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STATUS REPORT ON BOREXINO AND RESULTS OF THE MUON-BACKGROUND MEASUREMENTS AT CERN

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The aim of BOREXINO is the real-time detection of the solar neutrino spectrum with an energy threshold of about 250 keV via the pure leptonic process of neutrino electron scattering $\nu + e \rightarrow \nu + e$ in a liquid scintillator target. The main objective of BOREXINO is the first determination of the monoenergetic ^{7}Be solar neutrino flux ($E_\nu = 862$ keV). In this paper the physics that can be done with BOREXINO is reported and the challenging background requirements for this low-level counting experiment are discussed together with the results of the prototype detector, the Counting Test Facility (CTF). The muon identification system for BOREXINO is presented in addition to results of the measurements that have been performed at the CERN SPS-muon beam in order to determine the production cross sections of muon-induced radio instable isotopes in a liquid scintillator target. Finally, the status of the detector is reviewed.

Установка «Борексино» предназначена для детектирования с энергетическим порогом 250 кэВ в реальном времени спектра солнечных нейтрино посредством чисто лептонного процесса рассеяния нейтрино на электроне $\nu + e \rightarrow \nu + e$ в мишени из жидкого сцинтиллятора. Главной целью «Борексино» является регистрация моноэнергетического потока солнечных нейтрино от ^{7}Be ($E_\nu = 862$ кэВ). В работе приведены и обсуждаются задачи, которые могут быть поставлены и решены на «Борексино», а также уделено внимание проблеме достижения требуемого низкого фона для этого эксперимента с малой скоростью счета и результатам измерений проверки скорости счета на прототипе детектора. Представлена система идентификации мюонов на «Борексино», а также результаты проведенных на мюонном пучке в ЦЕРН измерений сечений образования мюонами радиоактивных изотопов в мишени из жидкого сцинтиллятора. В заключение описано современное состояние детектора.

INTRODUCTION

The motivation for the BOREXINO experiment comes from the long-standing solar neutrino puzzle that originates from the discrepancy between the predicted solar neutrino flux according to the Standard Solar Model (SSM) and the experimental results. Data analysis of the existing solar neutrino experiments GALLEX [6] and GNO [7], SAGE [8], Kamiokande [9] and Superkamiokande [10] show an energy-dependent deficit of the solar neutrino flux, whereas the combination of the results indicates a significant suppression of the ^{7}Be neutrino branch. The latter fact is often called the 2nd solar neutrino problem or neutrino paradoxon. Taking into account the model-independent constraint on the charged current ^{7}Be

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neutrino flux derived from the experimental results of Superkamiokande and GALLEX and the value of the solar luminosity, less than about 20 % of the expected ^{7}Be neutrino flux are compatible with experimental results within 90 % C.L. [11].

Modifications of the Standard Solar Model as a possible solution to the solar neutrino problems are strongly disfavoured since helioseismology confirmes the SSM to an accuracy better than 0.5 % [2]. Explanations based on a resonant change of the nuclear cross sections relevant for the neutrino production in the Sun are also ruled out to a large extent by experiments like LUNA [5]. In addition, the overall performance of the radiochemical gallium experiments has been checked using artificial neutrino sources showing a perfect agreement with the expected values.

Taking all together, the solar neutrino problem reveals a strong hint for a particle physics solution beyond the standard model whereas vacuum- and matter enhanced neutrino flavour oscillations are the most favoured scenarios that can provide a solution to all existing solar neutrino experiments.

1. THE BOREXINO DETECTOR DESIGN

The BOREXINO experiment is located in the Hall C of the Gran Sasso Underground Laboratory (LNGS) in Italy. A rock overburden of 3600 m.w.e. shields the detector against cosmic rays that are suppressed by a factor of 10^6 resulting in a residual muon flux of $1.1\ \mu/(h \cdot m^2)$ at the experimental site. Figure 1 gives a schematic overview of the experimental facilities in the Hall C, showing the BOREXINO detector and its Counting Test Facility (CTF) [15].

