Analytical response function for the Borexino solar neutrino analysis

Z Bagdasarian\textsuperscript{1}, X Ding\textsuperscript{2,3}, A Vishneva\textsuperscript{4}  
(\textit{on behalf of the Borexino Collaboration*})

\textsuperscript{1} IKP-2 Forschungszentrum Jülich, 52428 Jülich, Germany  
\textsuperscript{2} Gran Sasso Science Institute, 67100 L’Aquila, Italy.  
\textsuperscript{3} INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy  
\textsuperscript{4} Joint Institute for Nuclear Research, 141980 Dubna, Russia

E-mail: z.bagdasarian@fz-juelich.de

*The Borexino Collaboration:
M Agostini, K Altenmüller, S Appel, V Atroshchenko, Z Bagdasarian, D Basilico, G Bellini, J Benziger, D Bick, G Bonfini, D Bravo, B Caccianiga, F Calaprice, A Caminata, S Caprioli, M Carlini, P Cavalcante, A Chepurnov, K Choi, L Collica, D D’Angelo, S Davini, A Derbin, X F Ding, A Di Ludovico, L Di Noto, I Drachnev, K Fomenko, A Formozov, D Franco, F Froborg, F Gabriele, C Galbiati, C Ghiano, M Giammarchi, A Goretti, M Gromov, D Guffanti, C Hagner, T Houdy, E Hungerford, Aldo Ianni, Andrea Ianni, A Jany, D Jeschke, V Kobychev, D Korabiev, G Korga, D Krym, M Laubenstein, E Litvinovich, F Lombardi, P Lombardi, L Ludhova, G Lukyanenko, L Lukyanenko, I Machulin, G Manuzio, S Marcocci, J Martyn, E Meroni, M Meyer, L Miramonti, M Misiaszek, V Muratova, B Neumair, L Oberauer, B Opitz, V Orekhov, F Ortica, M Pallavicini, L Papp, Ö Penek, N Pilipenko, A Pocar, A Porcelli, G Ramucci, A Razeto, A Re, M Redchuk, A Romani, R Roncin, N Rossi, S Schönert, D Semenov, M Skorokhvatov, O Smirnov, A Sotnikov, L F Stokes, Y Suvorov, R Tagliatela, G Testera, J Thurn, M Toropova, E Unzhakov, A Vishneva, R B Vogelaar, F von Feilitzsch, H Wang, S Weinz, M Wojcik, M Wurm, Z Yokley, O Zaimidoroga, S Zavatarelli, K Züber, and G Zuzel

Abstract.

Borexino experiment is located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, and its primary goal is detecting solar neutrinos, in particular those below 2 MeV, with unprecedentedly high sensitivity. Its technical distinctive feature is the ultra-low radioactive background of the inner scintillating core, which is the basis of the outstanding achievements obtained by the experiment (fluxes of $^7$Be, pep, pp, and limit on CNO). A spectral fit in the whole energy range from 200 keV up to 2 MeV has been performed for the first time, allowing to obtain simultaneously fluxes of all the solar neutrino components. To make such a fit possible, one requires the exact shapes of neutrino signals and backgrounds, as seen in the detector. Therefore, the transformation of the spectra from the original energy scale to the scale of the desired energy estimator, such as the number of hit PMTs or photoelectrons, is one of the key steps of the analysis. This conversion accounts for the energy scale non-linearity and the detector’s energy response, and can be performed using two approaches: the Monte Carlo simulation and the use of analytical models. The details and advantages of the analytical approach are presented in this contribution.
1. Introduction

The Borexino experiment is located at the Laboratori Nazionali del Gran Sasso in Italy. The core of the detector is 278 t of ultra-pure organic liquid scintillator, namely PC (pseudocumene, 1,2,4-trimethylbenzene) as a solvent and 1.5 g/l of fluor PPO (2,5-diphenyloxazole) as a solute, contained in a 125 µm-thick nylon vessel of 4.25 m radius [1]. A non-scintillating buffer fills the space between the nylon vessel and a Stainless-Steel Sphere (SSS) of 6.85 m radius, which supports the PMTs. The entire detector is enclosed in a cylindrical tank filled with ultra-pure water, serving as an active Cherenkov muon veto and as a passive shield against external γs and neutrons. The detector structure is shown schematically in Figure 1. Neutrinos of any flavour interact via elastic scattering with electrons, whose recoil produces scintillation light (∼500 photoelectrons/MeV/2000 PMTs).

![Figure 1. Schematic view showing the internal structure of the Borexino detector, including its vessel system (inner and outer), the Stainless Steel Sphere serving as the boundary of the Inner Detector and the surrounding Water Tank Outer Detector.](image)

Recent results of the Borexino solar program, the first simultaneous measurement of the interaction rates of $^{7}\text{Be}$, and $^{pep}$ neutrinos [2], have been presented at TAUP 2017 (see contribution of G. Testera et. al.). The analysis is based on data collected between December 14$^{th}$ 2011 to May 21$^{st}$ 2016, which corresponds to an exposure of $1291.51\text{ days} \times 71.3\text{ t}$, approximately 1.6 times the exposure of Phase-I (2007-2010). This period belongs to the so-called Borexino Phase-II, which started after an extensive purification campaign with 6 cycles of closed-loop water extraction, which significantly reduced the radioactive contaminants: $^{238}\text{U} < 9.4 \times 10^{-20}\text{ g/g (95\% C.L.)}$, $^{232}\text{Th} < 5.7 \times 10^{-19}\text{ g/g (95\% C.L.)}$, $^{85}\text{Kr}$, reduced by a factor $\sim 4.6$, and $^{210}\text{Bi}$, reduced by a factor $\sim 2.3$.

