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Neutrino interactions at few MeV: results from Borexino at Gran Sasso

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Borexino, at the I.N.F.N. Gran Sasso Underground Laboratory in Italy, is an experiment designed to detect, in real-time, low energy solar neutrinos. After a brief presentation of the Borexino physics and detector, we illustrate some recent results and their physics implications. Borexino perspectives are also discussed.

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1. Borexino

1.1. The Physics

Borexino's primary scientific goal is the first *real − time* measurement of solar neutrinos with energy below few MeV: in particular the monoenergetic 862 keV ^7Be ν_e emitted in the *pp* cycle of the Sun.

This flux, never measured before Borexino, is $\sim$ 7% of the total solar neutrino flux - a value much higher than that of the well studied ^8B ν $_e$ flux (10^{-4})- and has by now a quite low theoretical error ($\sim$ 6%) [1]: a measurement with a 5% - or lower - error will provide a unique probe for studying the fundamental properties of the neutrinos and the solar composition.

Neutrino oscillations, as described in the Large Mixing Angle (LMA) Mykheyev-Smirnov-Wolfenstein (MSW) model [2] [3], offer a solution to the so called "solar neutrino problem", that is the long standing discrepancy between the observation of the solar neutrino interaction rates in the experiments and the predictions of the Standard Solar Model (SSM) [4]. A 5% (next Borexino goal, with respect to the published 10%) ^7Be ν_e interaction rate measurement will provide the final, high accuracy, low energy validation of the LMA-MSW solution.

A low error ^7Be ν_e interaction rate measurement could also shed some light in the presently debated surface metallic content of the Sun [5], [6], [7].

Other eventual periodical variations, due to day/night, can also be measured, allowing a comparison with the expected theoretical values and a selection among the proposed neutrino flavour changing models.

The unique very low Borexino threshold ($\sim 250keV$) has allowed also the measurements of the ^8B ν $_e$ interaction rate and the determination - for the first time in the same experiment - of the solar neutrino survival probability (P_{ee}) values both in the vacuum and matter oscillation regime.

All solar neutrinos are detected in Borexino by their elastic scattering on electrons in highly purified Liquid Scintillator (LS); from the inverse beta decay reaction ($\overline{\nu_e}$ $+ p \rightarrow n + e^+$) Borexino can also detect $\overline{\nu_e}$ from the Earth (the *geoneutrinos*). These antineutrinos are produced in the β decays of naturally occurring radioactive isotopes (^{40}K, ^{238}U and ^{232}Th) in the Earth, and are a unique and direct probe of our planet interior: to be able to measure their flux and spectrum means to know their distribution inside the Earth and to assess the radiogenic contribution to the total heat balance of the Earth.

1.2. The Detector

The subMeV - or few MeV- energy region under study is contaminated by the natural and cosmogenic radioactivity background. For this reason, the Borexino detector is located in the Gran Sasso underground Laboratory, under 3800 m.w.e. rocks, were the cosmic muon background is reduced by six orderd of magnitude and has a multi-shells structure, with a decreasing level of background from the outermost to the innermost parts.

The core of the detector are 278 tons of *ultra high purity* scintillator, 100 of which are the software defined "*Fiducial Volume* (FV)", inside a transparent, 8.5m diameter, Inner Vessel (IV), made of very thin (125 μm) nylon film. The scintillator is a mixture of Pseudocumene (1,2,4- trimethylbenzene) and PPO (2,5-diphenyloxazole, 1.5 g/l). The scintillation light produced by the recoil electrons is observed by an array of 2212 8-inches ETL-9351 photomultiplier tubes (PMTs), situated on the inside surface of a 13.7m diameter Stainless Steel Sphere (*SSS*).

In order to shield the Inner Vessel (IV) from the background due to the intrinsic radioactive contaminants in the PMT's, a non-scintillating buffer -made of pseudocumene plus a quencher (DMP)- is between the IV and the SSS. A second, 11.0 m diameter, nylon vessel sorrounds the IV, in order to prevent inward diffusion ot radon atoms. Both vessels are suspended to the SSS via a mechanical structure.

To shield the SSS from the surrounding rock γ and neutron background, 2 m of ultrapure water, contained in a 18 m diameter Water Tank (WT), sorround it.

