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Recent Results from Borexino

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Abstract. The Borexino experiment is taking data since 2007 at the Laboratori Nazionali del Gran Sasso in Italy accomplishing outstanding achievements in the field of neutrino physics. Its success is strongly based on the unprecedented ultra-high radio-purity of the inner scintillator core. The main features of the detector and the impressive results for solar and geo-neutrinos obtained by Borexino so far are summarized. The main focus is laid on the most recent results, i.e. the first real-time measurement of the solar pp neutrino flux and the detection of the signal induced by geo-neutrinos with a significance as high as 5.9σ. The measurement of the pp neutrino flux represents a direct probe of the major mechanism of energy production in the Sun and its observation at a significance of 10σ proves the stability of the Sun over a time of at least 10^5 years. It further puts Borexino in the unique position of being capable to test the MSW-LMA paradigm across the whole solar energy range. The geo-neutrino data allow to infer information concerning important geophysical properties of the Earth that are also discussed. The perspectives of the final stage of the Borexino solar neutrino program that are centered on the goal of measuring the CNO neutrinos that so far escaped any observation are outlined.

1. The Borexino Detector

The Borexino detector is located at the Laboratori Nazionali del Gran Sasso in Italy and shielded by ~ 3800 m.w.e., thus reducing the cosmic muon flux by a factor $\sim 10^6$ compared to the surface. A schematic view is shown in figure 1.

The whole detector is encompassed in a steel dome containing 2.1 kt of water. This part of

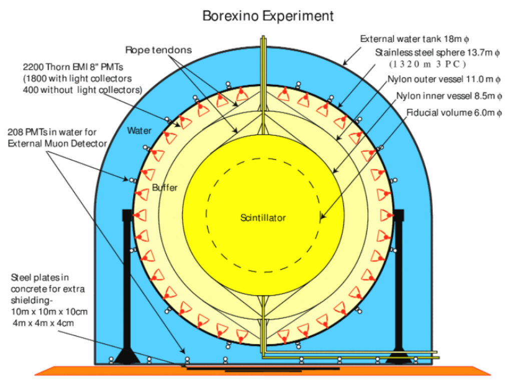

Figure 1. Schematic view of the Borexino detector.

the detector is used as a neutron and gamma shield and especially as a highly efficient muon veto. The Cherenkov light emitted by passing muons is collected by 208 photomultiplier tubes (PMTs) placed on the Stainless Steel Sphere (SSS) and the floor of the water rank. The SSS separates the outer water Cherenkov detector (OD) from the inner scintillator detector (ID), thus creating two independent detectors in terms of light propagation. On the inside surface of the SSS, 2212 PMTs are mounted to collect the scintillation light from the innermost part of the detector providing an optical coverage of 34%. The scintillator core is contained in the inner nylon vessel (IV) at a radius of 4.25 m that acts as a radon barrier. It is composed of 270 t of pseudocumene (PC, 1,2,4-trimethylbenzene, $C_6H_3(CH_3)_3$) with PPO (2,5-diphenyloxazole, $C_{15}H_{11}NO$) at a concentration of 1.5g/l added as a wavelength shifter. The so called buffer region between the IV and the SSS is filled with a mixture of PC and DMP (dimethylphytalate) as a quencher. Events from this region are strongly suppressed to prevent the external gamma background originating mainly from the PMTs and the SSS producing a signal. A further nylon vessel is placed at 5.5 m radius. For a detailed description of the Borexino detector, see [1].

2. Results of Solar Neutrino Measurements

Table 1 summarizes Borexino's solar neutrino measurements. With the measurements of all solar neutrino fluxes of the pp-chain but the hep-neutrinos, Borexino is the only experiment being capable to probe the entire solar neutrino spectrum and puts it in the unique position to test the Mikheyev-Smirnov-Wolfenstein large-mixing angle (MSW-LMA) paradigm across the whole solar energy range. Besides the measurements of the pp-chain, Borexino also provides the world-leading limit for the flux of neutrinos originating in the secondary CNO cycle. In addition,

Table 1. Solar Neutrino Measurements.