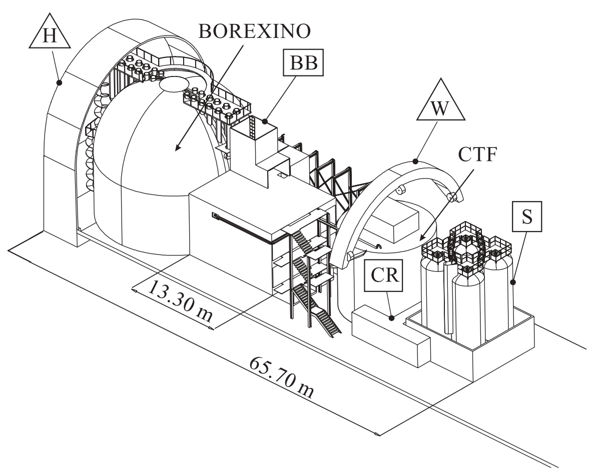

Fig. 1. Schematic overview of the Hall C at the Gran Sasso Underground Laboratory with the BOREXINO detector and the Counting Test Facility (CTF) [17]: H — tunnel walls of the Hall C; W — movable crane; CR — clean room of the CTF; S — storage vessel area for the liquid scintillator; BB — big building with electronic equipment, clean rooms, etc.

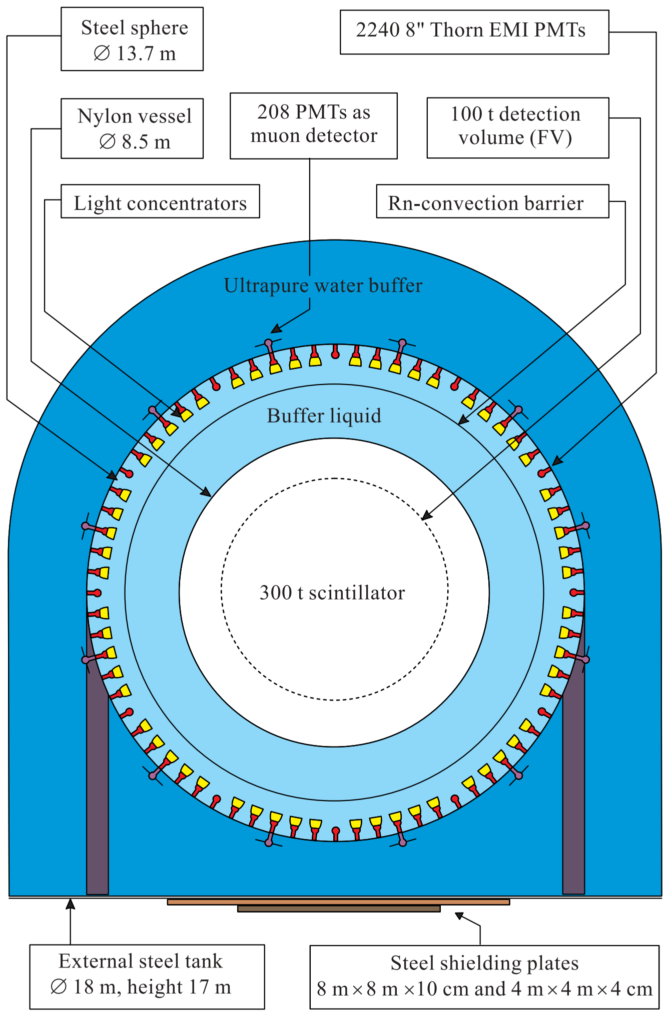

Fig. 2. Schematic view of the BOREXINO detector set-up, showing the most important structure elements of the detector

BOREXINO is an unsegmented scintillation detector with an onion-like shell structure to shield the target volume effectively against background radiation. The closer the materials are located to the center of the detector, the purer the materials have to be in terms of radioactivity. The BOREXINO detector set-up is displayed in Fig. 2.