Out of the 2212 PMT's, 1841 have light collector (20cm diameter) to detect signals coming only from the IV region, while the remaining 371 ones, without light collector, are sensitive to the light originated in all the SSS volume, in particular the Cherenkov light generated by the residual cosmic muons crossing the non-scintillating buffer (their flux, in hall-C, is $\sim$ 1.1 muon per square meter per hour). This residual cosmic muon flux is identified also by the Cherenkov light generated in the WT and detected by an array of 208 PMTs located on the outside of the SSS surface (174) and on the bottom of the WT (34).

Calibration systems (lasers, pulsers, CCD cameras) are also essential part of the detector, as well as the many ancillary plants necessary for the unloading, the storage, the handling and the purification of the PC, as well the purification of the PPO, the water and the Nitrogen [12].

A detailed description of the detector is in reference [13].

1.3. Detector performances

Two extensive calibration champaigns took place in 2009 and 2010 to be able to reach the 5% systematics error in the $^7Be\ \nu_e$ interaction rate measurement and to study its Day/Night and seasonal variations; the errors to reduce were related to the FV definition, the energy scale and the event position reconstruction.

Eight gamma sources (^{14}C, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{85}Sr, ^{54}Mn, ^{65}Zn, ^{40}K, ^{60}Co) plus a neutron source ($Am-Be$) have been inserted in the detector at various on/off axis positions (detected with a 2 cm error by the built in CCD cameras). For α and β calibration, a small vial with ^{222}Rn loaded scintillator was put inside the detector and a clean α, β tag was privided by the ^{214}Bi - ^{214}Po fast coincidence.

For a detector light yield of $\sim 500 p.e./MeV/2000$ PMTs, the energy resolution is shown in Table I.

The spacial resolution is 12 cm at 800 keV, 16 cm at 500 keV and 35 cm at 200 keV: this leads to a FV definition with a $+2.1\% - 2.6\%$ accuracy to be compared to a previous 6%.

The signals of the physics processes Borexino wants to study are at energies below few MeVs, where background from natural radioactivity is prominient. The main real Borexino challenge is to suppress this background coming not only from the sorrounding environment but also from the detector materials and the scintillator itself.

Table 1
The Borexino energy resolution (σ)

Energy (keV)	Syst. error
200	10
400	8
1000	6

The Borexino Collaboration has devoted fiteen years to $R\&D$ on new purification techniques *and* detection methods: this tremendous effort, successfully tested by the Counting Test Facility (CTF), not only has produced world record for many radiopurity values but has also set the standard for other similar experiments like SNO and $KamLAND$; see reference [14] for a comprehensive discussion on this subject.

2. Some recent Borexino results

2.1. ^7Be

Thanks to the ultralow radioactivity levels reached, after just three months of data taking, the Borexino Collaboration was able to report [15] the first real-time spectral measurement of sub-MeV solar neutrinos and the very first $^7Be\ \nu_e$ interaction rate: $47 \pm 7^{stat} \pm 12^{sys}$ counts/(day 100 ton). In a second paper [16], after 192 live days, the result was $49 \pm 3^{stat} \pm 4^{sys}$ counts/(day 100 ton): this measurement, even with a 10% systematic error, is inconsistent at the 4σ C.L. with the hypothesis of no oscillation for the ^7Be neutrinos. Under the assumption of the constraint coming from the high metallicity SSM (with 6% theoretical uncertainty on the ^7Be neutrino flux), we obtained $P_{ee} = 0.56 \pm 0.10(1\sigma)$ at 0.862 MeV: this is the first direct measurement of the P_{ee} survival probability for solar ν_e in the transition region between matter-enhanced and vacuum-driven oscillations.

2.2. ^8B

Borexino is the first experiment to succeed in suppressing all major backgrounds, above the

2.641 MeV γ from the decay of ^{208}Tl, to a rate below that of electron scatterings from solar neutrinos. This allowed to detect scattered electrons by ^{8}B solar neutrinos with a threshold of 3 Mev, the lowest ever reported for the electron scattering channel. The rate of solar induced electron scattering events above 3 MeV in Borexino is measured to be $0.217 \pm 0.038(stat) \pm 0.008(syst)$ counts/(day 100 ton), in good agreement with the rate predicted by the SSM and including the LMA-MSW effects. The final ^{8}B solar neutrino data spectrum is shown in figure 1.

