Borexino detector performances

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Borexino, a large volume detector for low energy neutrino spectroscopy, is currently taking data underground since 2007 at the Laboratori Nazionali del Gran Sasso, Italy. The main goal of the experiment is the real-time measurement of solar neutrinos, especially the low energy part of the spectrum. Neutrinos are detected via neutrino-electron scattering in an ultra-pure organic liquid scintillator. The light generated by the interaction is detected by 2212 phototubes. During many years of data taking the experiment provided several remarkable results as the first evidence of pep neutrinos, the real-time detection of the pp neutrinos, the evidence of CNO neutrinos, and the detection of antineutrinos from the Earth. All these results are based on an accurate modelling of the detector's response and performances. The contribution shows the design, the modelling of the detector's response, and the performances. Moreover it will be discussed how the performances and the response were studied by means of extensive calibration campaigns.

Keywords: Borexino; Neutrino; Solar neutrinos; calibrations

1. The Borexino detector

Borexino is a liquid-scintillator experiment at the hall C of the Laboratori Nazionali del Gran Sasso in Italy. Borexino looks for solar neutrinos scattering off electrons in its active volume. Given the tiny cross-section of neutrino interactions with electrons ($\sigma \sim 10^{-44}\,cm^2$ to $10^{-45}\,cm^2$ for the solar-neutrino energy range), the rates expected in Borexino are small, ranging from less than one to a few tens of counts per day per 100 tons for different solar-neutrino components. To cope with such a low event rate, Borexino has a large target mass (about 300 t) and it is housed deep underground, under 3,800 m water equivalent of dolomitic rock that suppresses the flux of cosmic radiation by a factor of approximately one million. The active core of the detector consists of about 300 t of pseudocumene (1,2,4-trimethylbenzene) doped with 1.5 g per litre of PPO (2,5-diphenyloxazole) and contained in a spherical nylon inner vessel (radius R = 4.25 m). The scintillator is surrounded by a non-scintillating pseudocumene-based buffer liquid which serves as a passive shield against external radioactivity (see Figure 1). The scintillator fluorescence light is collected by 2,212 photomultiplier tubes mounted on the Stainless Steel Sphere (radius R = 6.9 m). The entire detector is enclosed in a domed, cylindrical tank filled with high-purity water, equipped with 208 photomultiplier tubes, which provides extra shielding against external radioactivity (photons and neutrons), and also serves as an active water Cherenkov veto against residual cosmic muons.[1] Together with the lack of directionality information from the scintillation light, the low rate demands a high detector radiopurity, a deep understanding of the backgrounds, and an accurate modeling of the detector response.

To achieve the extreme sensitivity required by the experiment, very stringent procedures of material selection and cleaning were adopted to limit radioactive background in the experiment. Since usual materials are contaminated at the order of Bq/kg, material selection played a key role in the success of the experiment. One example is the choice of oil coming from deep wells to produce pseudocumene. In this way a low content of ^{14}C is achieved in the detector. Several cycles of scintillation purification were performed during the years achieving the unprecedented contamination of $^{238}U < 9.4 \cdot 10^{-20}$ g/g (95% C.L.) and $^{232}Th < 5.7 \cdot 10^{-19}$ g/g (95% C.L.). Further details on the purification strategy can be found here.[2]

The position and pulse-shape of each event are reconstructed by exploiting the number of detected photons and their detection times. The information about the event energy is carried by the number of detected photoelectrons or just the number of hit PMTs, as in our energy range the PMTs mainly work in a single photoelectron regime. Moreover, from the time distribution of the emitted light it is possible to statistically discriminate between α and β^- events[3] and between β^+ and β^- events.[4]

Due to a small leak in the nylon vessel, the vessel shape changes with time. At analysis stage it is updated every three weeks looking at radioactive decays happening on in (mostly due to ^{210}Bi, ^{40}K, ^{208}Tl) as shown by Figure 2. This method enables to reconstruct the vessel shape with a ± 5 cm uncertainty.

2. The Borexino calibration campaign

Calibrations in Borexino are performed inserting radioactive sources inside the liquid scintillator (internal calibrations) and placing a ^{232}Th source close to the stainless steel sphere (external calibrations). The former is used to map the detector's response while the latter is used to better understand and modeling the backgrounds that are coming from the construction materials. To insert sources inside the detector, a complex system of rods and cameras is exploited. This ensures knowing the position of the source at $\sim$cm level.[6] Table 1 shows the used sources and their purpose.