The target in the center of the detector consists of 300 tons of ultrapure liquid scintillator contained in a thin, transparent nylon vessel 8.5 m in diameter. As a first choice for the scintillator serves pseudocumene (PC) doped with a wavelengthshifter (PPO = 2.5 diphenyloxazole) at a mass concentration of about 0.15 %. The nylon vessel is surrounded by a stainless steel sphere 13.7 m in diameter that supports 2200 inward-looking 8 inch phototubes. 1800 of them are equipped with light collectors in order to enhance the geometrical coverage and light collection and thus the energy resolution of the detector.

The space between the nylon vessel and the steel sphere is filled with a transparent, ultrapure buffer liquid in order to shield against background radiation emanating from the steel sphere, the phototubes, the concentrators and related detector materials.

The steel sphere itself is immersed in about 2300 m^3 of deionized water contained in a cylindrical, external steel tank 18 m in diameter and 17 m high. The water buffer acts as a passive shielding against background radiation emanating from the rock walls as well as an active muon veto water Cherenkov system. The latter one consists of 208 outward-pointing photomultipliers fixed on the outer surface of the stainless steel sphere.

2. PHYSICS WITH THE BOREXINO DETECTOR

The main objective of BOREXINO is the first determination of the monoenergetic ^{7}Be solar neutrino flux ($E_\nu = 862$ keV) with an energy threshold of about 250 keV. The detection reaction in the liquid scintillator target is the pure leptonic process of neutrino electron scattering $\nu_x + e^- \to \nu_x + e^-$ giving rise to a distinct compton-like electron recoil spectrum with its edge at 660 keV. Since the ν–e scattering process is sensitive to neutral current (NC) as well as charged current (CC) interactions, BOREXINO is able to detect ν_e as well as $\nu_{\mu,\tau}$, whereas the cross section for $\nu_{\mu,\tau}$ scattering is suppressed by a factor of ~ 4 compared to ν_e scattering.

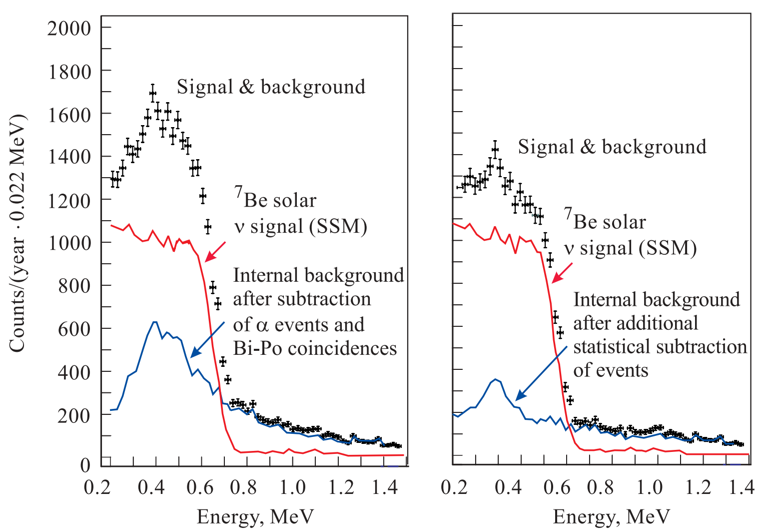

Fig. 3. Simulated energy spectra for solar neutrino events in BOREXINO under the assumption of the following background levels in the liquid scintillator target: ^{14}C/^{12}C = 1.94·10^{-18}, $^{238}\mathrm{U} = 10^{-16}$ g/g, $^{232}\mathrm{Th} = 10^{-16}$ g/g, $^{40}\mathrm{K}_{\mathrm{nat}} = 10^{-14}$ g/g. The internal background spectra have been calculated for different software cuts

Figure 3 displays the simulated neutrino event signature in BOREXINO with an expected counting rate of 55 counts/(d·100 t) according to the SSM (calculated for the energy interval $250 < E < 800$ keV) together with the estimated internal background spectrum after the application of different software cuts (e.g., α-, β-discrimination, statistical subtraction of events, etc.).

