Available online at www.sciencedirect.com

SciVerse ScienceDirect

Nuclear Physics B (Proc. Suppl.) 235–236 (2013) 55–60

NUCLEAR PHYSICS B
PROCEEDINGS SUPPLEMENTS

www.elsevier.com/locate/npbps

Recent results and future development of Borexino

M. Pallavicini[h,*], G. Bellini[a], J. Benziger[b], D. Bick[c], G. Bonfini[d], D. Bravo[e], M. Buizza Avanzini[a], B. Caccianiga[a], L. Cadonati[f], F. Calaprice[g], C. Carraro[h], P. Cavalcante[d], A. Chavarria[g], D. D'Angelo[a], S. Davini[h,i], A. Derbin[j], A. Etenko[k], K. Fomenko[l], D. Franco[m], C. Galbiati[g,a], S. Gazzana[d], C. Ghiano[m], M. Giammarchi[a], M. Göger-Neff[n], A. Goretti[g,d], L. Grandi[g], E. Guardincerri[h], S. Hardy[e], Aldo Ianni[d], Andrea Ianni[g], V. Kobychev[p], D. Korablev[l], G. Korga[i], Y. Koshio[d], D. Kryn[m], M. Laubenstein[d], T. Lewke[n], E. Litvinovich[k], B. Loer[g], P. Lombardi[a], F. Lombardi[d], L. Ludhova[a], I. Machulin[k], S. Manecki[e], W. Maneschg[q], G. Manuzio[h], Q. Meindl[n], E. Meroni[l], L. Miramonti[l], M. Misiaszek[o], D. Montanari[d], P. Mosteiro[g], V. Muratova[j], L. Oberauer[n], M. Obolensky[m], F. Ortica[r], K. Otis[f], L. Papp[e], L. Perasso[h], S. Perasso[h], A. Pocar[f], R.S. Raghavan[e,**], G. Ranucci[a], A. Razeto[d], A. Re[l], A. Romani[r], N. Rossi[d], A. Sabelnikov[k], R. Saldanha[g], C. Salvo[h], S. Schönert[q], H. Simgen[q], M. Skorokhvatov[k], O. Smirnov[l], A. Sotnikov[l], S. Sukhotin[k], Y. Suvorov[d,k], R. Tartaglia[d], G. Testera[h], D. Vignaud[m], R.B. Vogelaar[e], F. von Feilitzsch[n], J. Winter[n], M. Wojcik[o], A. Wright[g], M. Wurm[n], J. Xu[g], O. Zaimidoroga[l], S. Zavatarelli[h], G. Zuzel[q]

[a]*Dipartimento di Fisica, Universitá degli Studi e INFN, Milano 20133, Italy*
[b]*Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA*
[c]*University of Hamburg, Hamburg, Germany*
[d]*INFN Laboratori Nazionali del Gran Sasso, Assergi 67010, Italy*
[e]*Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA*
[f]*Physics Department, University of Massachusetts, Amherst 01003, USA*
[g]*Physics Department, Princeton University, Princeton, NJ 08544, USA*
[h]*Dipartimento di Fisica, Universitá e INFN, Genova 16146, Italy*
[i]*Physics Department, Houston University, Houston, USA*
[j]*St. Petersburg Nuclear Physics Institute, Gatchina 188350, Russia*
[k]*NRC Kurchatov Institute, Moscow 123182, Russia*
[l]*Joint Institute for Nuclear Research, Dubna 141980, Russia*
[m]*APC, Univ. Paris Diderot, CNRS/IN2P3, CEA/Irfu, Obs de Paris, Sorbonne Paris Cité, France*
[n]*Physik Department, Technische Universität München, Garching 85747, Germany*
[o]*M. Smoluchowski Institute of Physics, Jagellonian University, Krakow, 30059, Poland*
[p]*Kiev Institute for Nuclear Research, Kiev 06380, Ukraine*
[q]*Max-Plank-Institut für Kernphysik, Heidelberg 69029, Germany*
[r]*Dipartimento di Chimica, Universitá e INFN, Perugia 06123, Italy*

Abstract

This paper summarizes the main recent results of the Borexino experiment, a liquid scintillator neutrino detector of unprecedented radiopurity currently running at the Laboratori Nazionali del Gran Sasso in Italy. Particularly, the paper is focused on the precision measurement of the ^{7}Be solar neutrino flux, on the search of its day–night modulation, and on the first detection of pep neutrinos. The paper also covers a recent measurement of the CNGS neutrinos speed made in May 2012. A short discussion about the forthcoming scientific program on solar neutrinos, geoneutrinos, and sterile neutrino searches is included at the end.