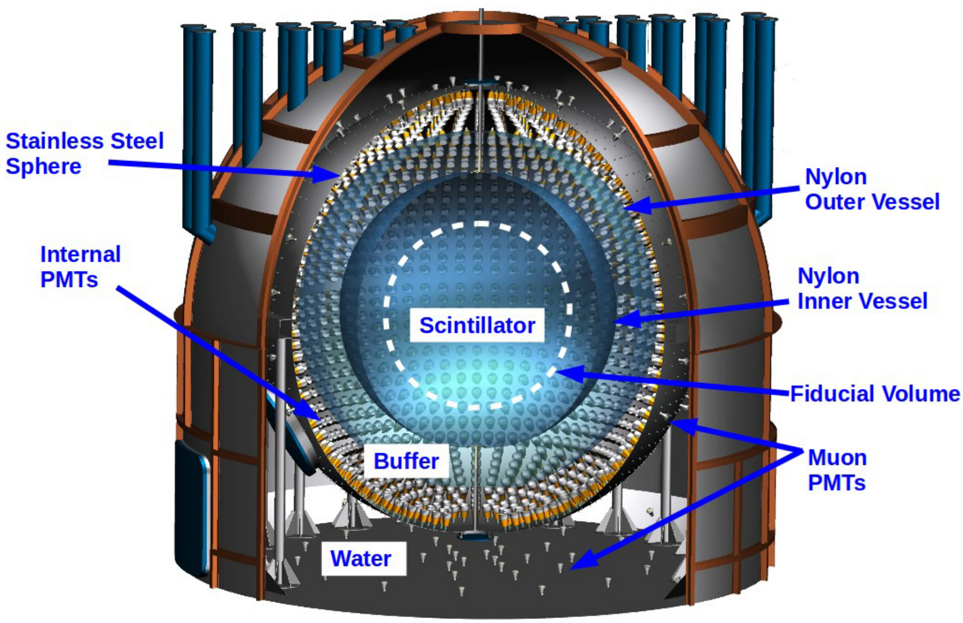

Fig. 1. The Borexino detector: Schematic view of the structure of the Borexino apparatus. From inside to outside: the liquid scintillator, the buffer liquid, the stainless steel sphere with the photomultipliers, and the water tank.[5]

Table 1. Used sources and placement during the internal calibration campaign.[6]

Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV
394 nm laser	light	-	center	PMT equalization

The position of an event is calculated by the time of arrival of the first photon on photomultipliers corrected by the hit multiplicity and minimizing a proper likelihood function. Figure 3 shows the resolution as function of the energy of the event. The reconstruction of calibration events and their comparison with the know source position shows a bias of maximum 4 cm in the vertical direction for events in the

