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Reactors antineutrino anomalies and searches for sterile neutrinos

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Abstract. Over the last 20 years a standard neutrino oscillation framework associated with small splitting between the neutrino mass states have become well established. Beyond this model, anomalies have been observed at short baseline in reactor, accelerator and gallium experiments. This suggests the existence of a fourth massive neutrino, affecting experiments through oscillation with active flavours with $\Delta m^2$ above 0.1 eV$^2$. To definitively test this $\Delta m^2$ region, several experiments on reactors or using neutrino or antineutrino sources are in preparation.

1. Introduction
Most results from neutrino experiments over the last 20 years can be quite accurately described by a model of oscillations between three $\nu$ flavors ($\nu_e$, $\nu_\mu$, $\nu_\tau$) that are mixtures of three massive neutrinos ($\nu_1$, $\nu_2$, $\nu_3$) separated by squared mass differences of $\Delta m^2_{21} = 8 \times 10^{-5}$ eV$^2$ and $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV$^2$. Apart from the confusing results of the LSND and MiniBoone experiments, the hypothetical existence of a fourth $\nu$ has been revived by a new calculation of the rate of $\bar{\nu}_e$ production by nuclear reactors [1] that yields a $\bar{\nu}_e$ flux about 3% higher than previously predicted and used in old esxperiments. This calculation then implies [2] that the measured event rates for all reactor $\bar{\nu}_e$ experiments within 100 meters of the reactor are about 6% too low. The deficit can be explained by an hypothetical fourth massive $\nu$ separated from the three others by a new $\Delta m^2 > 0.1$ eV$^2$. This new possible mixing can explain a similar deficit in the rate of $\nu$ interactions in gallium solar-$\nu$ detectors when exposed to artificial $^{51}$Cr and $^{37}$Ar MCi sources. The combination of these deficits is significant at the 99.8% C.L. In this contribution we will present some of the several experiments under construction to test this hypothesis.

2. Experimental evidences pointing toward a fourth neutrino
Several sets of experimental results could be explained by the presence of a fourth neutrino. In particular experiments of antineutrinos at moderate distance ($< 100$ m) of nuclear reactors on one hand and results of calibration of gallium solar neutrinos experiments with neutrino sources on the other hand point to oscillation toward a fourth neutrino state with very similar parameters of oscillation. Although every single results is not conclusive by itself, the whole set of results is coherent and thus call for experimental verifications.
2.1. Reactor antineutrino anomaly

Nuclear reactors are very intense sources of neutrinos that have been used all along the neutrino’s history, from its discovery up to the most recent oscillation studies. With an average energy of about 200 MeV released per fission and 6 neutrinos produced along the β-decay chains of the fission products, one expects about 2x10^{20} ν/s emitted in a 4π solid angle from a 1 GW reactor (thermal power). Since unstable fission products are neutron-rich nuclei, all β-decays are of β- type and the neutrino flux is actually pure electronic antineutrinos (ν_e). The neutrino oscillation searches at a reactor is always based on a disappearance measurement, using the powerful inverse beta decay (IBD) detection process to discriminate the neutrino signal from backgrounds. The observed neutrino spectrum at a distance L from a reactor is then compared to the expected spectrum. If a deficit is measured it can be interpreted in terms of the disappearance probability which, in the two neutrino mixing approximation, reduces to:

\[ P_{ee} = 1 - \sin^2(2\theta) \times \sin^2\left(\frac{\Delta m^2 L}{2E}\right) \]

with Δm^2 the difference between the squared masses of the two neutrino mass eigen-states and θ the mixing angle fixing the amplitude of the oscillation. In the last 20 years reactor antineutrino experiments were performed at distances below 100 m from the reactor core, in particular at ILL-Grenoble, Goesgen, Rovno, Krasnoyarsk, Savannah River and Bugey. These experiments employed only one detector and therefore depend on an accurate theoretical prediction for the emitted ν_e flux and spectrum to measure P_{ee}. Until late 2010, all data from reactor neutrino experiments measured a rate of ν_e in reasonable agreement with that predicted from the ‘old’ reactor antineutrino spectra [3], though slightly lower than expected, with the measured/expected ratio R at 0.980 ± 0.024, where the recent neutron mean lifetime, of 881.5 s is used to compute the cross section of the detection reaction of ν_e on free protons:

\[ \bar{\nu}_e + p \rightarrow n + e^- + F \]

2.1.1. Reevaluation of reactor antineutrino experiments.

In preparation for the Double Chooz reactor experiment, the Saclay reactor neutrino group re-examined the specific reactor antineutrino flux from fission of 235U, 239Pu, 241Pu, and 238U using the new existing nuclear data. In 2011, they reported their results [1], which correspond to a flux that is a few percent higher than the previous prediction. Based on this new antineutrino fluxes a reanalysis of the ratio of observed event rate to predicted rate for 19 published experiments at reactor–detector distances below 100 m was performed.