Keywords: Solar Neutrinos, Neutrino oscillations, MSW effect, Neutrino speed

0920-5632/$ – see front matter
http://dx.doi.org/10.1016/j.nuclphysbps.2013.03.011

1. Introduction

Borexino is a liquid scintillator calorimeter [1][2][3] designed for the real–time observation of low energy solar neutrinos, which are detected through their elastic scattering on electrons and by means of the consequent emission of scintillation light.

The total cross section of electron neutrinos depends on both charged and neutral currents weak interactions, while that of other neutrino flavors is induced by neutral currents only. The interaction rate depends therefore on the neutrino type at the target, a fact that makes the experiment sensitive to neutrino oscillations occurring along the path from the production site in the Sun's up to the detector

At the time of the proposal, the main goal of Borexino was the precise measurement of the rate induced by the monochromatic electron neutrinos (0.862 keV) produced by the electron capture decay of ^{7}Be in the Sun. However, the very high radio purity of the scintillator offered new unexpected results, such as a clear evidence of the pep solar neutrinos [4], a low energy threshold (3 MeV) detection of ^{8}B neutrinos [5], and an unambiguous detection of geo-neutrinos [6]. Other even more challenging goals like the detection of pp neutrinos and, possibly, a tight upper limit on CNO neutrinos, might be achievable in the near future.

The study of low energy solar neutrinos is very significant for two main reasons: on one hand, they offer a unique opportunity to investigate the behavior of the Sun's interior and test the predictions of the Standard Solar Model; on the other, they allow to probe the MSW-LMA neutrino oscillation scenario in an energy range that is not accessible to water Cherenkov detectors [7] [8], which can detect solar neutrinos only above an energy threshold of about 4 MeV.

This paper first describes (section 2.1) the precise measurement of the ^{7}Be neutrino flux obtained in 2011. This result comes from a very careful study of the detector response, which was made by means of an extensive calibration campaign and a careful Monte Carlo modeling of the scintillator properties, and of the light propagation inside the detector. A final precision better than 5% was obtained. As an interesting by–product of this work, we studied the day–night modulation of the same ^{7}Be neutrino flux (section 2.2). Although no modulation is expected in the MSW-LMA scenario, its lack has interesting consequences that we have explored. Finally, we report about the very first detection of the monochromatic pep neutrinos in section 2.3. This result, completely unexpected at the time of detector design, has been possible because of the very good radio–purity of the scintillator and thanks to very innovative techniques that were developed for the rejection of cosmogenic backgrounds.

In May 2012 we have done a measurement of the CNGS muon neutrinos speed, triggered by the initial announcement made by the Opera Collaboration that they might travel faster than light. Though the result was later proved to be incorrect and withdrawn by Opera, we have completed the measurement. The result, consistent with the speed of light in vacuum, is reported in section 3.

The unprecedented purity of the Borexino scintillator, further improved by a purification campaign carried out in 2010/2011, offers interesting possibilities for the future of the experiment, both in solar neutrino physics and in other fields. The collaboration has proposed to perform an experiment for the search of sterile neutrinos by means of neutrino sources (e.g. a ^{51}Cr source similar to that used in 1995 by the Gallex collaboration [9]) or anti–neutrino sources (e.g. ^{90}Sr or ^{144}Ce). These options are currently under investigation, and are brierfly described in section 4.

2. Solar neutrino results

2.1. Precise measurement of the ^{7}Be neutrino flux

At the Neutrino '08 conference we reported a direct measurement of the ^{7}Be solar neutrino flux with combined statistical and systematic errors of 10% [10]. Thanks to a long campaign of detector calibrations performed in 2009, a fourfold increase in solar neutrino exposure, and a substantial improvement in the Monte Carlo model used to simulate the scintillator behavior, the light propagation and the detector response, a new neutrino flux measurement with a total uncertainty less than 5% was recently published [11]. For the first time, the experimental uncertainty is smaller than the uncertainty in the Standard Solar Model ("SSM") prediction of the ^{7}Be neutrino flux [13]. The new result is based on the analysis of 740.7 livedays (after cuts) of data which were recorded in the period from May 16, 2007 to May 8, 2010, and which correspond to a 153.6 ton ·yr fiducial exposure.