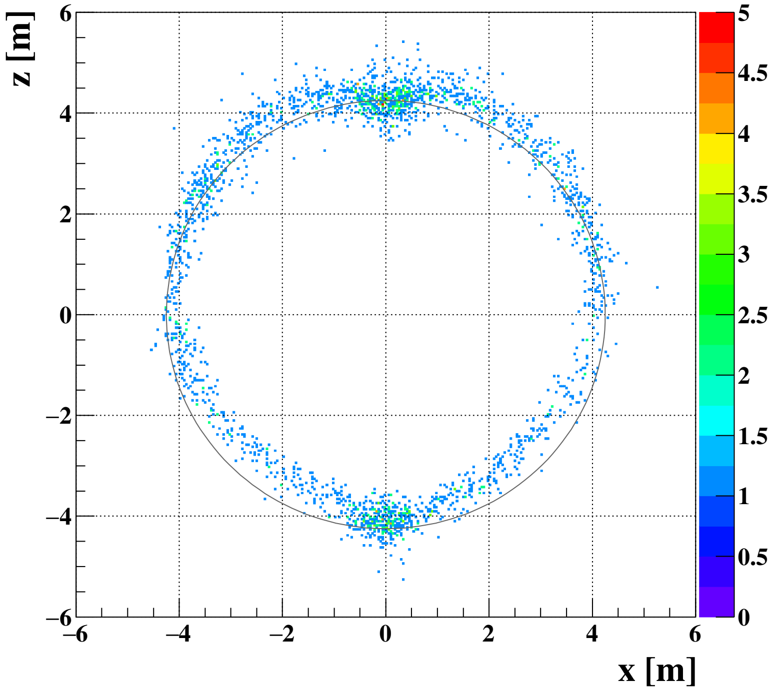

Fig. 2. A cross section (z-x plane, $|y| < 0.5\,\mathrm{m}$) view of the distribution of 2478 events, acquired during a 3 week period, and selected for the IV shape reconstruction. The color axis represents the number of events per cubic pixel of 0.04 m of size. This distribution reveals the IV shift and deformation with respect to its nominal spherical position shown in solid black line.[3]

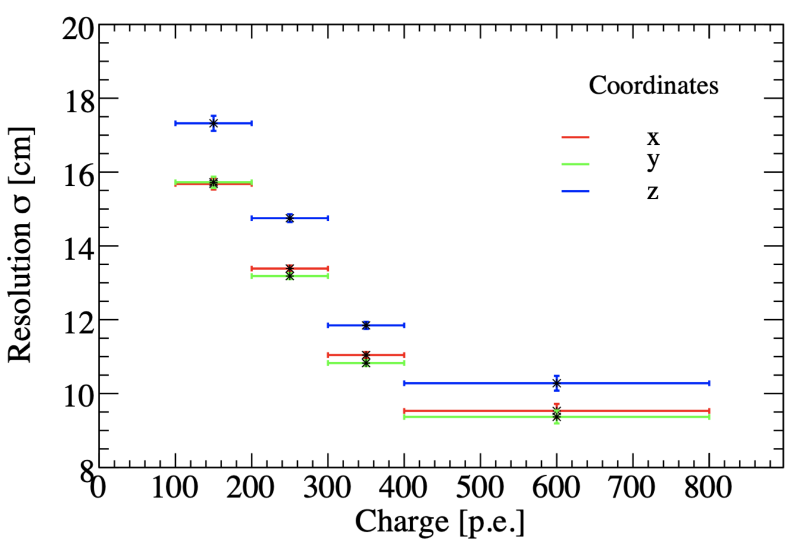

Fig. 3. Position resolution in Borexino as function of event energy.[6]

center. This bias has a small (less than 0.2%) impact on the fiducial volume determination. Since Borexino is a self triggering experiment, calibrations with laser and radioactive sources were performed to test the triggering efficiency, which is 100% at the energies of interest for solar neutrino detection.[7]

3. Modeling the detector response

The collaboration developed two independent approaches for modeling the detector's response. One is based on a particle physics simulation,[8] the other on an analytical model.[4]

The MC code developed for Borexino is a customized Geant4-based simulation package, which can simulate all processes following the interaction of a particle in the detector (energy loss including ionization quenching in the scintillator; scintillation and Cherenkov light production; optical photon propagation and interaction in the scintillator modelling absorption and re-emission, Rayleigh scattering, interaction of the optical photons with the surface of the materials; photon detection on the PMTs, and response of the electronics chain) including all known characteristics of the apparatus (geometry, properties of the materials, variable number of the working channels over the duration of the experiment as in the real data) and their evolution in time. The code thus produces a fully simulated detector response function because it provides a simulated version of all the measured physical variables. All the MC input parameters have been chosen or optimized using samples of data independent from the specific analysis (laboratory measurements and Borexino calibrations with radioactive sources.

In the analytical approach, a PDF for the energy estimator under consideration and analytical expressions for its mean value and variance are introduced. This PDF describes the detector's energy response function to monoenergetic events and, in brief, it is mainly influenced by the number of scintillation and Cherenkov photons and effects due to the nonuniformity of the light collection. The energy spectra of each species are transformed into the corresponding distributions of the energy estimators. Effects like the ionization quenching in the scintillator, the contribution of the Cherenkov light, the spatial dependence of the reconstructed energy and its resolution are accounted for through some parameters, part of which are fixed, while others are free to vary during the fit on the dataset.

