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Sterile neutrino search through disappearance studies with a High-intensity ^{51}Cr Source and the Borexino detector

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Solar neutrino experiments, reactor flux analysis and cosmological models suggest the existence of a new kind of neutrino. Immune to chromodynamic and electroweak interactions, the proposed particle would be called *sterile*. Other sets of data already provide strong constraints on its hypothetical mass splitting and mixing angles. New experiments are needed to test the light (~1eV) sterile neutrino models (3+1 or 3+N_s). Capitalizing on unique resolution and position reconstruction precision of the Borexino detector, we will explore the phase space where sterile neutrino(s) may lie. After the current solar program, a ~10MCi ^{51}Cr source will be placed under Borexino, where oscillations of its electron neutrino flux into the sterile state could be detected, if present. We show the status of the plans for chromium irradiation and source activity measurement, as well as future projects with neutrino sources inside Borexino.

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1. Introduction

Neutrino measurements by real-time detectors —of which Borexino is a world-class example, and the first to measure in real time the dominant, sub-MeV solar spectrum [1] — have confirmed neutrino oscillations between its three known flavour states, and their enhancement due to the weak interactions with electrons in matter through the MSW effect: Borexino results have excluded several MSW solutions, showing a clear preference for the *Large Mixing Angle* (LMA) parameters.

In addition, Borexino aims to clarify the question of the existence of neutrino oscillations into additional states, beyond the three known ν_e, ν_μ and ν_τ; in particular, into the so-called *sterile states*, detectable only as a deficit in a 'regular'-neutrino flux. The *Short-distance Oscillations with Borexino* (SOX) project aims to explore the mass-scale of $\sim 1eV^2$. This low L/E region is mostly unexplored: there are phase-space areas where sterile neutrinos may exist, even in light of constraints by recent experiments.

2. The Borexino detector

Borexino is a neutrino detector based on the principles of ultra-radiopure liquid scintillator and graded shielding. The overburden of the mountains over the Laboratori Nazionali del Gran Sasso (LNGS) provides ∼3600 meters of water-equivalent shielding against cosmic backgrounds. The detector itself —an 18-meter-diameter Stainless Steel Sphere (SSS), filled with ∼1100 tons of pseudocumene (PC) and 2212 photomultipliers (PMTs) mounted on its walls— is surrounded by a domed tank filled with ultra-pure water, which serves as a Čerenkov muon veto, with an efficiency greater than 99.99%. The PC volume is separated by two ultra-low-radioactivity nylon spheres: the outer vessel (OV), used to prevent radon gas emanating from the SSS's hardware from reaching the center of the detector; and the inner vessel (IV), which separates the buffer region outside the IV, doped with dimethylphthalate (DMP, 2 g/L), used to quench light emission; from the interior of the IV, doped with 2,5-diphenyloxazol (PPO, 1.5 g/L), used to shift the UV scintillation light to a longer wavelength closer to the maximum PMT efficiency. Finally, software cuts generate a ∼100-ton, radiopurest fiducial volume (FV) specially tailored for each particular data analysis [3].

The light yield is ∼500 photo-electrons/MeV, with a threshold of ∼60 keV (∼180 keV for analysis purposes). Scintillation light in Borexino can be generated in many ways indistinguishable from the neutrinos elastic-scattering off electrons in the PC: thus the extreme radiopurity levels sought and mantained. In order to filter out these background events, purifications, software discrimination of events and calibrations are used, on top of cleanliness and hardware design. Four major calibration campaigns have taken place since Borexino's activation in 2007, using different types of radiation sources (α, β, γ, neutrons) with energies ranging from the detector's lowest threshold to ∼10 MeV. Since most of these activities involved placing the calibration source *inside* the FV, special care was taken not to contaminate the pristine environment with long-lifetime radioactive substances: this was successfully achieved in all cases[2] .

3. ^{7}Be, *pep* and ^{8}B solar νs, *CNO* limit, and geo(anti)neutrinos

Borexino's main design goal was the measurement of the ^{7}Be neutrino Compton edge-like scattering signal. It has indeed provided the most precise determination of its rate to date: $46.0\pm$

$1.5_{sys}{}^{+1.5}_{-1.6stat}$cpd/100 tons [3]. This ^{7}Be signal was also used in the ***day/night assymetry*** measurement, which studied the regeneration that ν_e experience when traversing matter due to the MSW effect: analyzed with two different techniques, Borexino data showed no asymmetry ($A_{dn} = 0.001 \pm 0.012_{stat} \pm 0.007_{sys}$)[3], as expected using the LMA solution, rejecting LOW at the 8.5σ level. The ***annual modulation of the*** ^{7}***Be flux*** was studied with a Lomb–Scargle periodogram search method, which yielded a 0.98 year period (3σ c.l.) and an eccentricity of 0.0398 ± 0.0102, consistent with no anomalous effects apart from the 1/r^2 geometrical flux modulation (2σ c.l.) [3]. The first direct detection of *pep* neutrinos ($3.1 \pm 0.6_{stat} \pm 0.3_{sys}$ cpd/100 tons[3]) and the lowest limit yet on the *CNO* flux (<7.9 cpd/100 tons (90% c.l.)) were achieved by Borexino in 2011. Borexino also released in 2010 the lowest-threshold (3 MeV), first liquid scintillator measurement of the ^{8}B flux: $0.217 \pm 0.038_{stat} \pm 0.008_{sys}$ cpd/100 tons[3]. In 2013 Borexino has also provided a 50:1 signal-to-noise result for ***geoneutrinos***: 2.3 ± 0.7 cpy/100 tons[3], using a prompt-delayed signal profile from positron annihilation and neutron capture γs, improving the uncertainty of the previous measurement (from 2010) by ~50%. All these results used *only* Phase I data (until October 2011)