The ^{7}Be is obtained from a fit to the energy spectrum of the events that survive the cuts (see Fig. 1). The spectral fit is done in two different independent ways as described in the caption of Fig. 1.

*speaker: marco.pallavicini@ge.infn.it
**deceased

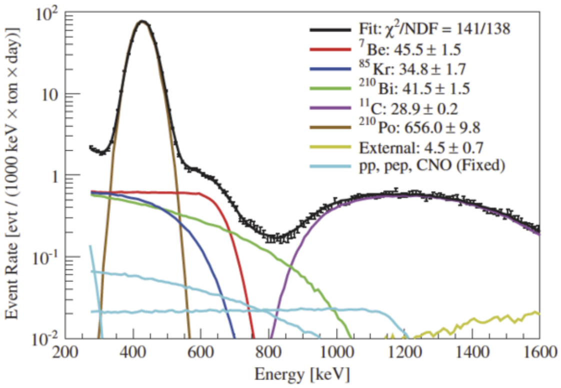

Figure 1: Two example fitted spectra; the fit results in the legends have units [counts/day·100 ton]. Top: A Monte Carlo based fit over the energy region 270–1600 keV to a spectrum from which some, but not all, of the α events have been removed using a pulse shape cut. Bottom: An analytic fit over the 290–1270 keV energy region to a spectrum obtained with statistical subtraction.

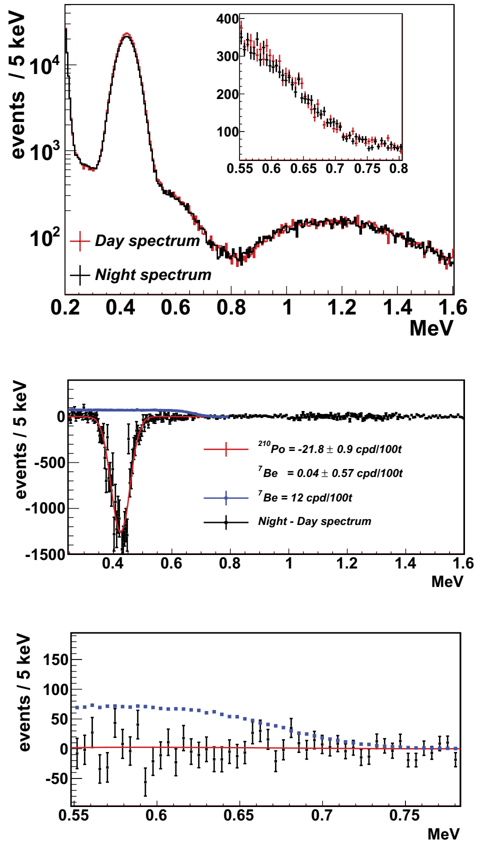

Figure 2: Top: energy spectrum of events during day (red) and night (black) normalized to the day live–time. The insert shows the ^{7}Be neutrino energy window. Middle: Difference of night and day spectra in the extended energy range including the region dominated by the ^{11}C background. Bottom: a zoom of the ^{7}Be energy window between 0.55 and 0.8 MeV. The blue curve shows the shape of electron recoil spectrum that would be seen assuming the LOW solution. See [12] for more details.

The main systematic uncertainties in our measurement of the ^{7}Be interaction rate come from the determination of the fiducial volume, from our understanding of the detector energy response, and from the variation between the results of the different fit procedures.

We note the remarkable decrease in the uncertainties associated with the detector energy response and the definition of the fiducial volume, by factors of 4.6 and 2.2, respectively, relative to [10]. The key factor for these improvements was a long calibration campaign made with α, β, γ and neutron sources that were placed in several different location inside and close to the solar neutrino fiducial volume. This calibration data have been crucial for the precise determination of the fiducial volume and for the precision tuning of the Monte Carlo parameters. For more details about the analysis and the systematic error evaluation the reader should refer to [11].

