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Scintillator Purification in the Borexino Detector

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Borexino, a real-time device for low energy neutrino spectroscopy, has completed the construction phase at the middle of 2006 in the Underground Laboratories at Gran Sasso, Italy. The detector has been filled with 1300 tons of highly purified scintillator and 2600 tons of ultrapure water as external shield and, since May 16th, 2007, is under data taking. The experimental goal, the direct measurement of flux of ^{7}Be solar neutrinos of all flavour via neutrino-electron scattering in an ultrapure scintillator liquid, has been achieved and further measurements (PP, PeP, CNO neutrinos, geoneutrinos, supernova) are object of future results. The paper describes the purification methods adopted in Borexino, to achieve unique and unprecedented results on the scintillator purity. Requirements and purification methods will be reported.

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1. Borexino overview

Borexino is an international experiment located in the underground Gran Sasso National Laboratory in Italy. The design of Borexino is based on the principle of graded shielding (see Fig. 1), with the scintillator at the center of a series of concentric shells of increasing radiopurity, and the entire detector located 1400 meter underneath the Gran Sasso mountain [1]. The 278 tons of scintillator, composed of pseudocumene (PC) and 1.5 g/l of the fluor 2,5-diphenyloxazole (PPO), are contained in a thin (125 μm) nylon inner vessel (IV) with a radius of 4.25 m. Within the IV, a fiducial mass (FV) of 100 tons can be defined by software selection of the events, based on their reconstructed position using timing data from the photomultipliers (PMT). A second nylon outer vessel (OV) with radius 5.50 m contains a passive buffer fluid composed of pseudocumene and 5.0 g/L dimethylphthalate (DMP). The DMP quencher reduces scintillation of the PC around the phototubes in the outer buffer. The function of the nylon vessel that separates the inner and outer buffer (the OV) is to keep serve as a diffusion or mixing barrier to keep impurities from the phototubes, light cones and stainless steel sphere from diffusing near the scintillator volume. Enclosing both scintillator and buffer regions is a stainless steel sphere (SSS), radius 6.85 m, which acts as a support structure for PMTs. The SSS holds the less dense organic fluids in position within a surrounding water tank used as a muon veto system and additional buffer layer.

2. Borexino requirements

To detect the ^{7}Be neutrino flux, the natural emitter isotopes with the energy inside the neutrino windows should be reduced in a way they do not hide the signal. Following a list with the isotopes of interest of Borexino:

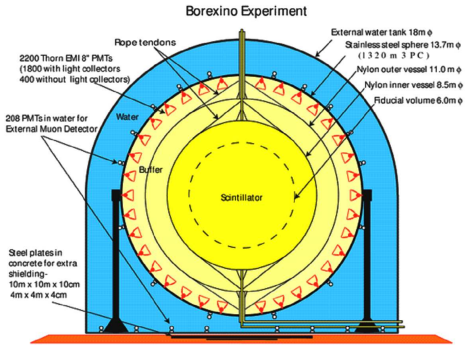

Fig. 1. Scheme of Borexino detector.

- ^{14}C — It is produced by cosmic activation of the ^{14}N, its typical level in liquid scintillator at earth surface at the equilibrium is $^{14}C/^{12}C \approx 10^{-12}$. The $^{14}C/^{12}C$ ratio in Borexino must be $\leq 10^{-18}$ to avoid the tail from the ^{14}C β-emission with an end point of 156 keV from contributing to the neutrino window. It is possible to match the requirements using a scintillator from particular petroleum layers (old carbon).

- ^{7}Be — It is produced by cosmic activation of the ^{12}C, its typical level in liquid scintillator at earth surface at the equilibrium is 2.7×10^3 cpd/ton (count per day/ton). The requirement for Borexino is < 0.01 cpd/ton. It can be removed by distillation and underground storage of scintillator.

- ^{222}Rn — It is present in air and it is emanated from materials. Assuming the equilibrium of Rn adsorption into PC from air (10–100 Bq/m^3), its contribution would be 1.3×10^7 cpd/ton. The requirement for Borexino is < 0.01 cpd/ton. It can be removed by nitrogen stripping and by a leak tight system.

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- ^{39}Ar, ^{85}Kr — They are both present in air. Assuming the equilibrium of Ar and Kr adsorption into PC from air with typical concentration, they would contribute with 218 and 2700 cpd/ton, respectively. The requirement for Borexino is < 0.01 cpd/ton. They can be removed by nitrogen stripping and by a leak tight system.
- ^{238}U, ^{232}Th — They are both present in suspended dust and in organometallics. Assuming 1 g of dust (1 ppm U, 10 ppm Th) in 1 ton of scintillator they would contribute with 10^3 cpd/ton. The requirement for Borexino is < 0.01 cpd/ton. They can be removed by distillation, filtration and surface cleaning.
- ^{40}K — It has been found as contaminant in the fluor. Its contribution would be 2700 cpd/ton. The requirement for Borexino is < 0.01 cpd/ton. It can be removed by water extraction, distillation and filtration of the fluor solution.
- ^{210}Bi, ^{210}Po — They come from the decay of ^{210}Pb in the Rn chain. Assuming as an example the inner vessel surface exposed to air with 10 Bq/m^3 of ^{222}Rn for 1 year, they would contribute with 2×10^4 cpd/ton. Because they can be tagged using the a/b discrimination, Borexino requirement is not stringent here and few tens cpd/ton can be tolerated. They can be removed from the surfaces by cleaning and from the scintillator by distillation (^{210}Pb included).