In summary, this re-evaluation has revealed some systematic biases in the previously published conversion of the ILL electron data. Indeed starting from very precise electron spectrum measured at ILL resulting from the fission of the above nuclei you have to predict the spectrum of antineutrino; if this operation called conversion is trivial for allowed β transitions it is more and more difficult when the β spectrum result from forbidden transitions.

Finally the net result of this reevaluation is a ±3% shift in the predicted emitted spectra. The origin of these biases were not in the principle of the conversion method but in the approximate treatment of nuclear data and corrections to the Fermi theory. A complementary work [4] confirmed the origin of the biases and showed that an extra correction term should be added increasing further the predicted antineutrino spectra at high energy. These most recent spectra are the new reference used for the analysis of the reactor anomaly in the next section. The prediction of the last isotope contributing to the neutrino flux of reactors, 238U, is also updated by ab initio calculations.
Figure 1. Illustration of the short baseline reactor antineutrino anomaly

With this re-analysis of these experiments the ratio for all these reactor experiments measured/expected $R = 0.927 \pm 0.023$ (figure 1). Moreover the first ILL experiment performed in 1980 at less than 9 m from the core and reanalysed in 1995 [5] show an even greater deficit and even an intriguing structure in the energy spectrum.

2.2. Gallium neutrino anomalies

The GALLEX and SAGE solar neutrino detectors have been tested in so-called “Gallium radioactive source experiments” which consist in the detection of electron neutrinos produced by intense artificial $^{51}$Cr and $^{37}$Ar radioactive sources placed inside the detectors. These radioactive nuclei decays through electron capture, emitting $\nu_e$ lines at energies below 1 MeV.

The neutrinos emitted by the radioactive sources have been detected through the same reaction used for the detection of solar neutrinos $\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$. In total four source experiments have been performed. The average ratios of measured to predicted $^7$Ge production rates in the GALLEX and SAGE source experiments is $R = 0.86 \pm 0.05$. Thus, the number of measured events is about $2.8 \sigma$ smaller than the prediction. This is the “Gallium anomaly”, which could be also a manifestation of short-baseline neutrino oscillations.
2.3. Global fits

Each set of experiments fitted separately leads to similar values of $\sin^2(2\theta_{\text{new}})$ and similar lower bounds for $\Delta m_{\text{new}}^2$. Hence, we performed a global fit of these results [2] taking into account the existing correlations between experimental results. This leads to a solution for a new neutrino oscillation, such that $\Delta m_{\text{new}}^2 > 1.5 \text{ eV}^2$ (95% C.L.) and $\sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08$ (95% C.L.), disfavoring the no-oscillation case at 99.8% C.L [2] as illustrated in figure 2.

![Figure 2](image-url)

Figure 2. Allowed regions in the parameter space from the combination of reactor neutrino experiments, Gallex and Sage calibration sources experiments.

3. Experimental tests of a fourth neutrino on reactors

Clearly the possible existence of a fourth neutrino suggested by the above results call for experimental tests. In that respect several groups around the world are preparing experiments using different techniques. Apart from experiments using beams of neutrinos, these efforts can be divided in experiments at very close distance of a nuclear reactor and experiments using man-made neutrino and antineutrinos sources. Several projects on reactors in Europe are planned and I choose only four of them.