Due to its ultra low internal background and the low-energy threshold, BOREXINO is capable of exploring the following main goals of its physics program:

- direct, real-time measurement of the ^{7}Be solar neutrino flux,
- test of the MSW neutrino oscillation solution,
- test of the vacuum neutrino oscillation solution,
- test of the so-called 'day/night' effect.

In scenarios of *matter enhanced neutrino flavour conversion* (MSW scenarios) [12], i.e., for neutrino mass differences $\Delta m^2 \approx 10^{-6}$ eV^2 (SMA), 10^{-5} eV^2 (LMA), 10^{-7} eV^2 (LOW), a maximal reduced flux of approximately 12 counts/d·100 t (SMA) would be measured due to the lower cross section of $\nu_{\mu,\tau}$ scattering, which occurs only via neutral current interaction. Figure 4 displays the energy-dependent ν_e survival probability curve due to resonant neutrino flavour conversion in the Sun for the SMA (a), LMA (b) and LOW (c) solution. The ^{7}Be neutrino line at 862 keV is almost fully suppressed in the SMA case, as indicated by experimental data, while for the LMA case the suppression factor is only about 50 %.

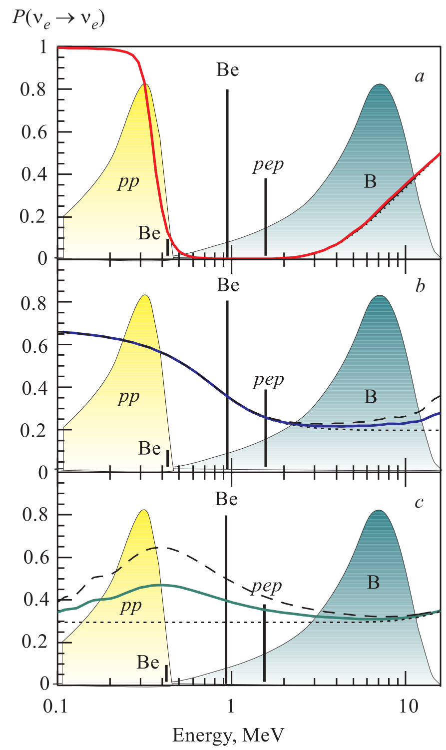

Fig. 4. The three different MSW neutrino oscillation scenarios in BOREXINO: (a) SMA ($\Delta m^2 \approx 5\cdot10^{-6}$), (b) LMA ($\Delta m^2 \approx 2\cdot10^{-5}$) and (c) LOW ($\Delta m^2 \approx 8\cdot10^{-8}$) solution. Displayed is the solar neutrino spectrum according to the standard solar model and the electron neutrino survival curve due to the three MSW scenarios of resonant neutrino flavour conversion. Solid curve — average; dotted curve — day; dashed curve — night

For the less probable MSW solution, which is referred to as the LOW solution for mass differences $\Delta m^2 \approx 10^{-7}$ eV^2 and almost full mixing, a 'day/night' effect due to electron neutrino recovery during their path through the earth could be observed in BOREXINO with high sensitivity. In contrast to Superkamiokande and SNO, BOREXINO is especially suited to test this effect due to its low-energy threshold and the fact that the 'day/night' fluctuations in the neutrino rate are especially distinctive for the monoenergetic ^{7}Be neutrino line.

Table 1 summarizes the expected solar neutrino counting rates via ν–e scattering in BOREXINO in 100 tons of scintillator (FV) per day, calculated for the three relevant intervals of the recoil electron energy and for the four scenarios: (i) the SSM according to the 1998

Table 1. **Expected solar neutrino counting rates via ν–e scattering in BOREXINO in 100 tons of scintillator (FV) per day, calculated for the three relevant intervals of the recoil electron energy and for the four scenarios**

