Muon induced Production of Radioactive Isotopes in Scintillation Detectors

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Abstract

The production of radioactive isotopes in scintillation detectors by muons and their secondary shower particles has been studied experimentally at the SPS muon beam at Cern. This paper shows results obtained in cross section measurements on liquid scintillator targets, especially on ^{12}C which is the most relevant target in these organic materials. Their energy dependence has been deduced from the cross sections determined at two muon energies 100GeV and 190GeV. Based on the measured cross sections the muon induced background rates for the forthcoming solar neutrino experiments Borexino and KamLand have been calculated for different energy regions that are relevant for solar neutrino physics.

1 Introduction

Low energy non-accelerator experiments will play a key role in the near future in investigating physics beyond the standard model. Besides the evidence for neutrino oscillations found in studying atmospheric neutrinos in the Super Kamiokande detector [16] it is very plausible that this phenomenon is also the solution to the long-standing solar neutrino puzzle. Hence, a large activity has been started in the field of real time measurements of solar neutrinos at low energies. These projects are based on the use of large

quantities of organic liquid scintillators as detection material and the main concern of these experiments is background suppression. Examples of such projects are the future solar neutrino experiments BOREXINO [14], KamLAND[1] [15, 22] and LENS [19, 20], which aim to perform spectroscopy of the low energy part of the solar pp-cycle. Besides the challenge to constrain the level of the intrinsic radioimpurities in liquid scintillators to very low limits (e.g. for BOREXINO the mass concentrations of Thorium and Uranium have to be less than typically 10^{-16}g/g) these experiments are faced to control cosmogenic created background. Background of this type may arise due to the creation of long-lived isotopes during the production and transport of the scintillator at surface level, and due to in-situ production of also short-lived nuclei during the experiment in underground laboratories. In both cases the hadronic and electromagnetic showers created by cosmic muons are by far the dominating source of cosmogenic background.

This paper shows results obtained in cross section measurements of muon induced background in liquid scintillators, especially on ^{12}C which is the most relevant target in these organic materials. In the frame of the NA54 [8] experiment, the SPS muon beam at CERN had been used to produce the background nuclei at 100GeV and 190GeV muon energy.

2 Relevant Isotopes for Cosmogenic Background in ^{12}C-Targets

This work was triggered by investigating background issues in the BOREXINO experiment, but our results are also relevant for KamLAND and LENS. Table 1 lists all radioactive isotopes which can be produced in reactions of high energetic cosmic muons with ^{12}C and hence in an organic liquid scintillator. In addition, the half lifes as well as the endpoint energies of the beta emitters are shown [7].

Near future solar neutrino experiments like BOREXINO and KamLAND aim to measure solar neutrinos via the elastic neutrino-electron scattering process, $\nu + e^- \rightarrow \nu + e^-$. Here the monoenergetic solar ^{7}Be-neutrinos (E_ν=0.86MeV) and pep-neutrinos (E_ν =1.44 MeV) generate electron recoil spectra with maximal energies of 0.66MeV and 1.2MeV, respectively. The neutrino rates in these experiments are about 50 counts per day in 100t of detector material for the ^{7}Be-line (250keV<E<800keV) and 1.5 counts per day for the pep-neutrinos (0.8MeV<E<1.4MeV) according to the standard solar model (SSM [4]), assuming that no neutrino flavour conversion appears. However, in case of total con-

[1] KamLAND has been approved as a *long-baseline reactor anti-neutrino* experiment. Nevertheless, in an upgraded detector configuration the experiment can exploit its principle potential to measure solar ^{8}B- and ^{7}Be-neutrinos.