3.1. Nucifer.

The Nucifer [7] detector target is a stainless steel vessel of 1.8 m in height, and 1.2 m in diameter filled with about 0.85 m$^3$ of Gd-doped liquid scintillator (EJ335 from Eljen technology). The internal surface of the vessel is coated with Teflon to ensure the compatibility with the liquid scintillator and to increase the light reflections. All mechanical parts, in particular welding materials, are low radioactive materials. The photodetection system is made of 16 large (8 inches in diameter, R5912) photomultipliers (PMTs) from Hamamatsu, providing a large dynamic of light detection from the single photoelectron to few hundreds of photoelectrons and ensuring an efficient light collection. PMTs are coupled to a 250 mm thick acrylic vessel placed at the top of the target vessel. This so-called acrylic buffer aims at ensuring the uniformity of the response in the whole target volume while reducing the light generated by the intrinsic PMT radioactivity in the scintillator. 80 liters of mineral oil are used to ensure the optical coupling between the PMTs and the acrylic.
The Nucifer experiment takes data at the Osiris research reactor (70 MWth) at only 7 meters from the core. This unique configuration, short distance and the compactness of Osiris core reduces the dispersion of neutrino paths. If an eV^2 sterile neutrino exists the measured energy spectrum could appear distorted according to the neutrino oscillation hypothesis. The shape-only analysis of the Nucifer data will be the first unambiguous test of the existence of a sterile neutrino, although the complete area of the reactor anomaly contour can not be covered by this experiment alone.

3.2. Stereo.

The Stereo setup [6], based on experience from the Double Chooz and Nucifer experiments, is illustrated in figure 3. The target liquid scintillator, doped with Gd, is contained in a 8 mm thick acrylic vessel. The section of the target is about 1m x 1m and the length is 2m. The target vessel is immersed in another liquid scintillator, not doped with Gd, contained in a second acrylic vessel. This 15 cm thick outer layer collects part of the energy of γ-rays escaping from the target, reducing the low energy tail of the detector response. 64 PMTs of 8 inches diameter are distributed across the lateral surfaces of the outer acrylic box. The roof and bottom planes are covered with diffusive white Teflon. Fixed optical coupling of the photomultipliers with thick lateral acrylic walls can be used to provide mechanical support and serve as a buffer layer for a more uniform detector response.

![Figure 3. The Stereo detector and its implementation at the ILL reactor in Grenoble](image)

The Spectrum in energy to illustrate the potential of the Stereo experiment is shown in Figure 4. The observed energy spectrum is compared to the expected spectrum, showing a significant deviation from the expected distribution. The parameters used are: $\Delta m^2 = 2.3 \text{ eV}^2$ and $\sin^2(2\theta) = 0.17$.

![Figure 4. Spectrum in energy to illustrate the potential of the Stereo experiment](image)
The Stereo detector will be installed in 2014 at the ILL reactor in Grenoble. Along the axis pointing toward the compact core, the detector is built long enough to see the phase of the new oscillation in the energy spectrum changing along this axis (fig. 4). To prove the existence of a sterile neutrino, emphasis is put on the shape-only analysis, looking for the relative deformation of the spectrum along the detector with as little as possible normalization input.

3.3. DANSs.

The DANSS detector will consist of highly segmented plastic scintillator with a total volume of 1 m$^3$, surrounded with a composite shield of copper (Cu), lead (Pb) and borated polyethylene (CHB), and vetoed against cosmic muons with a number of external scintillator plates.

The basic element of DANSS is a polystyrene-based extruded scintillator strip (1×4×100 cm$^3$) with a thin Gd-containing surface coating which is a light reflector and an (n,γ)-converter simultaneously. The coating (about 0.1–0.2 mm) is produced by co-extrusion and consists of polystyrene with 18% admixture of rutile and 6% of gadolinium oxide, so that the final Gd density is about 1.6 mg/cm$^2$, which corresponds to $\approx$ 0.35 % wt. Light collection from the strip is done via three wavelength-shifting Kuraray fibers Y-11, $\varnothing$ 1.2 mm, glued into grooves along all the strip. An opposite (blind) end of each fiber is polished and covered with a mirror paint, which decreases a total lengthwise attenuation of a light signal down to $\approx$ 5 %/m.

Each 50 parallel strips are combined into a module, so that the whole detector (2500 strips) is a structure of 50 intercrossing modules. Each 2 module is viewed by a compact photomultiplier tube (Hamamatsu R7600U-200) coupled to all 50 strips of the module via 100 WLS fibers, two per strip. In addition, to get more precise energy and space pattern of an event, each strip is equipped with an individual multipixel photosensor (SiPM) operating in the Geiger mode and coupled to the strip via the third WLS fiber.