Energy region of the recoil electrons	Neutrino source	SSM, d^{-1}	LMA, d^{-1}	SMA, d^{-1}	LOW, d^{-1}
0.25–0.80 MeV	*pp*	0.22	0.15	0.08	0.13
	^{7}Be	43.3	24.4	9.20	22.8
	pep	2.0	0.95	0.39	1.03
	^{13}N	4.0	2.27	0.87	2.13
	^{15}O	5.5	2.86	1.12	2.86
	^{17}F	0.07	0.03	0.01	0.03
	^{8}B	0.08	0.03	0.04	0.04
	sum	55.2	30.7	11.7	29.0
0.80–1.50 MeV	*pep*	1.43	0.68	0.28	0.73
	^{13}N	0.13	0.07	0.03	0.07
	^{15}O	1.80	0.86	0.35	0.92
	^{17}F	0.02	0.01	0.00	0.01
	^{8}B	0.10	0.04	0.05	0.05
	sum	3.48	1.66	0.71	1.78
1.50–5.50 MeV	^{8}B	0.454	0.174	0.217	0.232

Bahcall and Pinsonneault solar model [2], (ii) the LMA, (iii) the SMA and (iv) the LOW solution according to [4].

For the *vacuum oscillation scenario*, i.e., for neutrino mass differences $\Delta m^2 \approx 10^{-10}$ eV^2, BOREXINO would see a distinct time-dependent periodical neutrino signal due to the seasonal eccentricity of the Earth's orbit around the Sun.

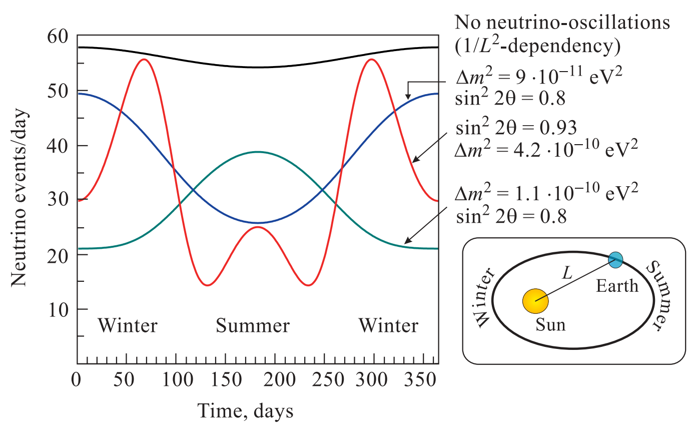

Fig. 5. Time-dependent counting rate of the expected ^{7}Be solar neutrino flux in BOREXINO for different vacuum oscillation parameters

Figure 5 displays the time-dependent counting rate of the expected ^{7}Be solar neutrino flux in BOREXINO for different vacuum oscillation parameters. For the parameter combination $\Delta m^2 = 4.2 \cdot 10^{-10}$ eV^2 and $\sin^2 2\theta = 0.93$ the ν flux varies between ~ 55 ν/d during spring and fall and almost complete suppression during summer (~ 15 ν/d). Due to this very distinct seasonal dependence of the ν flux it should be possible to distinguish between different vacuum oscillation scenarios.

Although BOREXINO is optimized for the detection of low-energy solar neutrinos, it is also an excellent detector for antineutrinos. The detection reaction occurs via the inverse beta decay $\bar{\nu_e} + p \rightarrow e^+ + n$ in the scintillator target providing a distinct event signature — a delayed coincidence between the prompt annihilation of the positron and the delayed 2.2 MeV γ correlated to the neutron capture on a proton ($\tau = 0.2$ ms). The threshold for this reaction is 1.8 MeV. BOREXINO can look for signals from geophysical neutrinos [13] as well as for neutrinos emitted by European nuclear power plants [14]. The latter would serve as a long baseline neutrino oscillation experiment probing the large mixing angle solution for the solar neutrino problem.