Species	Rate cpd/100 t	Flux $cm^{-2}s^{-1}$	Reference
pp	$144 \pm 13 \pm 10$	$(6.6 \pm 0.7) \cdot 10^{10}$	Nature512(2014)7515
^{7}Be	$46 \pm 1.5^{+1.5}_{-1.6}$	$(4.48 \pm 0.24) \cdot 10^9$	PRL107(2011)141302
pep	$3.1 \pm 0.6 \pm 0.3$	$(1.6 \pm 0.3) \cdot 10^8$	PRL108(2012)051302
^{8}B	$0.22 \pm 0.04 \pm 0.01$	$(2.4 \pm 0.4 \pm 0.1) \cdot 10^6$	PRD82(2010)033006
CNO	< 7.9(95% C.L.)	$< 7.7 \cdot 10^8$(95% C.L.)	PRL108(2012)051302

the absence of a day-night asymmetry in the ^{7}Be neutrino flux [5] and its yearly modulation [6] could be explored. Detailed studies of neutrons and further cosmogenic backgrounds [8] as well as the seasonal modulation of the muon flux [7] have been performed and the best limit on the e^- decay could be set recently [9].

3. Measurement of the solar pp-neutrino flux

In 99.76%, the solar pp-chain starts with the fusion of two protons into a Deuteron under the emission of a positron and an electron-neutrino. These neutrinos range from 0-420 keV, thus transferring a maximum energy of 264 keV to electrons in the scintillator via elastic scattering, the detection reaction. In order to extract the interactions from the solar pp-neutrinos, 408 live days of data acquired between January 2012 and May 2013 have been carefully analyzed above a threshold energy of 165 keV and within a fiducial volume of 85.5 t. This time period followed an extensive purification campaign performed in 2010 and 2011 during which especially the contents of ^{85}Kr and ^{210}Bi, important background sources in the low energy regime, were further reduced. Before, the pp-neutrino flux could only be inferred indirectly through the combination of the radiochemical experiments GALLEX and SAGE above a threshold energy of 233 keV [2].
Figure 2 shows the Borexino energy spectrum between 165-590 keV with fits of the pp-neutrino flux as well as relevant background sources. Due to its huge effect on the pp-neutrino measurement, the ^{14}C rate has been measured independently. In order to overcome trigger threshold effects, the shape and rate have been obtained by analyzing events that are found within the trigger window of 16 μs after an event that already issued a trigger. The measurement yields a ^{14}C rate of (40 ± 1) Bq/100 t. To estimate the contribution of pile-up events, i.e. events that occur so closely in time that they cannot be separated, a data driven method has been applied. Real triggered events without any selection cuts are overlaid by random data and the combined synthetic events selected and reconstructed. These events, thus, feature by construction all possible pile-up event combinations.
The pp-neutrino rate was obtained through a fit of the data between 165 and 590 keV with the ^{14}C and the synthetic pile being constrained and the ^{7}Be neutrino rate as measured in [3]. The ^{214}Pb rate has been fixed to the measured rate of fast, time correlated $^{214}\mathrm{Bi}(\beta) -^{214} \mathrm{Po}(\alpha)$ coincidences, the CNO and the pep neutrino rate to their values in the Standard Solar Model (SSM). Other free parameters of the fit are the ^{210}Po, the ^{85}Kr, and the ^{210}Bi background rates.

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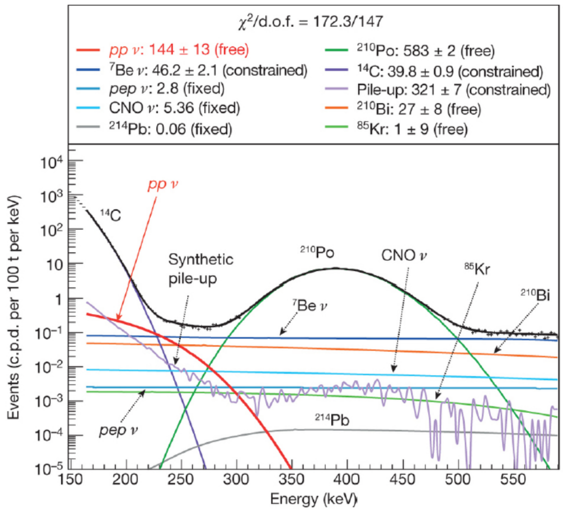

Figure 2. Energy spectrum between 165 and 590 keV. Data is shown in black together with fits to the pp-neutrino flux in red and several background sources. The ^{14}C spectrum is shown in dark and the synthetic pile-up in light purple. The best fit yields (144 ± 13) cpd as the pp-neutrino interaction rate.