The detector is installed under the industrial 3 GWth reactor of the Kalinin Nuclear Power Plant – KNPP) and a pilot version DANSSino is operated already [8].

3.4. Soliδ [6]

The SoLiδ experiment employes also a highly segmented plastic scintillator detector to control the high level of backgrounds present close to reactor cores. The detector provides unique gamma-neutron discrimination by using an innovative sandwich of plastic and $^6$LiF:ZnS(Ag) scintillator. In addition, the segmentation provides a very good localisation of interactions giving superior capability to reject backgrounds.

This collaboration will install its detector at the BR2 MTR research reactor in Mol, Belgium which has one of the smallest reactor core providing a near point-like source which enables high resolution on oscillation patterns and powerful enough to accumulate sufficient number of neutrino interactions per day.

4. Experimental tests of a fourth neutrino with sources

The definitive test of the reactor antineutrino anomaly is the observation of the oscillation pattern as a function of L/E. This can be realized either by using a monochromatic neutrino source like $^{51}$Cr or $^{37}$Ar or by using an antineutrino emitter with a continuous beta spectrum. In the first case, with a liquid scintillator detector, the reaction is through the elastic scattering of neutrino on electrons, in the second case the antineutrino interact with the free protons through the inverse beta decay reaction.

Indeed if the source is install at the center of a detector the radial dependance of the interaction is only sensitive to the oscilating term :

$$\frac{dN}{dR}(R, t) \propto \frac{A(t)}{4\pi R^2} \times \langle \sigma \rangle \times N_p \times 4\pi R^2 \times P_{ee} \left( \frac{\Delta m^2 R}{\langle E \rangle} \right)$$
If the source, for technical reason, has to be installed outside of the detector, the predicted distribution in absence of oscillation is well predicted analytically and every deviation is due to oscillation (figure 5).

![Graph showing deviation of the distribution in distance of the interaction due to oscillation for different $\Delta m^2$.](image)

**Figure 5. Deviation of the distribution in distance of the interaction due to oscillation for different $\Delta m^2$.**

4.1. $^{51}$Cr neutrino source.
Intense $^{51}$Cr neutrino sources have been made in the past by irradiation of enriched chromium which is still available. $^{51}$Cr emits two monoenergetic lines of neutrinos (751 keV and 480 keV) well suited to test the possible new oscillation at few meters.

4.1.1. Dual metallic Gallium target experiment
To investigate the sterile neutrino explanation for the Gallium source experiments, an improved version of these measurements made by Sage will be used [9]. The plan is to place a $^{51}$Cr source with initial activity of 3 MCI at the center of a 50-tonne target of liquid Ga metal that is divided into two concentric spherical zones, an inner 8-tonne zone and an outer 42-tonne zone. If oscillations to sterile neutrinos do not occur, then at the beginning of irradiation there is a mean of 65 atoms of $^{71}$Ge produced by the source per day in each zone. After an exposure period of a few days, the Ga in each zone is transferred to reaction vessels and the $^{71}$Ge atoms produced by neutrino capture are extracted.

These steps are the same as were used in the prior source experiments and are well tested. Finally, the Ge atoms are placed in proportional counters and their number is determined by counting the Auger electrons released in the transition back to $^{71}$Ge, which occurs with a half life of 11.4 days. A series of exposures is made, each of a few days duration, with the $^{71}$Ge atoms from each zone measured in individual counters.

If oscillations to a sterile neutrino are occurring with mass-squared difference of $\Delta m^2$ and mixing parameter $\sin^2(2\theta_{\text{new}})$, then the rates in the outer and inner zones of gallium will be different.
4.1.2. SoX phase 1
The solar neutrino detector Borexino is also perfectly suited to host a source experiment able to shed light on experimental hints, pointing to the possible existence of a sterile neutrino at the few eV² mass scale. The extreme radiopurity achieved in the liquid scintillator acting as detection medium, make Borexino an ideal choice for the sterile neutrino experimental investigation. Preliminary studies indicate, in particular, that Borexino could be a well suited location both for an external neutrino source experiment (with an ultimate background of about 50 eV/day mainly due to the irreducible contribution of solar neutrinos).

