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Solar and geoneutrino physics with Borexino

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ABSTRACT

The Borexino detector is a high-radiopurity liquid scintillator for low background neutrino physics. The detector is located in the Hall C of the Laboratori Nazionali del Gran Sasso (central Italy). During its seven years of operation, Borexino has detected and measured solar neutrinos from ^{7}Be, ^{8}B and pep reactions in the Sun, as well as geoneutrinos coming from the Earth.

1. Introduction

Solar neutrino physics began with the goal of studying the nuclear fusion reactions taking place in the core of the Sun. These reactions produce the solar energy and emit neutrinos that can be detected on Earth. The Davis experiment [1] was the first one to (radiochemically) detect solar neutrinos, measuring a significant deficit with respect to the predicted flux. More experiments were performed starting from the end of the 1980s, both in radiochemical mode [2–4] and in real-time mode [5,6]. At the same time the widely accepted model of the Sun structure and evolution evolved into what is known today as the Standard Solar Model [7,8].

Contrary to radiochemical experiments, real-time experiments have an energy threshold of about 5 MeV, mainly due to natural radioactivity. Because of this limitation, only $\sim 0.001\%$ of the solar neutrinos have been directly observed before 2007.

Borexino was specifically designed to measure neutrinos in real-time and with a low energy threshold; this program has required an intensive research and development, culminated with the filling of the detector in 2007. Borexino [9] is a real time experiment to study sub-MeV neutrinos, using the $\nu e \rightarrow \nu e$ elastic scattering for solar neutrinos and the inverse beta decay for neutrinos coming from the Earth (geoneutrinos). The experimental design threshold is of 50 keV while the analysis threshold is 200 keV. The events are observed in a large mass (100 t) of carefully shielded liquid scintillator.

The prediction of the ^{7}Be solar flux depends both on the Standard Solar Model and the value of the parameters of the large mixing angle (LMA) solution of neutrino oscillations [10,11]. Fig. 1 shows the predicted spectrum at production, together with the energy thresholds of past (on top) and future experiments. The Borexino experimental program makes it possible to directly test this prediction as well as opening up the previously unexplored territory of real time sub-MeV solar neutrino spectroscopy.

This paper summarizes the main achievements of Borexino in terms of detecting neutrinos from the Sun and the Earth during the years from 2007 to 2013. First of all, ^{7}Be neutrinos from the Sun were detected for the first time. Secondly, the ^{8}B component was detected for the first time with an energy threshold below 5 MeV, which was important to study the transition region between the vacuum and the matter-dominated solar neutrino oscillations (see below). Thirdly, the pep solar neutrino flux was measured for the very first time and the best limit was put on the CNO production cycle in the Sun. Finally, Borexino has measured with the highest confidence level to date neutrinos produced by radioactivity from the Earth itself (geoneutrinos).

2. The Borexino detector

Borexino [12] is an unsegmented scintillation detector featuring 300 t of ultrapure liquid scintillator viewed by 2200 photomultipliers

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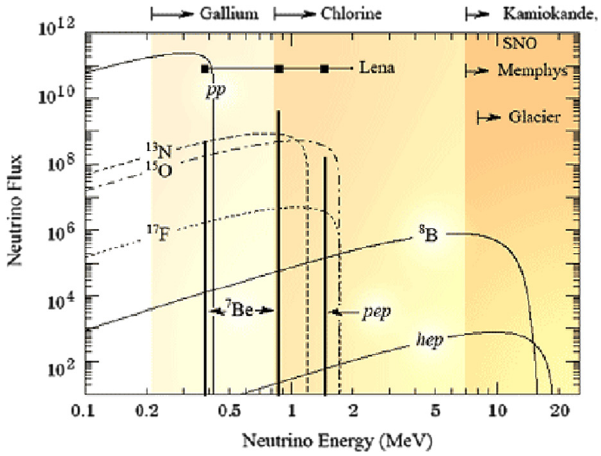

Fig. 1. Solar neutrino spectrum in the Standard Solar Model (see text).

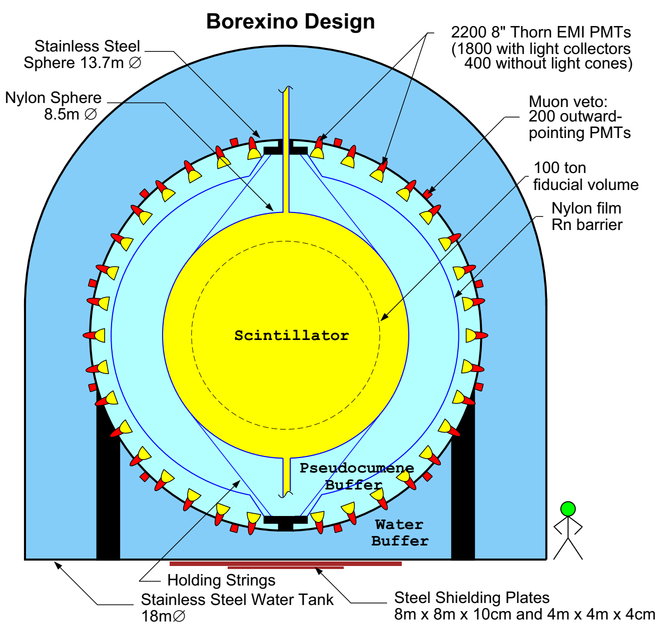

Fig. 2. Schematics of the Borexino detector (see text).