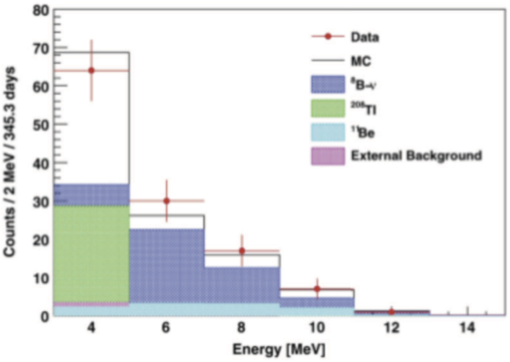

Figure 1. Comparison of the final spectrum after data selection (red dots)to Monte Carlo simulations (black line) [18].

Assuming the ^{8}B neutrino flux predicted by the high metallicity SSM BPS09 (GS98) [17], the average ^{8}B neutrino survival probability above 3 MeV is measured to be $0.29 \pm 0.10(1\sigma)$ [18].

2.3. P_{ee}

In the LMA-MSW scenario, neutrino oscillations are dominated by matter effects above 3 MeV and by vacuum effects below 0.5 MeV. The measurement of the $^{7}Be\ \nu_{\ e}\ P_{ee}$ combined with the $^{8}B\ \nu_{\ e}$ one, provides - for the first time from the same experiment - the solar neutrino survival probability (P_{ee}) values for neutrino of high ($^{8}B\ \nu_{\ e}$) and low ($^{7}Be\ \nu_{\ e}$) energy, that is in regions where dominate the matter and the vacuum oscillation respectively. In figure 2 is shown the electron neutrino survival probability as a function of the neutrino energy.

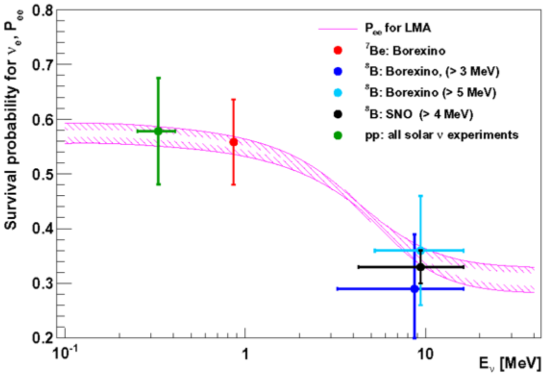

Figure 2. Electron neutrino survival probability as a function of the neutrino energy, evaluated for the ^{8}B solar neutrino [18].

2.4. Asymmetry Day Night

From the MSW mechanism a ν_μ interaction in the Earth could lead to a ν_e regeneration effect, and we could have a solar ν_e flux higher at night that during the day. The amount of this effect depends on the detector latitude, the oscillation parameter values and he neutrino energy. The present LMA solution offer a very small effect, contrary to the expectations from a LOW solution; still, there are models, see for example [19], where a Asymmetry Day-Nigh (ADN) is expected to be present. Borexino could provide an independent confirmation of the LOW exclusion if its ADN were very small. ADN has been evaluated for every bin (see figure 3) in the region: 250 < number og hit PMTs (nhits) < 700. After 3 years of data taking, our preliminary result is: $(N - D)/(N + D)/2 = 0.007 \pm 0.073(stat)$ [20]. This result is well consistent with zero and is, by itself, a confirmation of LMA solution with the Mass Varying Neutrino prediction disfavored within 3σ. Further analysis and the evluation of the contribution of possible systematic errors due to this selection of the data sample are in progress.

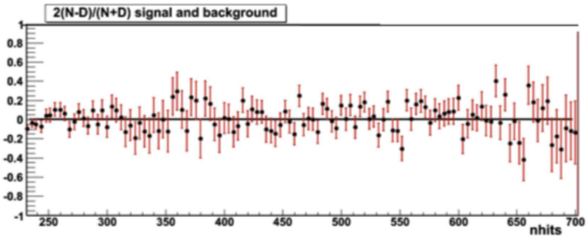

Figure 3. Binned Day Night Asymmetry as a function of nhits (number of hit PMTs) [20]

2.5. Geoneutrinos

Geoneutrinos were introduced long time ago [8], [9], but only recently KAMLAND [10], [11] and Borexino, with a much larger signal to noise ratio, have provided their first experimental indication; this thanks to two fundamental advances that occurred in the last few years: the development of extremely low background neutrino detectors *and* the progress on understanding neutrino propagation.