4. SOX project

Indications of the existence of more than 3 neutrino flavors have existed since the LSND experiment ($\bar{\nu_\mu} \rightarrow \nu_e$ at 20-60 MeV) saw an unexpected excess at 3.8σ in the 1990s. Later, gallium experiments (GALLEX, SAGE...), based on ν_e disappearance, gave further –albeit weak– support to this extra oscillation hypothesis, along with a recent re-evaluation of nuclear reactor $\bar{\nu}$ fluxes. Theoretical frameworks exist which could provide support for these results, including the existence of a ~ 1eV sterile neutrino state mixing with the three known weak eigenstates [4]. Still, there are also ambiguous and even contradictory results (MiniBooNE, MINOS, Planck's new data...).

In this climate of urgent need of further experimental data to confirm or reject the ample but confusing existing evidence, Borexino will use its sensitivity to check for anomalous rate deficits and unexpected spatial neutrino oscillations in the mostly-unexplored low L/E region, measuring the flux coming from external or internal ν sources [5].

4.1 SOX-A

Borexino was built over a small tunnel (~1 m^2 cross-section) designed for placing radioactive sources directly under the experiment, requiring no modifications to the detector itself or a disruption of normal operations. The aim of SOX-A is to deploy a ~10MCi ^{51}Cr source inside this pit, at ~8.25m from the center of the detector, producing neutrinos according to the electron capture decay:

$$^{51}Cr + e^- \rightarrow ^{51}V + \nu_e \; ; \; E_\nu \sim 750keV(90\%), 430keV(10\%)$$

A 320keV γ is emmited (b.r. ~10%), which can be attenuated to negligible levels with a few cm of W shielding which, however, needs to be thickened due to minute levels of impurities in the chromium that produce higher-energy γs which would otherwise be an issue for the experiment or the handling of the source. Thermal limits are not an issue however, and active cooling will not be necessary.

Design for the source's shielding and containers, is maturing and reaching the industry tender level. Quick transportation strategies (due to ^{51}Cr's low halflife: τ =27.7 days) and installation permissions for a ∼100 day campaign in 2015 are also underway. The available stock of 38%-enriched chromium from GALLEX is expected to be used, with the possibility of procuring new, higher-enriched material. It will be irradiated in a high-flux nuclear reactor: the High-Flux Isotope Reactor (HFIR) in Oak Ridge National Laboratory, USA; or the Mayak reactor in Russia. MonteCarlo simulations on the expected activity are already being performed. A ∼1% source activity determination is paramount for the sensitivity of the measurement. To this end, gamma and ^{51}V-assay of representative samples and, most notably, full-source calorimetry will be performed. A water-flow calorimeter will be built to perform a continuous decay measurement while the source is deployed and independently verify impurity contents. Some backgrounds, like ^{210}Po, are expected to have decayed away when SOX-A is deployed: in fact, the main irreducible background will be solar νs.

The accrued data will be analyzed with **rate** (more sensitive to θ_{14}) and **rate+shape** techniques: oscillations from ∼1eV neutrinos would be within both Borexino's size and position resolution. This would provide a direct measurement of both Δm^2_{14} and θ_{14}, covering most of the gallium+reactor anomaly phase space. Other precision results are expected: Weinberg angle, neutrino magnetic moment and the g_A, g_V parameters at low energies.

4.2 SOX-B and C

A ^{144}Ce-Pr internal source will be fabricated from spent nuclear fuel. SOX-B will deploy it inside the water tank (∼2016), while SOX-C is designed to use the whole SSS as the FV, placing it in the center of Borexino (2017 or later). These projects will require a refurbishment of the detector, and active cooling for the source, but are expected to cover all of the gallium+reactor anomaly 99%-allowed phase space to 95% and 99% c.l. respectively.

5. Conclusions

Borexino aims to build upon this prolific period (Phase I) using its most recent data (Phase II, where backgrounds are greatly reduced), by improving uncertainties in current measurements, and complementing this with the expected observation of the *pp* (and perhaps *CNO*) solar ν component. Additionally, the multi-step SOX source program is designed to test the current anomalous neutrino oscillation discussion in the low L/E region.

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