Our best value for the interaction rate of 862 keV ^{7}Be solar neutrinos in Borexino is $46.0 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{sys})$ counts/day · 100 ton. If the neutrinos are assumed to be purely electronic, this corresponds to an 862 keV ^{7}Be solar neutrino flux of $2.78 \pm 0.13\ 10^9\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. The corresponding flux prediction from the SSM is $4.48 \pm 0.31\ 10^9\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, which, if all the neutrinos remained electronics, would yield an interaction rate of 74.0 ± 5.2 counts/day ·100 ton in Borexino; the observed interaction rate is 5 σ lower.

2.2. Day–night modulation of the ^{7}Be neutrino flux

We have studied the day–night modulation of the ^{7}Be count rate in the detector. Although the standard MSW-LMA scenario does not predict any significant effect,

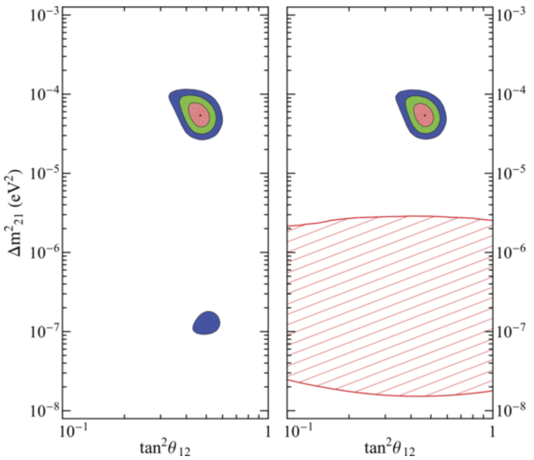

Figure 3: Neutrino oscillations parameter estimation in three solar neutrino data analyses (with 2 d.o.f.): 1) 99.73% c.l. excluded region by the Borexino ^{7}Be day–night data (hatched red region in the right panel); 2) 68.27%, 95.45%, and 99.73% c.l. allowed regions by the solar neutrino data without Borexino data (left panel); 3) Same c.l. allowed regions by all solar neutrino data including Borexino (filled contours in right panel). The best fit point in the left (right) panel is $\Delta m^2 = (5.2\ ^{+1.6}_{-0.9}) \cdot 10^{-5}$, $\tan^2\theta$=0.47 $^{+0.04}_{-0.03}$ (0.46 $^{+0.04}_{-0.03}$). The LOW region is strongly excluded by the ^{7}Be day–night data while the allowed LMA parameter region does not change significantly with the inclusion of the new data.

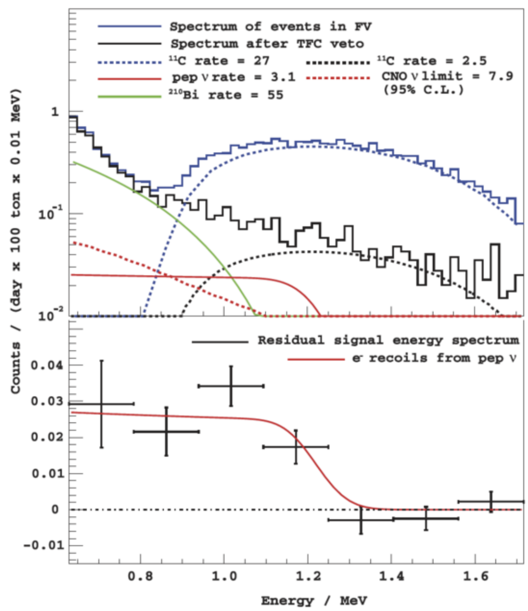

Figure 4: Top: energy spectra of the events before and after the three-fold veto is applied. The solid and dashed blue lines show the data and estimated ^{11}C rate before any veto is applied. The solid black line shows the data after the procedure, in which the ^{11}C contribution (dashed black line) has been greatly suppressed. The next largest background, ^{210}Bi, and the e$^-$ recoil spectra of the best estimate of the pep rate and of the upper limit of the CNO rate are shown for reference. Bottom: residual energy spectrum after best-fit rates of all considered backgrounds are subtracted.

many non–standard interaction models predict sizable effects, so a stringent upper limit may put useful constraints. Besides, we have shown in [12] that thanks to this result Borexino alone can exclude the LOW solution without any use of KamLAND anti–neutirno data.