Borexino detects $\overline{\nu_e}$ from the earth (the *geoneutrinos*) via the inverse beta decay reaction $\overline{\nu_e}\ + p \rightarrow n + e^+$, with a well defined tagging in energy, time and space: the 2 gamma 1.02 MeV/c^2 energy release from the quick positron-electron annihilation is followed (200 μs later) by the 2.2 MeV energy release due to the gamma emitted in the $H(n,\gamma)D$ reaction.

Considering the U and Th abundances and their distributions as from the Bulk Silicate Earth (BSE) geochemcal model, the expected geoneutrino interaction rate in Borexino is ∼ 2.5 count/(day 100 ton). This extremely low value is subject to another main background: the reactor anti-neutrinos. A great effort has been done in calculating this new background, using detailed information on the time profile and nuclear fuel composition of the 194 European reactors, contributing, by themselves, to the 97% of this background. Reducing, with the "usual" Borexino cuts, the detector background (see [21] for all the details), we are left with an amazing 0.14 ± 0.02 background events, per 100 ton/year. In 537.2 live days, we got 21 candidate events in the considered energy window ($1 - 2.5$ MeV), with an unprecedented Signal/Noise ∼ 50/1. With an unbinned maximum likelihood analysis of these observed $\overline{\nu_e}$ candidates, we got: $N^{geo} = 9.9^{+4.1}_{-3.4}(^{+14.6}_{-8.2}$ and $N^{reactor} = 10.7^{+4.3}_{-3.4}(^{+15.8}_{-8.0}$ at 68.3 % C.L.

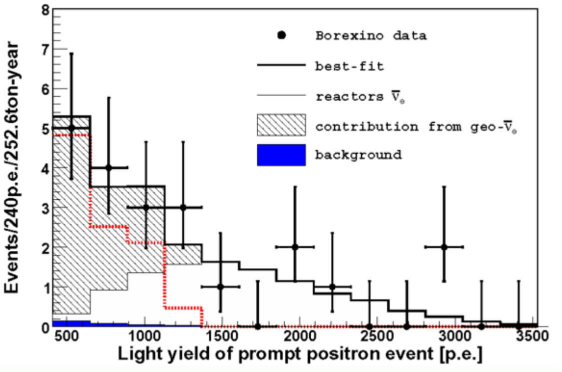

Figure 4. Light yield spectrum (in photoelectron number detected by the PMTs) for the positron prompt events of the 21 ($\overline{\nu_e}$) candidates and the best fit (solid thick line) [21]. The small filled area on the lower left part of the spectrum is the background. Thin solid line: reactor- ($\overline{\nu_e}$) signal form the fit. The conversion from p.e. to energy is ∼ 500 p.e./MeV.

In figure 4 is shown the final light yield spectrum for the positron prompt events of the 21 ($\overline{\nu_e}$) candidates and the best fit. This very interesting measurement is still affected by high statistical errors, being the systematics ones well under control, contrary to what is happening for the solar neutrino data; so we just have to wait to get more and more Borexino data and combine them with the results obtained from other detectors, located on different Earth places, to be able to "map" - for the first time - the Earth interiors.

2.6. Cosmic muons

All the previously presented physics results have been possible thanks to a very low intrinsic background of the detector and its ability to identify the - reduced - external backgrounds. One of these are the ~ 4200 cosmic muon/day that go across the detector. Muons produce unstable nuclei by spallation processes on their trajectory through the detector - particularly the Water Buffer and the LS - and their decay can mimic the expected signals. For short-lived radioisotopes, the good muon *identification* (higher than 99%) provided by the inside and outside PMT signals is enough to individually tag every muon and "veto" the detector for a time duration corresponding to several half-lifes of the given isotope. This technique is applied whenever the veto time is of the order of few seconds or less; however, when the half-life is longer, the induced dead time can become very large and, to overcome this problem, the veto is applied only to a cylindrical region around the muon track, instead of vetoing the whole detector volume. The mere muon identification is not sufficient and we need also a very good muon track reconstruction algorithm.