This analysis is performed with a global fit to the Borexino data in an extended energy range (0.19-2.93) MeV. To best disentangle the solar neutrino signals from radioactive backgrounds we performed the fit to the distributions of the candidate events in three parameter spaces: energy spectrum, the distance from the center of the detector and pulse-shape discrimination parameter. To improve the sensitivity on $^{pep}$ neutrinos the Three Fold Coincidence (TFC) technique is used to suppress the cosmogenic $^{11}\text{C}$. The technique tags events associated with a muon event and a subsequent neutron event(s) and divides the exposure in two data sets: one enriched in $^{11}\text{C}$ (tagging 92% of $^{11}\text{C}$ in 36% of total exposure) and the other depleted...
of it. The radial distribution, obtained from the simulations, helps to disentangle uniform components from external backgrounds. Using the fact that the probability density function (PDF) of the scintillation time profile is significantly different for $e^+$ and $e^-$ events, the disentanglement of the remaining $^{11}$C can be aided further in the $^{11}$C depleted sample. Pulse shape reference for $e^+$ is obtained from a selected $^{11}$C sample, while for $e^-$ events it is derived from simulations, and checked on data against electron-like events selected from $^{214}$Bi-$^{214}$Po coincidences. The signal and background reference spectral shapes used in the fit are obtained following two complementary strategies: one is based on the analytical description of the detector response function, while the second one is fully based on Monte Carlo (MC) simulations (see the contribution of S. Marcocci et al.)[3]. Analytical approach is described in more detail in the present contribution.

![Figure 2. Fit example for $^{11}$C-enriched (left) and $^{11}$C-subtracted (right) energy spectra. All the smooth spectral shapes are obtained with the analytical method, while the shapes of the external backgrounds ($^{214}$Bi, $^{208}$Tl, and $^{40}$K) are simulated by Monte Carlo.](image)

2. Analytical description of the energy response function

In the analytical method, the visible energy spectrum is predicted by convolving the deposited energy spectrum (calculated apriori from the Standard Solar Model) with the detector response function. While the model of the detector energy response is determined analytically, the values of its parameters are determined by the data (free fit parameters), extracted from the independent measurements or Monte Carlo simulations. In contrast to the MC approach, where only amplitudes of the solar neutrino and background rates are free, in the analytical spectral fit other parameters are left additionally free to vary: (i) the light yield, (ii) a resolution parameter which accounts for the non-uniformity of the response and is relevant for the high-energy part of the spectrum, (iii) a resolution parameter which accounts for the intrinsic resolution of the scintillator and effectively takes into account other contributions at low energy, (iv) the position and width of the $^{210}$Po-α peak (to account for non-uniform and time-varying spatial distribution of $^{210}$Po in the detector), and (v) the starting point of the $^{11}$C spectrum, corresponding to the annihilation of the two 511 keV $\gamma$s. Leaving the above listed parameters free gives the analytical fit the freedom to account for second-order unexpected effects or unforeseen variations of the detector response in time. Additionally, the spectral shapes obtained using the analytical approach, allow to consider pile-up by convolution of each spectral component with the solicited-trigger spectrum.

In the analytical approach, the details of the detector energy response are described with a model, which includes ionization quenching, fraction of Cherenkov radiation, as well as spatial
dependence of reconstructed energy and its resolution. The analytical description is derived from [5], with several improvements to extend the energy range of the fit and converts all the expected energy spectra into the $N_{pmt}^{dt1(2)}$ and $N_{pe}$ variables (see table for definitions).

**Table 1.** Definitions of energy variables used in the analytical fit.

| Variable | Description |
|----------|-------------|
| $N_{pe}$ | number of photoelectrons, collected from all the PMT hits in a cluster |
| $N_{pmt}^{dt1}$ | number of triggered PMTs in the time window of 230 ns |
| $N_{pmt}^{dt2}$ | number of triggered PMTs in the time window of 400 ns |

To account for the variation in the number of working channels as a function of time, all energy estimators are normalized to 2000 PMTs. For intrinsically integer $N_{pmt}$ variable such an equalization causes gaps in the spectrum which can be cured with the so-called masking procedure. The procedure includes equalizing an uniform spectrum using the same distribution of $N_{live}$ as in the data set, and applying the resulting pattern on the reference spectral shapes. Finally, all the components are summed up and the fit is performed using the method of maximum likelihood.