3. RESULTS OF THE COUNTING TEST FACILITY AND NEUTRON ACTIVATION ANALYSIS

Since BOREXINO is a low-level counting experiment with a signal rate of only a few counts/day, the demands on radiopurity levels of the detector components, especially of the liquid scintillator target, are very stringent and challenging. The intrinsic concentration of uranium and thorium should not exceed a level of 10^{-16} and the ratio of ^{14}C/^{12}C must not be higher than $\sim 10^{-18}$ to reduce the internal background rate down to 1 count/day. In order to test the feasibility of BOREXINO in terms of radioactive impurities of detector materials, a prototype detector, the Counting Test Facility [17], has been built up in the Hall C of the Gran Sasso Underground Laboratory with a scintillator target volume of ~ 5 m^3. The CTF was taking data from spring 1995 till summer 1997 and encouraging results have been obtained for the purity levels of the liquid scintillator [15–17]:

- ^{14}C/^{12}C = $1.94 \cdot 10^{-18}$,
- ^{238}U = $(3.5 \pm 1.3 \cdot 10^{-16})$ g/g,
- ^{232}Th = $(4.4 \pm 1.5 \cdot 10^{-16})$ g/g.

Besides, tests of the liquid scintillator handling- and purification system, tests of the water purification system and studies of the optical properties of the liquid scintillator target, of the calibration procedures and software analysis could be performed with the CTF. Furthermore the study of intersecting cosmic muons with a set of proportional chambers on top of the CTF detector showed the necessity of an outer muon veto system for BOREXINO. In addition to the determination of intrinsic radiopurity levels in the CTF, an independent method — highly developed neutron activation analysis (NAA) — has been performed in the new low-background underground laboratory in Garching. Those NAA measurements provide *direct* information on the radiopurity of scintillator samples and allow important tests on the secular equilibrium of the decay chains. With NAA an upper limit for the 'contamination' of uranium in the liquid scintillator PC/PPO of ^{238}U $< 2 \cdot 10^{-16}$ g/g (90 % C.L.) has been obtained. For details see Ref. [18].

4. THE MUON IDENTIFICATION SYSTEM FOR BOREXINO

Although the muon flux at the experimental site is reduced to a rate of 1.1 μ/h$\cdot\mathrm{m}^2$, careful analysis of the CTF data clearly indicated the necessity of an active muon identification system for BOREXINO. In order to suppress the external cosmogenic background to less than 1 count/d$\cdot$100 t, the leaking rate should not exceed a level of $\approx 10^{-4}$. The muon identification system is divided into three 'sub-systems':

• The *Outer Detector (OD)*:
The water buffer between the external tank and the inner steel sphere serves as an active water Cherenkov detection system for high energetic cosmic muons and their secondaries. The OD consists of 208 photomultiplier tubes that are mounted on the outer surface of the stainless steel sphere pointing towards the water buffer. The entire surface of the OD is covered with Tyvek sheets — a white polyolefin plastic with a diffuse reflectivity of over 90 % for visible light. The diffuse character of the reflection distributes the Cherenkov photons over a large surface area and hence increases the overall photoelectron yield as well as the number of triggered photomultipliers. Muons intersecting the water tank should be identified with high efficiency ($>$ 95 %).

• The *Inner Detector (ID)*:
2240 photomultipliers are homogeneously distributed on the inside of the internal steel sphere facing the scintillator vessel. 1866 of them are equipped *with* light collectors thus accepting photons mainly from the scintillator region, whereas the residual tubes *without* light collectors are able to accept photons from all directions in the buffer region. Therefore, phototubes without light collectors have a higher efficiency to detect Cherenkov photons created along the muon track in the buffer liquid. By comparing the sum of photoelectrons from these tubes without light collectors with the total sum of photoelectrons, one is able to separate between muon background events and events from the scintillator vessel. The separation efficiency of the ID should be $>$95 %.

• The *Offline Analysis*:
Analyzing the CTF data we have found several strategies to discriminate between beta- and muon events. Most of them are based on the unique timing distribution of muon signals. Monte Carlo calculations gave an indication that muon- and beta events can be distinguished with an efficiency better than 95 %.

These 'sub-systems' can be tested and calibrated mutually, thereby reducing systematic errors. In addition to signal generation by Cherenkov photons of traversing muons, neutrino-like events can be generated by the decay of cosmogenic induced radio-instable isotopes in the scintillator target. The cosmogenic background is being discussed in the next section.