	Isotopes	$T_{1/2}$	E_{max}
β^-	^{12}B	0.02 sec	13.4 MeV (β^-)
	^{11}Be	13.80 sec	11.5 MeV (β^-)
	^{11}Li	0.09 sec	20.8 MeV (β^-)
	^{9}Li	0.18 sec	13.6 MeV (β^-)
	^{8}Li	0.84 sec	16.0 MeV (β^-)
	^{8}He	0.12 sec	10.6 MeV (β^-)
	^{6}He	0.81 sec	3.5 MeV (β^-)
β^+, EC	^{11}C	20.38 min	0.96 MeV (β^+)
	^{10}C	19.30 sec	1.9 MeV (β^+) (+0.72 MeV γ, 98.53%)
	^{9}C	0.13 sec	16.0 MeV (β^+)
	^{8}B	0.77 sec	13.7 MeV (β^+)
	^{7}Be	53.3 days	0.478 MeV (γ, 10%)

Table 1: *Radioactive isotopes which are produced by muons and their secondary shower particles when passing through a scintillator (^{12}C) target). Of particular relevance for Borexino are the isotopes ^{7}Be,^{11}C, ^{10}C and ^{11}Be. Radio instable isotopes which emit $\beta-$neutron cascades as ^{8}He, ^{9}Li and ^{11}Li are important for anti-neutrino spectroscopy.*

version of ^{7}Be- and pep-neutrinos in the sun (MSW effect [17]) the rates are reduced by a factor ≈5. If vacuum oscillations are the solution to the solar neutrino puzzle both experiments would register seasonal variations in the signal rate. In any case both projects are low level experiments and the background due to cosmic muons has to be compared with the numbers quoted above. Measurements of the prototype detector of Borexino, the Counting Test Facility (CTF) have shown that the content of ^{14}C in the liquid scintillator is too high in order to allow the detection of pp-neutrinos with energies up to 422keV [1, 2].

To a smaller extent continuous spectra from ^{13}N ($E_{\nu max}$=1.2MeV) and ^{15}O ($E_{\nu max}$= 1.7MeV) and from ^{8}B ($E_{\nu max}$=14 MeV) contribute to the solar neutrino signal.

In addition both detectors are capable searching for terrestrial electron antineutrinos $\bar{\nu}_e$ [18] and for long baseline reactor neutrino measurements [21] via the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Here the neutron is recognized via the characteristic 2.2MeV radiation emitted after neutron capture in hydrogen, taking advantage of the spatial and delayed time coincidence between the positron and neutron.

Most of the isotopes have half lifes in the sub-sec scale. Since Borexino and KamLand use outer cherenkov detectors for muon recognition, it is possible to discard these activities with a moderate loss of measuring time by imposing a veto cut subsequent to a

muon signal in the off-line analysis. However, this is not the case for ^{11}Be, ^{11}C, ^{10}C and ^{7}Be. Their life times are too long to veto the whole detector after every muon traversing the detector. Here we discuss shortly their potential background contribution for real time solar neutrino detection.

- Solar ^{7}Be-ν: Since the energy deposition of all positron emitters is shifted by $\approx$1MeV due to the annihilation process, only ^{7}Be and ^{11}Be are relevant for low energy neutrino (i.e. $E_\nu < 1$MeV) detection like the solar ^{7}Be-ν. However, the 478keV gamma radiation of ^{7}Be coincides with the compton like electron recoil spectrum which is the signature in Borexino and KamLand. Due to the high beta endpoint energy of ^{11}Be this isotope gives only a minor contribution here.

- Solar pep-ν: The most relevant isotope here is ^{11}C. Due to the annihilation shift the energy release is between 1MeV and 2MeV. In addition a part of the ^{11}Be decays contribute to this background. All other isotopes are not dangerous, even ^{10}C, since their energy release is out of the relevant energy window. This background consideration applies also for ^{13}N and ^{15}O neutrinos from the solar CNO cycle.

- Solar ^{8}B-ν: The actual lower limits of solar neutrino experiments aiming for ^{8}B-ν are at $\approx$5.5MeV [16, 12]. Below ca. 1.7MeV the ^{8}B-spectrum is dominated by the far more abundant CNO- and pep-neutrinos. However, it would be extremly interesting to measure solar ^{8}B-ν in between these limits, because flavour conversion could deform the spectral shape significantly in this regime. The most relevant cosmogenic nuclei which can create background events here are ^{11}Be, ^{10}C, and to a smaller extent ^{11}C.

In the energy range relevant for electron anti-neutrino detection ($\approx$8MeV for reactor $\bar{\nu}_e$; $\approx$3MeV for terrestial $\bar{\nu}_e$) ^{8}He, ^{9}Li and ^{11}Li can emit $\beta-$neutron cascades mimicking the anti-neutrino signature. The muon correlated event sequence can be discriminated from $\bar{\nu}_e$ signals by the characteristic triple coincidence, if the muon is recognized by the detector.

