approximate $\gamma$ ray attenuation in a shield of ~35 cm of tungsten alloy with an exponential attenuation law accounting for Compton scattering and photoelectric effect. The intensity these $\gamma$ rays is then decreased by a factor $< 10^{-12}$ [29], to reach a tolerable rate. An important remaining background source could be the tungsten alloy shield itself. Activities at the level of ten to hundreds $\text{mBq/kg}$ have been reported, suitable for the experiment. Assuming a ~5 tons shield a prompt and delayed event rates of 50 Hz and 25 Hz, respectively source induced background become negligible beyond a distance of 1.5 m from the source. An oil buffer surrounding the shielding or a composite shielding could further suppress both source and shield backgrounds if necessary; Any of the photons or shielding backgrounds can account for either the prompt or delayed event, depending on their energy. The sum of the backgrounds integrated over their energy spectrum is shown on Fig. 3 supporting the case of kCi $\bar{\nu}_e$ source versus MCi $\nu_e$ source for which solar-$\nu$‘s become an irreducible background. Assuming a new neutrino oscillation with $\Delta m^2_{\text{new}} = 2 \text{ eV}^2$ and $\sin^2(2\theta_{\text{new}}) = 0.1$, the interaction rate decreases from 40,000 to 38,000 per year. The sensitivity of an experiment with a 50 kCi $^{144}\text{Ce}$ source running for 1 year, using only events between 1.5 m and 6 m is displayed on Fig. 4. The 95% C.L. sensitivity is extracted through a Pearson $\chi^2$ test assuming a 2% fully uncorrelated systematic error, and accounting for a fiducial volume uncertainty of 1% in a calibrated detector, as well as for $(e^+, n)$ space-time coincidence detection efficiencies uncertainties at the sub-percent level. The source activity uncertainty is taken as a normalization error of 1% Results indicates that 50 kCi of $^{144}\text{Ce}$ allows us to probe the whole combined reactor and Gallium anomaly parameter space at least at 95% C.L. An analysis assuming no knowledge on the source activity shows that the oscillatory behavior can be established for $\Delta m^2_{\text{new}} < 10 \text{ eV}^2$.

5.2.2. $^{144}\text{Ce}$-$^{144}\text{Pr}$ in Daya-Bay

Following the original CeLAND proposal [25] the far site detector complex of the Daya Bay reactor experiment is being considered for the deployment of a 500 kCi $^{144}\text{Ce}$-$^{144}\text{Pr}$ towards the search of sterile neutrinos [22]. The far site detector complex of the Daya Bay reactor experiment houses four 20-ton $\bar{\nu}_e$ detectors with a separation of 6 m. When combined with a compact radioactive $\bar{\nu}_e$ source the detectors provide a well suited
Figure 5: 95% C.L. exclusion limit of the ν source projects planned towards the search of a fourth neutrino state, in the $\Delta m_{\text{new}}^2$ and $\sin^2(2\theta_{\text{new}})$ plane (2 dof). The best sensitivity is provided by the 50 kCi $^{144}$Ce project (CeLAND, thick black curves). Results are compared to the 95% C.L. inclusion domains given by the combination of reactor neutrino experiments, Gallex and Sage calibration sources, and compared to the 95% C.L. inclusion domains given by the combination of reactor neutrino experiments, Gallex and Sage calibration sources, and $^{13}$C$
u_e$ sources projects currently being developed, each facing the challenges of the source production, transportation, and deployment. In the forthcoming years these novel efforts could disprove or confirm convincingly the sterile neutrino hypothesis [7].

5.3. Conclusion

The implications of the existence of an additional sterile neutrino states would be profound. This would require the evolution of the current adopted paradigm of the standard model of Particle Physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos. Novel $\nu$ source experiments could play a major role in order to provide a definitive resolution of the current neutrino anomalies. The global superior characteristic of the $\bar{\nu}_e$ scenario is illustrated on sensitivity curves in fig. 5, where the 95% sensitivity contour covers the entire 95% joint gallium-reactor anomaly region. At this early stage both MCi $^{51}$Cr $\nu_e$ and $^{144}$Ce kCi $\bar{\nu}_e$ sources projects are currently being developed, each facing the challenges of the source production, transportation, and deployment. In the forthcoming years these novel efforts could disprove or confirm convincingly the sterile neutrino hypothesis [7].

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