The lack of asymmetry is clearly shown in Fig. 2.

This result is an essentially new and independent way to probe the MSW-LMA prediction and is potentially sensitive to new physics affecting low energy electron neutrino interactions. As an example, we note that our daynight asymmetry measurement is very powerful in testing mass varying neutrino flavor conversion scenarios. We find, for example, that our data excludes the set of MaVaN parameters chosen in [14] to fit all neutrino data at more than 10 σ.

This tight constraint on the daynight effect in ^{7}Be solar neutrinos has interesting implications on our understanding of neutrino oscillations. To investigate this, we calculated the expected daynight asymmetry for 862 keV neutrinos under different combinations of mixing parameters in the MSW oscillation scenario. The comparison of these predictions with our experimental number is displayed on the right panel of Fig. 3. The red region is excluded at 99.73% c.l. (2 d.o.f.). In particular, the minimum day–night asymmetry expected in the LOW region (10^{-8} eV^2 < Δm^2 < 10^{-6} eV^2) is 0.117, which is more than 8.5 σ away from our measurement, assuming gaussian errors.

2.3. First detection of pep neutrinos

We observed, for the first time, solar neutrinos in the 1.0-1.5 MeV energy range, where the flux is dominated by the pep and CNO components. We determined the rate of pep solar neutrino interactions in Borexino to be 3.1 ± 0.6 (stat) ± 0.3 (syst) counts/day · 100 ton.

Assuming the pep neutrino flux predicted by the standard solar model, we obtained a constraint on the CNO solar neutrino interaction rate of <7.9 counts/day · 100 ton (95% C.L.). The absence of the solar neutrino signal is disfavored at 99.97% C.L., while the absence of the pep signal is disfavored at 98% C.L.

The necessary sensitivity was achieved by adopting data analysis techniques for the rejection of cosmogenic ^{11}C, the dominant background in the 1-2 MeV region.

Assuming the Mikheyev-Smirnov-Wolfenstein large mixing angle solution to solar neutrino oscillations, these values correspond to solar neutrino fluxes of 1.6

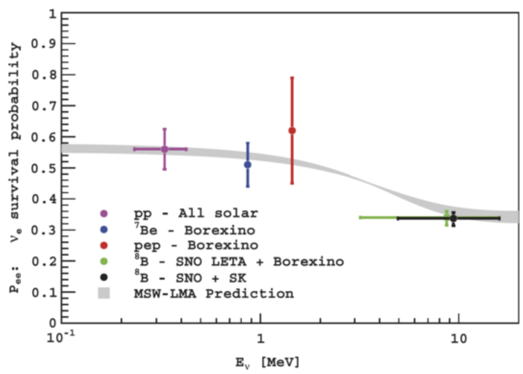

Figure 5: Electron neutrino survival probability as a function of energy. The points are the contribution of the Borexino experiment accomplished so far. The MSWLMA prediction band is the 1 σ range of the mixing parameters given in [18].

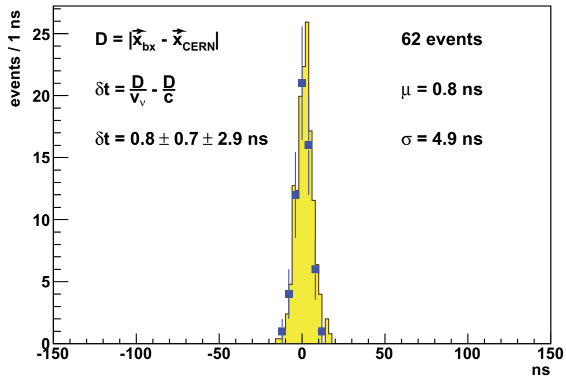

Figure 6: Final distribution of the difference between the neutrino time–of–flight and that expected for a particle moving at speed c (data points). The mean value is consistent with zero and the width agrees with Monte Carlo simulation of known time jitters (yellow filled histogram). The small asymmetry is predicted by Monte Carlo and is due to the spherical shape of the Borexino detector. The asymmetry does not affect the estimation of the central value by more than 200 ps. The mean value and its statistical error are obtained from the gaussian fit. The systematic error is explained in the text. D is the distance between the proton target at CERN and the center of the Borexino detector.