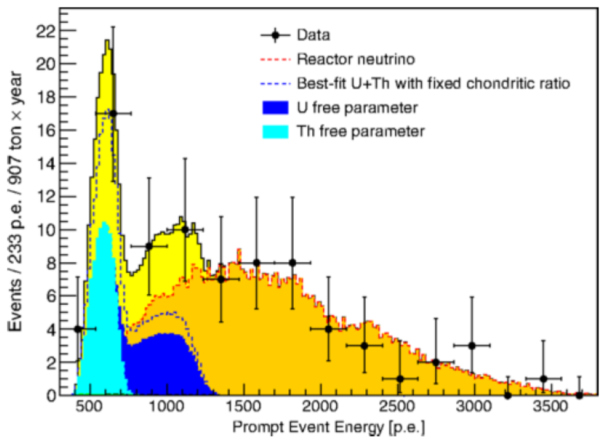

Figure 3. Light yield spectrum of $\overline{\nu}_\mathrm{e}$ candidates and the best fit, where 500 p.e. $\sim$ 1 MeV. Dotted lines show the best fit for geo and reactor $\overline{\nu}_\mathrm{e}$ assuming the chondritic ratio, colored areas show the result of a separate fit with U (blue) and Th (light blue) left as free and independent parameters.

The solar pp-neutrino rate measured by Borexino is $(144 \pm 13(\mathrm{stat.}) \pm 10(\mathrm{syst.}))\,\mathrm{cpd}/100\,\mathrm{t}$ [2]. The stability of the result was verified by altering the initial fit conditions, such as the energy range or data selection criteria. The absence of a pp-neutrino signal can be excluded a 10σ. The measured interaction rate by Borexino corresponds to a solar pp-neutrino flux of $\Phi(\mathrm{Borexino}) = (6.6 \pm 0.7) \cdot 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and is in good agreement with the prediction from the SSM of $\Phi(\mathrm{SSM}) = (5.98 \cdot (1 \pm 0.006)) \cdot 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as well as with the combined best fit value of the radiochemical and other solar experiments of $\Phi(\mathrm{other}) = (6.14 \pm 0.61) \cdot 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$[4]. The survival probability of pp-neutrinos is found to be $P(\nu_\mathrm{e} \to \nu_\mathrm{e}) = 0.63 \pm 0.12$ putting a constraint on the MSW-LMA solution.

With the first direct measurement of the pp-neutrino flux made possible by the unprecedented radio-purity of the detector, Borexino could prove the proton-proton fusion reaction to be the major process for energy production in the Sun and Sun-like stars as well as the Sun's stability over a timescale of at least 10^5 years. Although the experimental uncertainty does not allow the discrimination between low or high metallicity solar models, future Borexino inspired experiments might reach the necessary 1% precision.

4. Geo Neutrino Results

Geo neutrinos are electron-antineutrinos ($\overline{\nu}_\mathrm{e}$) that are produced in radioactive β decays of long-lived radio-isotopes naturally abundant in the Earth's crust and mantle such as elements from the ^{238}U and ^{232}Th chains or ^{40}K. Borexino detects $\overline{\nu}_\mathrm{e}$ via the inverse β decay $\overline{\nu}_\mathrm{e} + p \to \mathrm{n} + \mathrm{e}^+$ at a threshold energy of 1.806 MeV. This threshold leaves only the decays of ^{238}U and ^{232}Th to contribute to the signal at Borexino. The deposited energy by the $\overline{\nu}_\mathrm{e}$ results in a prompt signal from the positron, to which the kinetic energy of the $\overline{\nu}_\mathrm{e}$ is transferred, and the emission of a γ after the neutron was captured on Hydrogen (99%) or Carbon (1%). The delayed coincidence between the positron signal and the capture γ with the mean neutron capture