While information on the muon track has already been exploited in the ^8B analysis, it is of the uttermost importance for the CNO and *pep* neutrino search: here the most prominent background arises from cosmogenic ^{11}C (half life = 20.38 minutes) that surpasses the expected neutrino rate by an order of magnitude.

The Borexino muon tracking algorithms show resolutions down to ~ 3.5^o (azimuth) and ~ 2^o (zenith) and ~ 10 cm lateral. The angular distribution of muons produced by the CNGS ν_μ beam are shown in 5: note that the Borexino detector has been optimized to detect - and track - muons coming down vertically and not - as these muons - horizontally (angle of 3.2^o). The study of the cosmic muon annual modulation is in progress and a ±1.5% effect is evident in the very preliminary - 3 years - data shown in 6

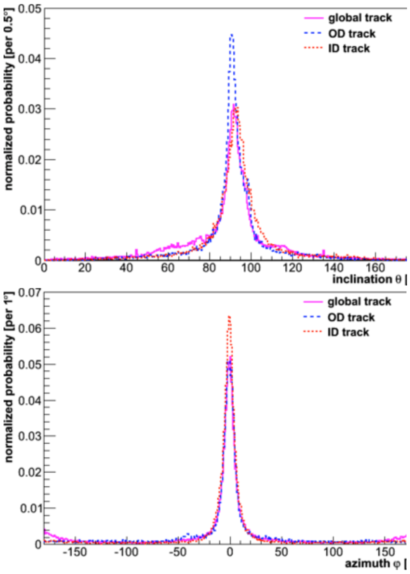

Figure 5. Angular distribution of muons produced by the CNGS ν_μ beam. In the figures, the beam direction is associated with $\phi=0^o$, $\theta=93.5^o$.

3. Borexino perspectives and Conclusions

Work in progress is about the ^7Be neutrino interaction rate measurement with a 5% accuracy and its seasonal modulation. With more statistics, new - more accurate - values will be provided on the ^8B neutrinos and geoneutrinos interaction rates and cosmic muon seasonal modulations.

Liquid scintillator purification campaigns - based on water extraction and nitrogen sparging - have just terminated and we hope to reduce the ^{85}Kr and ^{210}Bi - besides the U and Th - content, to be able to reduce even more the systematic effects and to be able to measure the interaction rates of other low energy solar neutrinos, in particular the *pep* and *CNO* neutrinos: the measurement of the first one will help in the direct determination of the preponderant *pp* neutrino solar flux, while information about the second one will

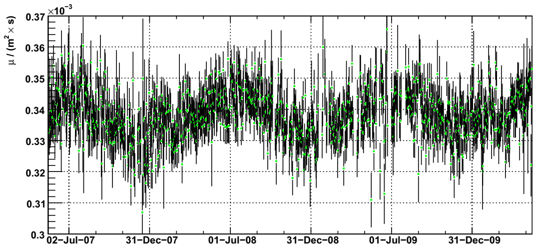

Figure 6. Cosmic muons signal (daily binning): the seasonal modulation is evident.

be useful to get information about the *CNO* cycle which, while not so important in the Sun, plays a fundamental role in stellar evolution.

If Borexino will be able to measure also the *pep* neutrinos P_{ee}, located just in the transition between the vacuum and matter dominated regions, this measurement will be fundamental in disentangling the still many proposed neutrino oscillation models.

Borexino is also set - with a dedicated, no dead time trigger - to detect (anti)neutrinos from SuperNovae and belongs to the SNEWS network.

In conclusion: Borexino, thanks to its extraordinary low background and residual low background identification techniques, has proved that it is possible to go below the "natural radioactivity barrier" of few MeV. It has measured - at 10% in real time - the ^7Be neutrino interaction rate and the ^8B neutrino interaction rate with the lowest (3 MeV) energy threshold. It has measured the P_{ee} at low (vacuum oscllation regime) and high (matter oscillation regime) energies; it has detected geoneutrinos at 4.2σ with the largest signal-to-noise ratio (50:1).

It has set the best limit on the Pauli exclusion Principle with violating nuclear transitions and strong limit on neutrino effective magnetic moment (both not reported here).

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