Neutrino source experiments have been part of the Borexino program since the very beginning of the project and thus a small tunnel was built right below the water tank, providing a location as close as 8.25 m to the scintillator inner vessel center. This tunnel is ready to be used. This location, together with other possible locations inside the detector which have been also investigated, is very appropriate for a sterile neutrino search with the current Borexino set-up. The distance between the source and the detector, and the size of the detector itself, are of the order of few meters, thus comparable with the expected oscillation length : therefore a possible striking signature of the occurrence of the oscillation involving the putative sterile neutrino would be the development across the detector of a clearly visible “spatial wave of detected neutrino events.

By irradiating the enriched chromium previously used in Gallex, an intense (> 6 MCi) neutrino source can be realized.

4.2. ¹⁴⁴Ce-¹⁴⁴Pr antineutrino sources
The elastic scattering of neutrino can be easily mimic by a Compton scattering, thus the constraints for an experiment with a neutrino source are severe. On the contrary the use of an antineutrino source allow the detection via IBD with a delayed coincidence. This offer an efficient rejection of gamma induced background.

A suitable $\nu_e$ source must have Q$_\beta$ > 1.8 MeV (the IBD threshold) and a lifetime that is long enough (≈ 1 year) to allow for production and transportation to the detector. For individual nuclei, these two requirements are contradictory so we expect candidate sources to involve a long-lived low-Q nucleus that decays to a short-lived high-Q nucleus. Four such pairs $^{144}$Ce-$^{144}$Pr [Q$_\beta$ $^{144}$Pr = 2.996 MeV], $^{106}$Ru-$^{106}$Rh, $^{90}$Sr-$^{90}$Y and $^{42}$Ar-$^{42}$K were identified [10,11]. The first three are common fission products from nuclear reactors that can be extracted from spent fuel rods. 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. Delays obtaining authorizations for transportation and deployment of the source into an underground laboratory should be addressed at the start of the project. Now we concentrate on the $^{144}$Ce source (Fig. 6) because its high Q$_\beta$ and because it is easier to extract chemically than $^{106}$Ru.

We note also that it has a low production rate of high energy g-rays ( > 1 MeV) from which the $\nu_e$ detector must be shielded to limit background events. Finally, Cerium is present in fission products of uranium and plutonium at the level of a few percent. The specific activity of $^{144}$Ce is 3.18 kCi/g, but this radioactive isotope remains mixed with the other stable Cerium isotopes. The heat output 7.90 W/kCi allow the measurement of the activity at the 1% level with calorimetry.

4.2.1. Detectors
Three large liquid scintillators detectors are operating around the world in underground laboratories : Borexino in Italy, KamLAND in Japan and SNO+ in Canada. Apart from the size of the target, the choice of a detector is mainly driven by the interest of the existing collaboration to perform this search of a fourth neutrino and by the interference with the existing program of physics detectors.
4.2.2. KamLAND
The CeLAND experiment aims at deploying a 75 - 100 kCi of $^{144}\text{Ce-}^{144}\text{Pr}$ in the outer veto of the KamLAND detector. The source will be produced at PA Mayak in Russia in a unique installation able to separate at the industrial level every rare earth fission product. The transport to the experimental site has to follow the constraining international legislation edicted by IAEA, it constitute one of the most difficult step to achieve in these projects. The data taking will last 18 months. Thanks to the well known performances of the detector a virtually background free experiment could be envisaged. Both energy and interaction point can be known event by event and the L/E distribution could be plotted as shown in figure 7.

4.2.3. SoX phase 2 in Borexino
A very similar program is considered in Borexino (SoX phase 2) after the test with the $^{51}\text{Cr}$ neutrino source. The $^{144}\text{Ce-}^{144}\text{Pr}$ will be produced also in Mayak but the activity envisaged is twice higher to compensate the smaller sensitive target. Transportation issue, although challenging, might be easier than in CeLAND.
5. Conclusion
In summary, there are a number of experimental results that appears anomalous in the context of the standard 3 neutrino framework, and that can be explained by a sterile neutrino with mass around 1 eV. The need thus arises to provide a more ardent and complete test of the sterile neutrino hypothesis, which will unambiguously confirm or refute the interpretation of past experimental results. In the next 2-3 years results will be obtained with experiments using different techniques and different sources [6]. As shown in figure 8 these experiments will test the sterile neutrino hypothesis covering the full range of oscillation parameters.

Figure 7. Expected result of CeLAND in L/E

Figure 8. Comparison of the different experiments testing the sterile neutrino hypothesis
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