4. Conclusion

Borexino is a neutrino detector able to measure the flux of all the neutrinos emitted by the Sun and the existence of antineutrinos emitted by the Earth.[3–5,9] Thanks to a wide calibration campaign the performances of the detector were assessed: for a 1 MeV event the energy resolution is $\sim 50\,\mathrm{keV}$ and the position resolution is $\sim 10\,\mathrm{cm}$. The triggering efficiency is 100% for energies typical of solar neutrinos events. Moreover the Monte Carlo and analytical models were tested on calibration data with agreement better than 1%.

References

1. G. Alimonti, C. Arpesella, H. Back, M. Balata, D. Bartolomei, A. de Bellefon, G. Bellini, J. Benziger, A. Bevilacqua, D. Bondi, S. Bonetti, A. Brigatti, B. Caccianiga, L. Cadonati, F. Calaprice, C. Carraro, G. Cecchet, R. Cereseto, A. Chavarria, M. Chen, A. Chepurnov, A. Cubaiu, W. Czech, D. D'Angelo, F. Dalnoki-Veress, A. De Bari, E. De Haas, A. Derbin, M. Deutsch, A. Di Credico, A. Di Ludovico, G. Di Pietro, R. Eisenstein, F. Elisei, A. Etenko, F. von Feilitzsch, R. Fernholz, K. Fomenko, R. Ford, D. Franco, B. Freudiger, N. Gaertner, C. Galbiati, F. Gatti, S. Gazzana, V. Gehman, M. Giammarchi, D. Giugni, M. Goeger-Neff, T. Goldbrunner, A. Golubchikov, A. Goretti, C. Grieb, C. Hagner, T. Hagner, W. Hampel, E. Harding, S. Hardy, F. Hartmann, R. von Hentig, T. Hertrich, G. Heusser, M. Hult, A. Ianni, A. Ianni, L. Ioannucci, K. Jaenner, M. Joyce, H. de Kerret, S. Kidner, J. Kiko, T. Kirsten, V. Kobychev, G. Korga, G. Korschinek, Y. Kozlov, D. Kryn, P. La Marche, V. Lagomarsino, M. Laubenstein, C. Lendvai, M. Leung, T. Lewke, E. Litvinovich, B. Loer, F. Loeser, P. Lombardi, L. Ludhova, I. Machulin, S. Malvezzi, A. Manco, J. Maneira, W. Maneschg, I. Manno, D. Manuzio, G. Manuzio, M. Marchelli, A. Martemianov, F. Masetti, U. Mazzucato, K. McCarty, D. McKinsey, Q. Meindl, E. Meroni, L. Miramonti, M. Misiaszek, D. Montanari, M. Monzani, V. Muratova, P. Musico, H. Neder, A. Nelson, L. Niedermeier, S. Nisi, L. Oberauer, M. Obolensky, M. Orsini, F. Ortica, M. Pallavicini, L. Papp, R. Parcells, S. Parmeggiano, M. Parodi, N. Pelliccia, L. Perasso, A. Pocar, R. Raghavan, G. Ranucci, W. Rau, A. Razeto, E. Resconi, P. Risso, A. Romani, D. Rountree, A. Sabelnikov, P. Saggese, R. Saldhana, C. Salvo, R. Scardaoni, D. Schimizzi, S. Schönert, K. Schubeck, T. Shutt, F. Siccardi, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sonnenschein, F. Soricelli, A. Sotnikov, S. Sukhotin, C. Sule, Y. Suvorov, V. Tarasenkov, R. Tartaglia, G. Testera, D. Vignaud, S. Vitale, R. Vogelaar, V. Vyrodov, B. Williams, M. Wojcik, R. Wordel, M. Wurm, O. Zaimidoroga, S. Zavatarelli and G. Zuzel, The borexino detector at the laboratori nazionali del gran sasso, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **600**, 568 (2009).
2. J. Benziger, L. Cadonati, F. Calaprice, M. Chen, A. Corsi, F. Dalnoki-Veress, R. Fernholz, R. Ford, C. Galbiati, A. Goretti, E. Harding, A. Ianni, A. Ianni, S. Kidner, M. Leung, F. Loeser, K. McCarty, D. McKinsey, A. Nelson, A. Pocar, C. Salvo, D. Schimizzi, T. Shutt and A. Sonnenschein, A scintillator purification system for the borexino solar neutrino detector, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **587**, 277 (2008).
3. 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, L. Cappelli, P. Cavalcante, F. Cavanna, A. Chepurnov, K. Choi, D. D'Angelo, S. Davini, A. Derbin, A. Di Giacinto, V. Di Marcello, X. F. Ding, A. Di Ludovico, L. Di Noto, I. Drachnev, G. Fiorentini, A. Formozov, D. Franco, F. Gabriele, C. Galbiati, M. Gschwender, C. Ghiano, M. Giammarchi, A. Goretti, M. Gromov, D. Guffanti, C. Hagner, E. Hungerford, A. Ianni, A. Ianni, A. Jany, D. Jeschke, S. Kumaran, V. Kobychev, G. Korga, T. Lachenmaier, T. Lasserre, M. Laubenstein, E. Litvinovich, P. Lombardi, I. Lomskaya, L. Ludhova, G. Lukyanchenko, L. Lukyanchenko, I. Machulin, F. Mantovani, G. Manuzio, S. Marcocci, J. Maricic, J. Martyn, E. Meroni, M. Meyer, L. Miramonti, M. Misiaszek, M. Montuschi, V. Muratova, B. Neumair, M. Nieslony, L. Oberauer, A. Onillon, V. Orekhov, F. Ortica, M. Pallavicini, L. Papp, O. Penek, L. Pietrofaccia, N. Pilipenko, A. Pocar, G. Raikov, M. T. Ranalli, G. Ranucci,