The preparation of the plants to reduce the above isotopes at the level to measure the ^{7}Be neutrinos and further unique research, several requirements have to be underlined that made the difference: choice of materials, construction in controlled environments, leak tightness, cleaning in place.

3. Purification of the scintillator

Borexino used the distillation and the stripping systems to purify the scintillator [2], achieving unique results reported in several papers during the last years [3], and entering new fields never detected before as Borexino is doing now (PP neutrinos, geoneutrinos, PeP neutrinos, CNO neutrinos, sterile neutrinos). During the last year 2010 and at the beginning of year 2011, Borexino performed an additional available purification to further reduce the already unique background in the detector, namely the counter current water extraction followed by the vacuum stripping process. NSF and INFN funds gave to Borexino the possibility to improve furthermore the purification of the master solution, to be prepared to perform a final distillation of the scintillator into the inner vessel. In the mean time, results from the water extraction proved as such an additional purification reduced almost at zero of the total background in Borexino. Distillation and stripping are based on differences in the equilibrium composition between liquid and vapor and have been deeply reported in previous papers and conferences [2].

Water extraction (WE) is based on a difference in the equilibrium concentration between an organic liquid and water. Radioactive impurities, such as ^{238}U, ^{222}Rn, ^{210}Po and ^{85}Kr that are associated with distinct molecular identities can be separated from the scintillator. Instead, ^{14}C is part of the molecular structure of the scintillator and cannot be removed. The purification is also needed to remove chemical impurities that degrade the optical quality of the scintillator. The WE performed in Borexino is similar to the one applied years ago to the CTF prototype [3–5]. Scintillator is circulated from the detector to the purification plant where it is passed counter-current to extra-purity water in a packed column. The WE is effective to remove impurities that are polar or charged, and such impurities have a greater affinity for water than the non-polar aromatic scintillator. Most of the inorganic radioactive impurities such as K, U, Th, and Pb are expected to be present as particulates and ionic species, which should be effectively removed by water extraction. Even if the WE is not effective at removing some of the inorganic impurities (for instance, ^{210}Po forms compounds that do not have a strong affinity for water and therefore remain in the scintillator), the results achieved after the three campaigns of water extraction in Borexino, showed a reduction equal to zero for Kr and at the level of 10^{-18} g/g in term of U and Th, as you can see in Table.

TABLE

Preliminary results for the most important radioisotopes of interest in Borexino.

Radioisotope	Goal	Preliminary WE purification
^{14}C/^{12}C	10^{-18} g/g	2×10^{-18} g/g
^{238}U (by ^{214}Bi–^{212}Po)	10^{-16} g/g	1×10^{-18} g/g, 90% C.L.
^{232}Th (by ^{214}Bi–^{212}Po)	10^{-16} g/g	5×10^{-18} g/g, 90% C.L.
^{210}Po	≈ 1 cpd/t	5.0 cpd/t
^{40}K	$\approx 10^{-18}$ g/g	$< 3\times10^{-18}$ (90%) g/g
^{85}Kr	≈ 1 c/d/100t	1.7 c/d/100t
^{39}Ar	≈ 1 c/d/100t	$\ll {}^{85}$Kr

The experience had, during the three campaigns of WE (see in Fig. 2a sketch of the system), fixed the attention upon the quality of the water used. Borexino takes water directly from the rock of the Gran Sasso mountain and uses a dedicated plant to purify the water removing all the radioactive elements other than all the minerals and ionic impurities. A reverse osmosis unit, an electro-deionizer system, and ultrafilter followed by an Ultra-Q system in loop to a storage tank, are all parts of the Borexino water plant. Then a stripping column has been added, to further reduce the high radon content into the rock water (at the level of 3 Bq/l). An additional new unit (a modern membrane degasser from Liqui–Cel®), has been added just now, with the intention of partly

reduce the radon in water, prior the water to enter the reverse osmosis. The main reason to be the reduction of radon daughters that cannot be removed both with the water plant and with the water extraction plant.

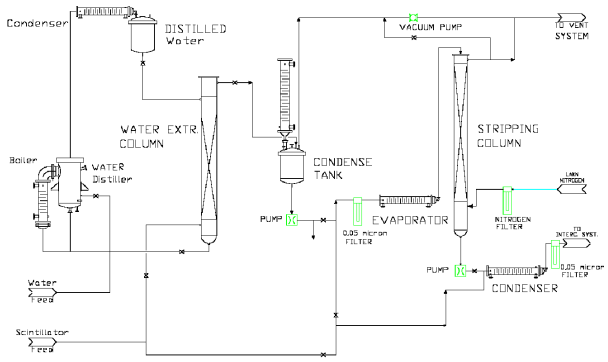

Fig. 2. WE purification sketch.

Acknowledgments

All the Borexino Collaboration achieved such a unique results. Moreover special thanks go to Prof. F. Calaprice that put all his experience trying to achieve always the best results in a field that is opening to new frontiers in term of particle physics.

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