3 Experimental Set-Up

The production of radio isotopes by muons and their secondaries has been studied experimentally in the frame of the NA54 experiment at the SPS muon beam at Cern in November 1997.
In order to simulate similar experimental conditions as encountered in underground neutrino experiments like Borexino or KamLand, water and concrete have been chosen

as absorber materials for the muon shower production. The muon shower builds up in 240cm of concrete followed by 200cm of water placed in front of the ^{12}C targets and reaches saturation after typically 1-2 meters [13, 8].
Since the half lifes of the muon induced radio isotopes differ very much from a few micro seconds to several days, three different detection techniques as well as ^{12}C targets have been used:

1. For ^{7}Be with a half life of $T_{1/2}$=53.3d polyethylen (PE) disks with a diameter of 7cm and a thickness of 2cm have been used as ^{12}C target. Two sets have been used for the 100GeV and 190GeV runs, respectively. After irradiation the ^{7}Be activity was determined by low-background gamma spectroscopy using Ge-spectrometers at the *Max Planck Insititut für Kernphysik* in Heidelberg and the *Laboratori Nazionali del Gran Sasso* LNGS in Italy (see chapter 4).

2. For the determination of the muon induced ^{11}C with a half life of $T_{1/2}$=20.38min we used polyethylene bottles filled with ≈1l of the liquid scintillator Pseudocumene (1,2,4-Trimethylbenzene) as ^{12}C target. The activity was measured on-site via the β-γ-coincidence counting technique which will be described in the next chapter and in addition via in-situ-scintillation spectroscopy discussed in chapter 5.2.

3. For the determination of the residual short-lived isotopes with half lifes in the range of a few μs to several seconds, in-situ scintillation spectroscopy has been chosen as detection technique. As described in chapter 5 four scintillator cells filled with the liquid scintillator NE235C have been used as ^{12}C target and detector at once.

In order to measure the lateral activation profile of ^{7}Be and ^{11}C, the PE-disks as well as the scintillator bottles were positioned next to each other, perpendicular to the muon beam extending to a distance of about 30cm from the muon track. A schematical drawing of the entire experimental set-up with the spatial arrangement of the targets and detectors is shown in Fig. 1.

Two muon energies, 100GeV and 190GeV, were available at the SPS during the period of data taking and various muon (μ^+) intensities were selected. The maximal intensity available was a few 10^8 muons per spill of 2.4s duration at a repetition time of 14.4s. The muon beam had a diameter of ∼53mm in front of the absorber and an energy resolution of 3%. The muon beam intensity was monitored with the Hodoscope H5 [6] and two independent scintillation- and ionization counters.

4 Measurements of the Long-Lived Isotopes ^{11}C, ^{7}Be

This section deals with the production of ^{7}Be and ^{11}C from a matrix containing ^{12}C. The specific saturation activity produced in a liquid scintillator target is proportional to the inverse of the half life of the isotope which is 20.38min for ^{11}C and 53.3d for ^{7}Be. This makes it difficult to measure the activation in positions off center by in situ methods.

The concern of the solar neutrino experiments is the overall production of radio nuclides which means that the production along the muon track has to be determined as well as the fraction which is produced within a certain distance from the muon track. All cross sections we have determined refer to the production of radioactive nuclides within a radius of 45cm perpendicular to the muon beam axis. As we will show later on (see equation 1) for ^{11}C this region covers 96% of the overall production. Since the lateral distribution changes significantly over the target dimensions its extension has been taken into account in the data analysis. Therefore we have measured the lateral distribution for the production of ^{11}C and ^{7}Be.

Previous experiments dealing with the production of ^{56}Co, ^{57}Co, ^{58}Co and ^{54}Mn from ^{58}Ni, ^{60}Ni and ^{54}Fe revealed that the lateral activation profil can be well described by a superposition of a gaussian function around the center of the muon beam and an exponential slope, dominating for radii above ∼15cm [13, 8].

The production rate of ^{11}C was measured via the activation of Pseudocumene, the solvent of the scintillator for Borexino. The bottles with a diameter of 90mm containing approximately 1l of scintillator were irradiated for at least 60 minutes. This has been done continuously over a period of ∼2 weeks for both muon energies 100GeV and 190GeV.