5. MEASUREMENTS AT THE SPS MUON BEAM AT CERN

In order to understand the cosmogenic induced background in BOREXINO the production of radio-isotopes by muons and their secondaries in a scintillator target

$$\mu(\&\,\mathrm{shower}) + {}^{12}\mathrm{C} \rightarrow {}^{A}_{Z}X \tag{1}$$

has been studied experimentally in the framework of the NA54 experiment at CERN [19]. Depending on the lifetime of the nuclei, its signal can be correllated in space and time with the generating muon. Table 2 lists the radioactive isotopes which are produced by muons and their secondary shower particles when passing through a scintillator (^{12}C) target.

Table 2. **Radioactive isotopes that can be produced by muons and their secondary shower particles when passing through a scintillator target consisting mainly of ^{12}C and ^{1}H**

Decay	Isotope	$T_{1/2}$	$E_{\max}(\beta^-, \beta^+)$	+ E_γ (BR)
β^-	^{12}B	0.02 s	13.4 MeV (β^-)	
	^{11}Be	13.80 s	11.5 MeV (β^-)	
	^{10}Be	$1.5{\cdot}10^6$y	0.56 MeV (β^-)	
	^{11}Li	0.09 s	20.8 MeV (β^-)	
	^{9}Li	0.18 s	13.6 MeV (β^-)	
	^{8}Li	0.84 s	16.0 MeV (β^-)	
	^{8}He	0.12 s	10.6 MeV (β^-)	
	^{6}He	0.81 s	3.5 MeV (β^-)	
β^+	^{11}C	20.38 min	0.96 MeV (β^+)	
	^{10}C	19.30 s	1.9 MeV (β^+)	+ 0.72 MeV (98.53 %)
	^{9}C	0.13 s	16.0 MeV (β^+)	
	^{8}B	0.77 s	13.7 MeV (β^+)	
EC	^{7}Be	53.3 d		0.478 MeV (10 %)

Of particular relevance for BOREXINO are the isotopes ^{7}Be,^{11}C, ^{10}C and ^{11}Be due to their relatively long half-lives and decay energies, thus generating signals in the ^{7}Be neutrino energy window (250–800 keV), in the *pep* neutrino energy window (800–1500 keV) and in the high-energy range relevant for ^{8}B neutrinos which are undistinguishable from ν events. Furthermore radio-instable isotopes which emit β–n cascades, such as ^{8}He, ^{9}Li and ^{11}Li, can mimic the $\bar{\nu}_e$ tag relevant for anti-neutrino spectroscopy [13].

In addition to the cross sections for muon-induced isotopes the lateral activation profile of ^{11}C has been measured, i.e., the probability that this isotope is produced at a given distance from the muon track. The latter is of relevance, for example, in the case that spatial spallation cuts will be applied in the BOREXINO data analysis.

Similar experimental conditions, as encountered in BOREXINO, were simulated in the CERN experiment. The shower is built up in a concrete and water absorber placed in front of the ^{12}C targets and reaches saturation after typically 1–2 m. Two muon energies, 100 and 190 GeV, were available during this period of measurements (mean muon energy at the BOREXINO experimental site is 320 GeV). Depending on the decay mode of the produced isotopes different detection techniques were chosen. This comprises low-level gamma spectroscopy for ^{7}Be, β–γ coincidence counting for ^{11}C and in-situ scintillation spectroscopy for short-lived isotopes.

Table 3 summarizes the calculated counting rates due to the muon-induced isotopes in BOREXINO based on the measurements at CERN [19]. In addition to the total counting rates, Table 3 lists the muon background rates in the different energy regions that are relevant for the detection of ^{7}Be neutrinos ($250 < E < 800$ keV), *pep* neutrinos ($0.8 < E < 1.4$ MeV) and ^{8}B neutrinos ($2.8 < E < 5.5$ MeV). As one can deduce from Table 3, the largest background contribution in the energy region $250 < E < 800$ keV results from the isotope ^{7}Be.