A. Razeto, A. Re, M. Redchuk, B. Ricci, A. Romani, N. Rossi, S. Rottenanger, S. Schönert, D. Semenov, M. Skorokhvatov, O. Smirnov, A. Sotnikov, V. Strati, Y. Suvorov, R. Tartaglia, G. Testera, J. Thurn, E. Unzhakov, A. Vishneva, M. Vivier, R. B. Vogelaar, F. von Feilitzsch, M. Wojcik, M. Wurm, O. Zaimidoroga, S. Zavatarelli, K. Zuber and G. Zuzel, Comprehensive geoneutrino analysis with borexino, *Phys. Rev. D* **101**, p. 012009 (Jan 2020).

4. 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. Gabriele, C. Galbiati, C. Ghiano, M. Giammarchi, A. Goretti, M. Gromov, D. Guffanti, C. Hagner, T. Houdy, E. Hungerford, A. Ianni, A. Ianni, A. Jany, D. Jeschke, V. Kobychev, D. Korablev, G. Korga, D. Kryn, M. Laubenstein, E. Litvinovich, F. Lombardi, P. Lombardi, L. Ludhova, G. Lukyanchenko, L. Lukyanchenko, 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. Raikov, G. Ranucci, A. Razeto, A. Re, M. Redchuk, A. Romani, R. Roncin, N. Rossi, S. Schönert, D. Semenov, M. Skorokhvatov, O. Smirnov, A. Sotnikov, L. F. F. Stokes, Y. Suvorov, R. Tartaglia, G. Testera, J. Thurn, M. Toropova, E. Unzhakov, F. L. Villante, A. Vishneva, R. B. Vogelaar, F. von Feilitzsch, H. Wang, S. Weinz, M. Wojcik, M. Wurm, Z. Yokley, O. Zaimidoroga, S. Zavatarelli, K. Zuber, G. Zuzel and T. B. Collaboration, Comprehensive measurement of pp-chain solar neutrinos, *Nature* **562**, 505 (2018).
5. M. Agostini, K. Altenmüller, S. Appel, V. Atroshchenko, Z. Bagdasarian, D. Basilico, G. Bellini, J. Benziger, R. Biondi, D. Bravo, B. Caccianiga, F. Calaprice, A. Caminata, P. Cavalcante, A. Chepurnov, D. D'Angelo, S. Davini, A. Derbin, A. Di Giacinto, V. Di Marcello, X. F. Ding, A. Di Ludovico, L. Di Noto, I. Drachnev, A. Formozov, D. Franco, C. Galbiati, C. Ghiano, M. Giammarchi, A. Goretti, A. S. Göttel, M. Gromov, D. Guffanti, A. Ianni, A. Ianni, A. Jany, D. Jeschke, V. Kobychev, G. Korga, S. Kumaran, M. Laubenstein, E. Litvinovich, P. Lombardi, I. Lomskaya, L. Ludhova, G. Lukyanchenko, L. Lukyanchenko, I. Machulin, J. Martyn, E. Meroni, M. Meyer, L. Miramonti, M. Misiaszek, V. Muratova, B. Neumair, M. Nieslony, R. Nugmanov, L. Oberauer, V. Orekhov, F. Ortica, M. Pallavicini, L. Papp, L. Pelicci, Ö. Penek, L. Pietrofaccia, N. Pilipenko, A. Pocar, G. Raikov, M. T. Ranalli, G. Ranucci, A. Razeto, A. Re, M. Redchuk, A. Romani, N. Rossi, S. Schönert, D. Semenov, G. Settanta, M. Skorokhvatov, A. Singhal, O. Smirnov, A. Sotnikov, Y. Suvorov, R. Tartaglia, G. Testera, J. Thurn, E. Unzhakov, F. L. Villante, A. Vishneva, R. B. Vogelaar, F. von Feilitzsch, M. Wojcik, M. Wurm, S. Zavatarelli, K. Zuber, G. Zuzel and T. B. Collaboration, Experimental evidence of neutrinos produced in the cno fusion cycle in the sun, *Nature* **587**, 577 (2020).
6. H. Back, G. Bellini, J. Benziger, D. Bick, G. Bonfini, D. Bravo, M. B. Avanzini, B. Caccianiga, L. Cadonati, F. Calaprice, C. Carraro, P. Cavalcante, A. Chavarria, A. Chepurnov, D. D. Angelo, S. Davini, A. Derbin, A. Etenko, F. von Feilitzsch, G. Fernandes, K. Fomenko, D. Franco, C. Galbiati, S. Gazzana, C. Ghiano, M. Giammarchi, M. Goeger-Neff, A. Goretti, L. Grandi, E. Guardincerri, S. Hardy, A. Ianni, A. Ianni, A. Kayunov, S. Kidner, V. Kobychev, D. Korablev, G. Korga, Y. Koshio, D. Kryn, M. Laubenstein, T. Lewke, E. Litvinovich, B. Loer, F. Lombardi, P. Lombardi, L. Ludhova, I. Machulin, S. Manecki, W. Maneschg, G. Manuzio, Q. Meindl,

E. Meroni, L. Miramonti, M. Misiaszek, D. Montanari, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, K. Otis, M. Pallavicini, L. Papp, L. Perasso, S. Perasso, A. Pocar, R. S. Raghavan, G. Ranucci, A. Razeto, A. Re, A. Romani, N. Rossi, D. Rountree, A. Sabelnikov, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R. B. Vogelaar, J. Winter, M. Wojcik, A. Wright, M. Wurm, J. Xu, O. Zaimidoroga, S. Zavatarelli and G. Zuzel, Borexino calibrations: hardware, methods, and results, *Journal of Instrumentation* **7**, P10018 (oct 2012).