$\pm$ 0.3 10^8 cm^{-2} s^{-1} and $<$7.7 10^8 cm^{-2} s^{-1} (95% C.L.), respectively, in agreement with both the high and low metallicity standard solar models. These results represent the first direct evidence of the pep neutrino signal and the strongest constraint of the CNO solar neutrino flux to date.

The detection of neutrinos resulting from the CNO cycle has important implications in astrophysics, as it would be the first direct evidence of the nuclear process that is believed to fuel massive stars ($>$1.5 M_s). Furthermore, its measurement may help to resolve the solar metallicity problem [15] [16].

A key point of the analysis is the ability to reject the cosmogenic ^{11}C, the dominant background in the 1-2 MeV region. This rejection is done by exploiting two facts: ^{11}C can be tagged by the three-fold coincidence of the events generated by the muon, the capture of the spallation neutron, and the decay of ^{11}C [17]; the β^+ ^{11}C decay can be statistically subtracted using the fact that positronium formation in the scintillator modifies the pulse shape of the scintillation. The result is shown in Fig. 4. See caption for details.

The impact of the Borexino experiment on solar neutrino physics is shown in Fig. 5. Since the beginning of data taking in May 2012, three measurements of solar components have been accomplished, two of which never observed before: ^{7}Be, pep and low energy ^{8}B. The future improvement, possibly of all three measurements, and eventually the first real–time detection of the pp component, will strongly probe the MWS-LMA scenario. Besides, a strong upper limit on the CNO component might help solving the long standing metallicity problem.

3. Neutrino speed measurement

CNGS neutrinos travel about 730 km in matter with one of the highest relativistic γ factors ever artificially produced. The neutrino mass is at most $\simeq$ 2 eV/c^2 or possibly much less, while the CNGS average beam energy is 17 GeV, so γ is always $>10^{11}$, much bigger than that obtained in any charged particle beam. A test of Special Relativity with these particles is therefore meaningful. Besides, the measurement may also put an upper limit on the effect of non-standard propagation of neutrinos in matter.

This effort was also motivated by the claim, made by the Opera Collaboration in Sep. 2011 [19], that CNGS neutrinos travel faster than the speed of light in vacuum. This claim, however, was later withdrawn [20].

We have designed and installed a new GPS system with a carefully calibrated time link between CERN and Gran Sasso. The system is too complex to be described here, but it is fully described in [21]. The total systematic error induced by the time–link only is proved to be 1.1 ns, smaller than other effects as shown later. We have also performed a brand new geodetic measurement of the location of the LNGS laboratory and of the Borexino detector. The total distance from the target to the Borexino detector is 730472.082 $\pm$ 0.038 m. The uncertainty should be considered as 1 σ.

The measurement of the speed and a detailed description of the error budget is reported in [22]. The final result obtained in May 2012 for the time–of–flight difference of <E>=17 GeV muon neutrinos with respect to the speed of light is shown in Fig. 6 and is δt = 0.8 ± $0.7_{stat} \pm 2.9_{sys}$ ns, consistent with zero.

4. Future perspectives

The Borexino experiment has successfully completed the first phase of data taking. The obtained results exceed even the most optimistic expectations, thanks to the unprecedented low radioactive background in the scintillator. The Borexino design goal for ^{238}U and ^{232}Th contamination was set to 10^{-16} g/g: the current contamination is lower than 10^{-18} g/g for ^{238}U and lower than 3×10^{-18} g/g for ^{232}Th.

The collaboration has decided in 2010 to endeavor a purification campaign aimed at reaching even lower background levels. The results are very encouraging, and a new phase of data taking with much reduced ^{85}Kr, ^{238}U, and ^{232}Th backgrounds and significantly reduced ^{210}Bi has begun. This new data taking campaign, together with a very careful calibration effort that will be done in the future, may yield significant improvements in all measurements, and offer the opportunity to perform the first real time detection of pp neutrinos and put very stringent upper limits on CNO neutrinos.