After each irradiation 70ml of the liquid scintillator were filled into a transparent counting vial which was placed inbetween a Ge-detector and a photomultiplier tube. The stopping β^+ particle was detected in the liquid scintillator in coincidence with the annihilation photons that were observed in the Ge-detector. This permitted to determine the production within a radius of 33cm and to reconstruct the activation profile originated by muons and secondary shower particles.

The probability distribution has been evaluated by a χ^2 minimization of the function $\Phi(r)$ with respect to the data describing the production of an isotope in a ring with the area $2\pi r dr$.

The distribution $\Phi(r)$ is normalized as $\int_0^\infty \Phi(r) 2\pi r dr = 1$. From the data one obtains

$$\Phi(r) = \frac{1}{166} \cdot e^{-0.0403\, r^2} + \frac{1}{1223} \cdot e^{-0.098\, r} \qquad (1)$$

for ^{11}C with r given in cm as depicted in Fig. 2. This agrees well with the distribution

observed for ^{7}Be.

For the determination of σ the following sources of uncertainties have been taken into account:

- detection efficiency: $\sim 1\%$
- statistical uncertainty for the measurement of $\Phi(r)$: $\sim 3\%$
- relative position of the targets to the muon beam axis: $\sim 6\%$
- calibration of the muon beam intensity: $\sim 6\%$

In total the combined uncertainty in the calculated cross section σ is about 10%. With $\Phi(r)$ we can calculate the total production cross section from this detection method to be:

$$\begin{aligned} E_\mu = 100\text{GeV}: \quad \sigma(^{11}\text{C}) = \quad (582 \pm 58)\,\mu barn \\ E_\mu = 190\text{GeV}: \quad \sigma(^{11}\text{C}) = \quad (925 \pm 93)\,\mu barn \end{aligned}$$

Gamma-spectroscopy was chosen to determine the production rates of ^{7}Be. The two different sets of PE-disks mentioned in section 3 were used as a target for the production of ^{7}Be and laterally aligned to the left and the right of the beam axis. ^{7}Be was accumulated during the 100GeV and the 190GeV period and measured after each irradiation in low-level $\gamma-$spectrometers at the *Max Planck Insititut für Kernphysik* in Heidelberg and the LNGS. The number of nuclei produced was determined by the number of ^{7}Be disintegrations which can be observed via the 478keV $\gamma-$ray, being emitted with a branching ratio of 10%. Taking into account $\Phi(r)$ the evaluation yielded the cross sections for the 100GeV and 190GeV irradiation period to be

$$\begin{aligned} E_\mu = 100\text{GeV}: \quad \sigma(^{7}\text{Be}) = \quad (126 \pm 13)\,\mu barn \\ E_\mu = 190\text{GeV}: \quad \sigma(^{7}\text{Be}) = \quad (230 \pm 23)\,\mu barn. \end{aligned}$$

The detection efficiencies of the different detectors employed were calibrated by a ^{7}Be source which was especially prepared for this purpose.

5 Measurements of the Short-Lived Isotopes

With the two detection techniques described in the previous section, low-level γ-spectroscopy and β-γ coincidence counting, it was possible to determine the cross sections of long-lived radio isotopes with half lifes greater than a few minutes. In order to measure also the short-lived muon induced isotopes with decay times of a few seconds (^{11}Be, ^{10}C, ^{8}Li, ^{6}He, ^{8}B) or milliseconds (^{12}Be, ^{11}Li, ^{8}He, ^{9}C) a third detection technique - *in-situ scintillation spectroscopy* - was necessary. In this section the detector set-up and the results of the scintillation spectroscopy measurements will be described.

5.1 Set-Up of the Scintillator Cell Arrangement

A group of four liquid scintillator cells was placed on the muon beam axis behind the concrete and water absorber in which the muon shower builds up. Each of those cells has a detection volume of 88cm·20cm·9cm that is filled with the mineral oil based liquid scintillator NE235C and is viewed by four photomultiplier tubes with a diameter of 7.5cm. Compared to the number density of ^{12}C in pure PC, oxygen and nitrogen are present in NE235C at a level of $\sim 10^{-4}$. Hence the contribution of cosmogenic produced nuclei from oxygen and nitrogen can be neglected. Besides this fact, the composition of NE235C is very similar to the scintillators going to be used in BOREXINO and KamLAND were PPO is chosen as wavelength shifter.