7. G. Bellini, J. Benziger, D. Bick, G. Bonfini, D. Bravo, M. Buizza Avanzini, B. Caccianiga, L. Cadonati, F. Calaprice, P. Cavalcante, A. Chavarria, A. Chepurnov, D. D'Angelo, S. Davini, A. Derbin, A. Empl, A. Etenko, K. Fomenko, D. Franco, F. Gabriele, C. Galbiati, S. Gazzana, C. Ghiano, M. Giammarchi, M. Göger-Neff, A. Goretti, L. Grandi, M. Gromov, C. Hagner, E. Hungerford, A. Ianni, A. Ianni, V. Kobychev, D. Korablev, G. Korga, D. Kryn, M. Laubenstein, T. Lewke, E. Litvinovich, B. Loer, F. Lombardi, P. Lombardi, L. Ludhova, G. Lukyanchenko, I. Machulin, S. Manecki, W. Maneschg, G. Manuzio, Q. Meindl, E. Meroni, L. Miramonti, M. Misiaszek, M. Montuschi, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, K. Otis, M. Pallavicini, L. Papp, C. Pena-Garay, L. Perasso, S. Perasso, A. Pocar, G. Ranucci, A. Razeto, A. Re, A. Romani, N. Rossi, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R. B. Vogelaar, F. von Feilitzsch, J. Winter, M. Wojcik, A. Wright, M. Wurm, J. Xu, O. Zaimidoroga, S. Zavatarelli and G. Zuzel, Final results of borexino phase-i on low-energy solar neutrino spectroscopy, *Phys. Rev. D* **89**, p. 112007 (Jun 2014).
8. M. Agostini, K. Altenmüller, S. Appel, V. Atroshchenko, Z. Bagdasarian, D. Basilico, G. Bellini, J. Benziger, D. Bick, G. Bonfini, L. Borodikhina, D. Bravo, B. Caccianiga, F. Calaprice, A. Caminata, M. Canepa, S. Caprioli, M. Carlini, P. Cavalcante, A. Chepurnov, K. Choi, D. D'Angelo, S. Davini, A. Derbin, X. Ding, L. Di Noto, I. Drachnev, K. Fomenko, A. Formozov, D. Franco, F. Froborg, F. Gabriele, C. Galbiati, C. Ghiano, M. Giammarchi, M. Goeger-Neff, A. Goretti, M. Gromov, C. Hagner, T. Houdy, E. Hungerford, A. Ianni, A. Ianni, A. Jany, D. Jeschke, V. Kobychev, D. Korablev, G. Korga, D. Kryn, M. Laubenstein, E. Litvinovich, F. Lombardi, P. Lombardi, L. Ludhova, G. Lukyanchenko, I. Machulin, M. Magnozzi, G. Manuzio, S. Marcocci, J. Martyn, E. Meroni, M. Meyer, L. Miramonti, M. Misiaszek, V. Muratova, B. Neumair, L. Oberauer, B. Opitz, F. Ortica, M. Pallavicini, L. Papp, A. Pocar, G. Ranucci, A. Razeto, A. Re, A. Romani, R. Roncin, N. Rossi, S. Schönert, D. Semenov, P. Shakina, M. Skorokhvatov, O. Smirnov, A. Sotnikov, L. Stokes, Y. Suvorov, R. Tartaglia, G. Testera, J. Thurn, M. Toropova, E. Unzhakov, A. Vishneva, R. Vogelaar, F. von Feilitzsch, H. Wang, S. Weinz, M. Wojcik, M. Wurm, Z. Yokley, O. Zaimidoroga, S. Zavatarelli, K. Zuber and G. Zuzel, The monte carlo simulation of the borexino detector, *Astroparticle Physics* **97**, 136 (2018).
9. G. Bellini, J. Benziger, D. Bick, G. Bonfini, D. Bravo, B. Caccianiga, L. Cadonati, F. Calaprice, A. Caminata, P. Cavalcante, A. Chavarria, A. Chepurnov, D. D'Angelo, S. Davini, A. Derbin, A. Empl, A. Etenko, K. Fomenko, D. Franco, F. Gabriele, C. Galbiati, S. Gazzana, C. Ghiano, M. Giammarchi, M. Göger-Neff, A. Goretti, M. Gromov, C. Hagner, E. Hungerford, A. Ianni, A. Ianni, V. Kobychev, D. Korablev, G. Korga, D. Kryn, M. Laubenstein, B. Lehnert, T. Lewke, E. Litvinovich, F. Lombardi, P. Lombardi, L. Ludhova, G. Lukyanchenko, I. Machulin, S. Manecki, W. Maneschg,

S. Marcocci, Q. Meindl, E. Meroni, M. Meyer, L. Miramonti, M. Misiaszek, M. Montuschi, P. Mosteiro, V. Muratova, L. Oberauer, M. Obolensky, F. Ortica, K. Otis, M. Pallavicini, L. Papp, L. Perasso, A. Pocar, G. Ranucci, A. Razeto, A. Re, A. Romani, N. Rossi, R. Saldanha, C. Salvo, S. Schönert, H. Simgen, M. Skorokhvatov, O. Smirnov, A. Sotnikov, S. Sukhotin, Y. Suvorov, R. Tartaglia, G. Testera, D. Vignaud, R. B. Vogelaar, F. von Feilitzsch, H. Wang, J. Winter, M. Wojcik, A. Wright, M. Wurm, O. Zaimidoroga, S. Zavatarelli, K. Zuber, G. Zuzel and B. Collaboration, Neutrinos from the primary proton–proton fusion process in the sun, *Nature* **512**, 383 (2014).