time of $259.7 \pm 1.3(\text{stat.}) \pm 2.0(\text{syst.})\,\mu\text{s}$ [8] constitutes an unambiguous signal. The only relevant background source producing more than one event in the data sample are reactor $\overline{\nu}_\text{e}$. 75% of the events that could mimic a $\overline{\nu}_\text{e}$ signal are produced by ^{9}Li or ^{8}He decays, $\alpha - n$ reactions, and accidental coincidences. These mimicking backgrounds have been estimated independently and been found to contribute in sum less than one coincidence in the data sample.
Figure 3 shows an un-binned likelihood fit of the energy spectrum of the 77 selected prompt $\overline{\nu}_\text{e}$ candidate events in a total exposure of $907 \pm 44\,\text{t} \cdot \text{yr}$. The spectra of geo and reactor-neutrino spectra are obtained from Monte Carlo simulations. In the fit, the signal contributions from geo and reactor-neutrinos are left free, whereas the contributions of the mentioned background sources are constrained to their estimated values. Remaining minor background sources are left out due to uncertainties of their energy spectra and contribute $\sim 1\%$ to the best fit. Their contribution to the systematic uncertainty is covered in the uncertainty of the energy scale.
Under assumption of the ratio for the masses of U and Th as suggested by the chondritic model of $m(\text{Th})/m(\text{U}) = 3.9$, the best fit yields $S_\text{geo} = 23.7^{+6.5}_{-5.7}(\text{stat.})^{+0.9}_{-0.6}(\text{syst.})$ events $= 43.5^{+11.8}_{-10.4}(\text{stat.})^{+2.7}_{-2.4}(\text{syst.})$ TNU and $S_\text{reactor} = 52.7^{+8.5}_{-7.7}(\text{stat.})^{+0.7}_{-0.9}(\text{syst.})$ events$=96.6^{+15.6}_{-14.2}(\text{stat.})$ $^{+4.9}_{-5.0}(\text{syst.})$ TNU, where 1 Terrestrial Neutrino Unit = 1 event / year / 10^{32} protons and the prediction for reactor neutrino events being (87 ± 4) TNU [10].
With this measurement, Borexino alone observes geo-neutrinos at 5.9σ significance. The fluxes of $\overline{\nu}_\text{e}$ for U and Th are measured to be $\Phi(\text{U}) = (2.7 \pm 0.7) \cdot 10^6\,\text{cm}^{-2}\text{s}^{-1}$ and $\Phi(\text{Th}) = (2.3 \pm 0.6) \cdot 10^6\,\text{cm}^{-2}\text{s}^{-1}$, respectively. Leaving the U and Th contributions as free parameters in the fit, Borexino would with more exposure be able to separate those contributions and perform real-time geo-neutrino spectroscopy. The radiogenic heat production H(U+Th) for the present result is limited to the range of 23-36 TW, including the uncertainty of the distribution of heat producing elements inside the Earth. Considering the estimation of the total geo-neutrino signal from the local crust and the contribution from the rest of the crust, a signal from the mantle of $20.9^{+15.1}_{-10.3}$ TNU is measured excluding the absence of a mantle contribution at 98% C.L.

5. Prospects and Goals of Borexino Phase II

The goals of the second phase of the Borexino solar neutrino program are mainly centered around improving the limit of the CNO neutrino flux and possibly measure it. To allow this, a strong effort was made to control the temperature of the detector and prevent convective motions that disturb the measurement of the ^{210}Bi contamination in the detector. Its precise estimation is crucial for a possible CNO neutrino measurement since its spectrum and the CNO neutrino spectrum are quasi-degenerate. Besides this, all the results of Phase I for fluxes of the pp-chain shall be updated with the special goal of a precision better than 3% for the ^{7}Be neutrino flux. With already approximately five years of high quality data after the purification campaign being already acquired and about one year until the SOX campaign will start, six years of excellent data will be available for Borexino to enhance the extraordinary results already obtained.

References

[1] Alimonti G *et al.* 2009 *Nucl. Instr. and Meth.* **600**(3) 568-93
[2] Borexino Collaboration 2014 *Nature* **512** 583-6
[3] Bellini G *et al.* 2011 *Phys. Rev. Lett.* **107** 141302
[4] Ianni A 2014 *Physics of the Dark Universe* **4** 44-9
[5] Bellini G *et al.* 2012 *Phys. Lett.* B **707** 22-6
[6] Bellini G *et al.* 2014 *Phys.Rev.* D **89** 112007
[7] Bellini G *et al.* 2012 *Journ. of Cos. and Astropart. Phys.* **2012**(05) 015
[8] Bellini G *et al.* 2013 *Journ. of Cos. and Astropart. Phys.* **2013**(08) 049
[9] Agostini M *et al.* 2015 *Phys. Rev. Lett.* **115** 231802
[10] Agostini M *et al.* 2015 *Phys. Rev.* D **92** 031101