(Fig. 2). Several layers of shielding with increasing purity are used in order to define an inner Fiducial Volume of 100 t where the residual background is dominated by the intrinsic radiopurity of the scintillator.

The scintillator mixture is pseudocumene (PC) and PPO (1.5 g/l) as a fluor. It is contained in a transparent spherical vessel (Nylon Sphere, 100 μm thick), 8.5 m of diameter, and surrounded by 1000 t of high-purity buffer liquid (PC with the addition of DMP as light quencher). The photomultipliers are supported by a Stainless Steel Sphere, separating the inner part of the detector from the external shielding, provided by 2400 t of ultrapure water. An additional containment vessel (Nylon film Radon barrier) is placed between the Scintillator Nylon Sphere and the photomultipliers, serving the purpose of reducing Radon diffusion towards the inner part of the detector.

The outer water shield is equipped with 200 outward-pointing photomultipliers; they are used to veto for penetrating muons, the only significant remaining cosmic ray background (~ 1 muon m^{-2} h^{-1}) at the Gran Sasso depth (about 3700 m of water equivalent).

The 2200 inner photomultipliers are divided into a set of 1800 devices equipped with light cones (so that they see light only from the Nylon Sphere region) and a set of 400 PMTs without any light cone, sensitive to light originated in the whole Stainless Steel Sphere volume. This design increases the capability of rejecting the background generated by muons crossing the PC buffer (and not the scintillator).

Borexino features several external systems conceived to purify the fluids (water, nitrogen and the scintillator itself) used by the experiment (see e.g. Ref. [13]).

The Borexino detector was completed in 2007 and the experimental data taking in the final configuration began in May 2007.

The main detection reaction of Borexino, $\nu e \to \nu e$, is sensitive to all neutrino flavors, while having a higher cross-section for electron neutrinos. The Reines–Cowan inverse beta decay $\overline{\nu} p \to e^+ n$ reaction is also used, especially for the detection of geoneutrinos, which are produced as electron antineutrinos.

The energy deposited in the active target produces scintillation light which is collected by the photomultipliers. The energy of the event can be reconstructed from the number of photoelectrons (~ 500/MeV), while the position of the event is reconstructed from the photoelectron arrival times.

3. ^{7}Be flux measurement

Borexino reported the first detection of ^{7}Be solar neutrinos a few months after the start of the data taking [14]. The evidence was based on detecting the recoil spectrum of the electron from the $\nu e \to \nu e$ elastic scattering. Since solar neutrinos from ^{7}Be (the higher-energy component) have 0.862 MeV of energy, the feature being searched for is a Compton-like shoulder at 664 keV.

Cuts were applied to remove muons and Rn daughters, to discriminate against alpha particles (notably from ^{210}Po) and ^{85}Kr. The radiopurity of the scintillator was also essential in producing the evidence of the 664 keV Compton-like neutrino shoulder (generated by 861 keV monochromatic neutrinos, Fig. 3). This constituted the first experimental evidence of the ^{7}Be nuclear reaction inside the Sun.

Subsequent analyses have profited from better statistics [15] and a subsequent intensive calibration campaign [19], so that the best measurement of ^{7}Be solar neutrinos in Borexino is now $46.0 \pm 1.5(stat.)^{+1.5}_{-1.6}(syst.)$ counts/(day 100 t), in excellent agreement with the Standard Solar Model and the Mikheyev–Smirnov–Wolfenstein (MSW) LMA neutrino oscillation mechanism.

A day–night asymmetry study was also performed on the ^{7}Be solar neutrino rate [20]. The result found in Borexino was of $2(N-D)/(N+D) = 0.01 \pm 0.012(stat.) \pm 0.007(syst.)$, consistent with no significant day–night variation.

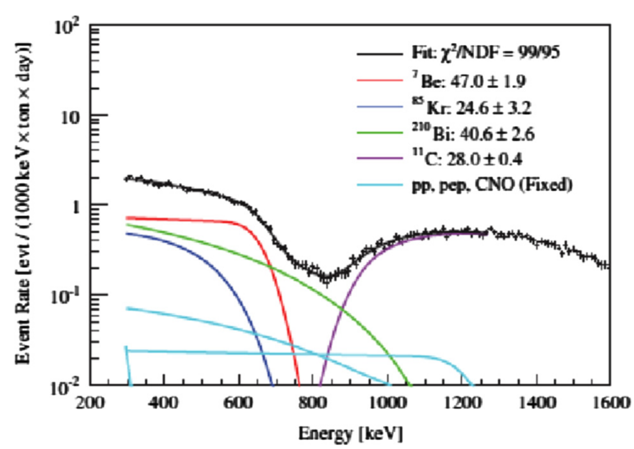

Fig. 3. ^{7}Be solar neutrino fit, with the signal and the various background components, from Ref. [19].