2.1. Absolute Energy Scale

$N_{pe}$ may be expressed in terms of the dominant contribution from scintillation photons and a small contribution from the Cherenkov light ($f_{Ch} \cdot Ch(E)$). As the scintillator response is, to first order, linear, it is possible to summarize any non-linearity by a multiplicative unitless quenching term ($Q(E)$). Finally, we may conveniently express the estimated number of photoelectrons as:

$$N_{pe}(E) = LY \cdot [Q(E) \cdot E + f_{Ch} \cdot Ch(E)]$$

where the position and time dependence of the scintillation light is contained in the photoelectron yield ($LY$).

The mean number of photomultipliers (PMT) hit, $N_{pmt}$, assuming the event takes place at the center of the detector would be

$$N_{pmt} = N_{live} \cdot p_1 = N_{live} \left(1 - e^{-\frac{N_{pe}}{N_{live}}} \right)$$

After considering the threshold effect and the dependence of the detection efficiency on the event position inside the fiducial volume (FV), we obtain

$$N_{pmt} = N_{live} \left(1 - e^{-\mu_0} \left[1 + p_t \frac{N_{pe}}{N_{live}} \right] \right) \left(1 - g_C \frac{N_{pe}}{N_{live}} \right)$$

$p_1 = 1 - e^{-\mu_0}$ - the probability of having a signal at any one PMT;

$\mu_0 = N_{pe}/N_{live}$ - the number of photoelectrons collected, on average, by one PMT;

$N_{live}$ - number of live PMTs in the given data set;

$g_C$ - fixed, geometric correction factor for the given FV, contained within the radius $R<2.8$ m and the vertical coordinates $-1.8 < z < 2.2$ m;

$p_t$ - fixed, part of a single electron response under the threshold.
2.2. Energy Resolution

The full variance for equalized (normalized to 2000 PMTs) $N_{pmts}$ is

for $\beta$ particles:

$$\sigma^2_{pmts} = f_{eq} (1 - [1 + v_1] p_1) N_{pmts} + v_2^q (\mu p_0 / p_1)^2 N_{pmts}^2 + (\sigma p_1 / N_{pmts})^2 N_{pmts}$$

for $\alpha$ particles:

$$\sigma^2_{pmts} = f_{eq} (1 - [1 + v_1] p_1) N_{pmts} + v_2^q N_{pmts}^3$$  \hspace{1cm} (4)

$f_{eq} = 2000/N_{live}$ - equalization factor;

$v_1$ - fixed, the relative variance of the PMT triggering probability for events uniformly distributed in the detector volume:

$$v_1 = \left( \frac{\sigma p_1}{p_1} \right)^2 = \left( \frac{\sigma p_1}{N_{pmts} / N_{live}} \right)^2$$  \hspace{1cm} (5)

$v_N$ - free, intrinsic resolution of the scintillator for $\beta$s (caused by $\delta$ electrons);

$v_2^q$ - fixed, accounts for the non-uniformity of the light collection, the same parameter as in the formula for the charge variance;

$v_2^f$ - free, accounts for the spatial dependence of the number of triggered PMTs;

$v_2^l$ - free, resolution from the spatial non-uniformity, corresponding to the width of $^{210}$Po-$\alpha$ peak.

3. Conclusions

For the first time the fit has been performed in the full range and using multivariate approach by both Monte Carlo and analytical fit. This was possible thanks to the switch to the GPU programming (see the contribution of X. Ding et. al.). The positive aspects of the analytical approach include the method of convolution of ideal spectral components with the solicited trigger spectrum and better $^{14}$C range fit. Furthermore, the analytical approach has advantage of accommodating possible small changes in the detector properties, hence the consistent results with Monte Carlo fit not only provide cross-check for the results, but further confirm the precision of Monte Carlo and the stability of the detector.

4. Acknowledgements

The Borexino program is made possible by funding from INFN (Italy), NSF (USA), BMBF, DFG, HGF and MPG (Germany), RFBR (Grants 16-02-01026A, 15-02-02117A, 16-29-13014 of-m, 17-02-00305A) and RSF (Grant 17-12-01009) (Russia), JINR Grant 17-202-01, and NCN Poland (Grant UMO-2013/10/E/ST2/00180). We acknowledge the generous hospitality and support of the Laboratory Nazionali del Gran Sasso (Italy). We also acknowledge the computing services of INFN-CNAF data centre (Bologna) and LNGS Computing and Network Service (Italy), ACK Cyfronet AGH Cracow (Poland), and of Jülich Supercomputing Centre at FZJ (Germany).

References

[1] G. Alimonti et. al. (Borexino Collaboration) 2009 Nuclear Instruments and Methods A. 600 568
[2] M. Agostini et. al. (Borexino Collaboration) 2017 arXiv: 1707.09279 [hep-ex]
[3] S. Marcocci et. al. (Borexino Collaboration) 2017 arXiv: 1704.02291 [hep-ex]
[4] O. Smirnov 2008 Nucl. Inst. Meth. in Physics Research Section A. 595 410
[5] G. Bellini et. al. (Borexino Collaboration) 2014 Physical Review D 89 112007 (arXiv: 1308.0443 [hep-ex])