Table 3. **Muon-induced background rates in BOREXINO, calculated for different energy regions that are relevant for the detection of solar ^{7}Be, *pep* and ^{8}B neutrinos. The rates are given in counts/d normalized to 100 tons of target mass [19]**

Isotope	Full energy range	$250 < E < 800$ keV ^{7}Be-ν region	$0.8 < E < 1.4$ MeV *pep*-ν region	$2.8 < E < 5.5$ MeV ^{8}B-ν region
^{11}C	14.55 ± 1.49	0	7.36 ± 0.75	0
^{7}Be	0.34 ± 0.04	0.34 ± 0.04	0	0
^{11}Be	< 0.034	$< 4.3 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-4}$	< 0.01
^{10}C	1.95 ± 0.21	0	0	0.56 ± 0.06
^{8}Li	0.070 ± 0.017	$(2.5 \pm 0.6) \cdot 10^{-4}$	$(8.0 \pm 2.0) \cdot 10^{-4}$	0.020 ± 0.005
^{6}He	0.26 ± 0.03	0.040 ± 0.004	0.07 ± 0.01	0.011 ± 0.001
^{8}B	0.11 ± 0.02	0	$(3.3 \pm 0.6) \cdot 10^{-5}$	0.020 ± 0.004
^{9}C	0.077 ± 0.025	0	0	0.016 ± 0.005
^{9}Li+^{8}He	0.034 ± 0.007	$< 6.8 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-3}$	< 0.014
Sum	~ 17.4	~ 0.38	~ 7.4	~ 0.65
ν rate (SSM)		~ 50	~ 1.5	~ 0.53

Compared with an expected ^{7}Be ν rate of ~ 50 counts/(d·100 t) (according to the SSM) a total cosmic-ray-induced background rate of ~ 0.4 counts/(d·100 t) in BOREXINO is tolerable. Even for total neutrino flavour conversion the signal rate of ~ 10 counts/(d·100 t) exceeds this background contribution significantly.

The large muon-induced background contribution of ~ 7 counts/(d·100 t) jeopardizes the detection of the solar *pep* neutrinos with an event rate of 1.5 counts/(d·100 t) in this energy interval in BOREXINO (according to the SSM). In MSW scenarios the signal-to-background rate due to ^{11}C production is even expected to be well below 0.1.

Although the background rate in the interval $2.8 < E < 5.5$ MeV is of the same order as the neutrino event rate in this energy range ($R_\nu = 0.53$ ν/(d·100 t)), it seems to be possible to determine the ^{8}B ν rate by using the method of statistical subtraction. Since BOREXINO, KamLAND and LENS are the only solar neutrino experiments which are capable of detecting the ^{8}B-neutrino spectrum with an energy threshold less than 5.5 MeV, this region is of special interest, too. A spectral distortion of the ^{8}B-neutrino spectrum according to the MSW effect [12] would especially affect this medium energy region.

CONCLUSIONS

BOREXINO is dedicated to detect low-energy solar neutrinos in a real-time measurement. Although neutrino counting rates of less than 55 counts/d·100 t put very stringent and challenging limits on the purity requirements of detector materials, data from the CTF and NAA show very encouraging results on the radiopurity of liquid scintillators. NAA in Garching has been developed to detect concentration levels far below the 10^{-16} range.

Based on the measurements at the CERN SPS-muon beam, the muon-induced background in the BOREXINO detector has been calculated and was found to be tolerable in the energy range for ^{7}Be and ^{8}B neutrinos but jeopardizes the detection of *pep* neutrinos.

The external tank and the internal steel sphere of BOREXINO have been finished in the Hall C of the underground laboratory at Gran Sasso. The design of the experimental subsystems has been finalized. The CTF for the qualification of the BOREXINO scintillator and the test of the purification system has been rebuilt (CTF2) and has been taking data since May 2000. BOREXINO should be ready for filling by the end of 2001.

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