The energy resolution of each cell is 14% at E=477keV. The arrangement of the four cells in the total experimental set-up is shown in Fig. 1. The innermost scintillator cell - *the target cell* - is directly aligned with the beam axis acting as ^{12}C-target and detector at once. The target cell is surrounded by 3 *trigger cells*, that were used to detect the two 511keV gammas from the annihilation of the positron which is produced by β^+-emitters in the target cell. With this cell arrangement two different sets of data could be recorded simultaneously, to distinguish between β^-- and β^+-emitters. Firstly, the single counting rate in the target cell for both β^-- and β^+ decays (SGL-mode) was recorded and secondly, a 3-fold coincidence between the target cell and two of the trigger cells was applied to select the β^+ decays (TFC-mode).

Directly after each muon spill, the counting rates of the target cell $a_i(t)$ (i=1; ...; 100) were read out every 1/10s for a counting time of 10s duration. To avoid any damage to the target cell in the muon beam, the high voltage has been applied some milliseconds prior to the end of the muon spill for the data set with a counter read-out time interval of 1/10s. For the determination of the very short-lived isotopes, the scintillator cells were operated continuously and the read-out time interval was set to 1/100s (see chapter 5.3.3).

To distinguish between different radio isotopes with similar half lifes, the counting rate of the target cell was recorded in seven separate electronic counters with different energy thresholds. For the single counting mode, five channels with an energy threshold of 110keV, 1MeV, 4MeV, 12MeV, 20MeV and for the 3-fold coincidence counting mode, two channels with a threshold of 110keV and 1MeV have been used.

The in-situ scintillation spectroscopy measurements have been performed at two different muon energies E_μ=100GeV and E_μ=190GeV with a typical muon rate of $\Phi_\mu = 6 \cdot 10^7 \mu/spill$ (at 100GeV) and $\Phi_\mu = 3 \cdot 10^7 \mu/spill$ (at 190GeV). Our strategy for the analysis of the muon induced short-lived isotopes was

- firstly, to determine the cross section for the production of the long-lived isotope

^{11}C with $T_{1/2}$=20.38min. By comparing this result with the cross section that was obtained with the $\beta - \gamma$ coincidence measurement of the irradiated scintillator bottles, the detector efficiency ϵ was determined. This efficiency has also been calculated via Monte-Carlo simulations and was found to be in excellent agreement (within 3%) with the experimental value.

- Secondly, to evaluate the cross sections for the actual short-lived isotopes using the calibration done for ^{11}C.

5.2 Analysis of ^{11}C

During our beam time at the CERN SPS-muon beam the muon flux fluctuated a lot and did not run continuously over the periods of data taking. Therefore two different fits to the data have been performed for the ^{11}C analysis. Runs with an extended muon spill break of at least 60 minutes could be used directly to fit the data in this time window with a simple exponential decay function according to the life time of ^{11}C. Since those extended spill breaks did not occur in every single run, a second more global fit was applied to the data that included the ^{11}C decay as well as the build-up over the entire run. Fig. 3 displays a fit to the data, showing the time variation of the ^{11}C counting rate $A_{^{11}C}(t)$ in the target cell with respect to the muon flux $\Phi_\mu(t)$ in each spill. One can observe very well the build-up of the ^{11}C isotope in the liquid scintillator while the muon beam was running continuously and the decay of the ^{11}C during muon spill breaks.