Furthermore, other physics topics are under investigation. The possibility to search for sterile neutrinos by means of neutrino and anti-neutrino artificial sources located near or even inside the detector is being pursued. One option is that of building a neutrino source very similar to that used by the Gallex experiment in the years 1995-1996. This source, made with several kg of enriched ^{51}Cr activated in a suitable nuclear reactor, might reach an activity of 10 MCi and provide a sample of several thousands neutrino events with a source-detector distance of 8-12 m and neutrino energy less than 1 MeV. This experiment may conclusively probe the Gallium anomaly region, and cover almost completely the reactor anomaly region at 3σ level. Even more powerful would be an experiment with a ^{144}Ce internal anti-neutrino source located at the center of the detector. While technically more challenging, this experiment would cover at 3σ level the whole reactor anomaly region and have a potential of discovery sterile neutrino in the $\Delta m^2 \simeq 1$ eV^2 region for $\sin^2 2\theta_s > 0.02$. This very good sensitivity is due also to the fact that the expected oscillation length for neutrinos of about 1 MeV energy is of the order of 1 m, a figure that is larger than spatial reconstruction resolution and smaller than detector size. Neutrino waves might be detected in this experiment, yielding a beautiful model independent signature. A proposal for these experiments has been submitted to INFN and to the Gran Sasso Laboratory, and a decision will be taken in the next months.

Acknowledgements

The speaker willingly acknowledge the kind hospitality and the perfect organization of the Neutrino 2012 conference in Kyoto. The Borexino program is made possible by funding from INFN (Italy), NSF (USA), BMBF, DFG, and MPG (Germany), NRC Kurchatov Institute (Russia), and MNiSW (Poland). We acknowledge the generous support of the Gran Sasso National Laboratories (LNGS). This work is dedicated to the memory of R. Raghavan, a friend and a mentor.

References

[1] G. Alimonti et al. (Borexino collaboration), Nucl. Instr. and Meth. **A 600** (2009) 568
[2] G. Bellini et al. (Borexino collaboration), JINST **6** (2011) P05005
[3] G. Bellini et al. (Borexino collaboration), Nucl. Instr. and Meth. **A 609** (2009) 5878
[4] G. Bellini et al. (Borexino collaboration), Phys. Rev. Lett. **108** (2012) 051302
[5] G. Bellini et al. (Borexino collaboration), Phys. Rev. **D 82** (2012) 033006
[6] G. Bellini et al. (Borexino collaboration), Phys. Lett. **B 687** (2010) 299304
[7] K. Abe et al. (Super-Kamiokande Collaboration) Phys. Rev. **D 83** (2011) 052010
[8] B. Aharmin et al. (SNO collaboration) Phys. Rev. **C 81** (2010) 055504
[9] W. Hampel et al. (GALLEX Collaboration) Phys. Lett. **B 420** (1998) 114-126
[10] C. Arpesella et al. (Borexino Collaboration), Phys. Rev. Lett. **101** (2008) 091302
[11] G. Bellini et al. (Borexino Collaboration), Phys. Rev. Lett. **107** (2011) 141302
[12] G. Bellini et al. (Borexino Collaboration), Phys. Lett. **B 707** (2012) 22-26
[13] A. M. Serenelli, W. C. Haxton, and C. Peña-Garay, arXiv:1104.1639
[14] P.C. de Holanda, JCAP 0907 (2009) 024
[15] A. M. Serenelli, W. C. Haxton, and C. Peña-Garay, Astrophys. **J 743** (2011) 24
[16] S. Basu, Astron. Soc. Pac. Conf. Ser. **416** (2009) 193
[17] H. Back et al. (Borexino Collaboration), Phys. Rev. **C 74** (2006) 045805
[18] K. Nakamura et al. (Particle Data Group), J. Phys. **G 37** (2010) 075021
[19] T. Adams et al., Opera collaboration arxiv: hep-ex/1109.4897v2
[20] M. Dracos, these proceedings; T. Adams et al., Opera collaboration arxiv: hep-ex/1109.4897v4 (accepted by JHEP)
[21] B. Caccianiga et al., JINST **7**, P080228
[22] P. Alvarez-Sanchez (Borexino Collaboration) hep-ex: 1207.0591 accepted by PLB