After each muon spill at the time t the counting rates $a_i(t)$ (i=1,2,...,100) of each 0.1s time bin were summed up over the counter read-out time of 10sec duration

$$A(t) = \sum_{i=61}^{100} a_i(t) \quad . \tag{2}$$

Hence A(t) is the sum of the activity of all produced isotopes in the target cell. To avoid the influence of the short-lived isotopes with $T_{1/2} < 1s$ in the ^{11}C counting rate, only the last 4 seconds of the total read-out time were taken into account for the summation. The cross section σ for the muon induced production of a radio instable isotope in a liquid scintillator target can then be calculated as follows:

$$\sigma = \frac{\tau \cdot A_{isotope}(t_0)}{\eta_{^{12}\mathrm{C}} \cdot N_\mu^{eff}(t_0) \cdot \epsilon} \tag{3}$$

where $A_{isotope}(t_0)$ is the activity of the isotope at the counting time t_0 that can be derived from an exponential fit to the data A(t) and τ is the lifetime of the isotope e.g. $\tau(^{11}\mathrm{C})$ = 1764.13s. $\eta_{^{12}C}$ is the surface density of ^{12}C atoms in the liquid scintillator target cell. For our set-up $\eta_{^{12}C}$ is equal to $3.26 \cdot 10^{24} cm^{-2}$.

The efficiency of the detector array for a certain decay mode and isotope is called ϵ. We have measured the response function of each scintillator cell with a γ-ray calibration source. Based on this information the efficiency ϵ for each isotope has been calculated by a Monta-Carlo code based on the measured activation profile for ^{11}C. For the isotope ^{11}C, the simulated detector efficiency could be compared with the result obtained from the β-γ-coincidence measurement and we found both values for ϵ to be in very good agreement.

$N_\mu^{eff}(t_0)$ is the effective muon number at t_0. The muon number $N_\mu(t)$ at a certain time t is weighted with the exponential decay term for the ^{11}C isotope with lifetime τ:

$$N_\mu^{eff}(t_0) = \int_0^{t_0} N_\mu(t') \cdot e^{-\frac{(t_0-t')}{\tau}} dt' \tag{4}$$

Since ^{11}C is a β^+-emitter, two data sets could be analyzed. (1) The 3-fold coincidence counting (TFC-) mode with a target cell energy threshold of E_{thr} =110keV and a detector efficiency $\epsilon_{TFC} = (6.08 \pm 0.3)\%$. (2) The single counting (SGL-) mode with the same energy threshold of 110keV but with a much higher detector efficiency of $\epsilon_{SGL} = (83.0 \pm 0.4)\%$.

Detection mode- and Technique	$\sigma(^{11}\mathrm{C})$ in μbarn for E_μ =100GeV	E_μ =190GeV
(A) $\beta - \gamma$ coincidence measurement (scintillator bottles)	582 ± 58	925 ± 93
(B) in-situ scintillation spectroscopy (scintillator cells):	566 ± 73	892 ± 74
mean value from (A) and (B)	576 ± 45	905 ± 58

Table 2: *Comparison of the cross sections σ for muon induced ^{11}C obtained with two different detection techniques: (A) $\beta - \gamma$ coincidence counting and (B) in-situ scintillation spectroscopy. The weighted mean value for $\sigma(^{11}C)$, assuming non correlated uncertainties is shown in the last line.*

Table 2 summarizes the results of the calculated cross sections $\sigma(^{11}\mathrm{C})$ from in-situ scintillation spectroscopy and from the β-γ-coincidence measurement described in section 4, for the two muon energies 100GeV and 190GeV.

As one can deduce from Table 2, the result obtained from the irradiated scintillator bottles (A) is in very good agreement with the cross section evaluated from the analysis of the TFC mode data (B). In the 3-fold coincidence counting mode a much better

background- and noise reduction compared to the SGL-mode was achieved. In addition the counting rates in the SGL-mode showed noise fluctuations leading to a bad fit with χ^2 ≈2.4. However, the fit to the TFC-mode data showed an excellent χ^2 value (χ^2 ≈1.0). Therefore only the TFC-mode result was considered for the calculation of the combined mean value of the muon-induced cross section for ^{11}C in a liquid scintillator target, which is:

$$E_\mu = 100\text{GeV}: \quad \sigma(^{11}\text{C}) = \quad (576 \pm 45)\,\mu barn$$
$$E_\mu = 190\text{GeV}: \quad \sigma(^{11}\text{C}) = \quad (905 \pm 58)\,\mu barn$$

5.3 Analysis of the short-lived isotopes with $T_{1/2}$ <20sec

The short-lived isotopes can be divided into three subgroups according to their different half lifes:

- isotopes with $T_{1/2} > 1$s as ^{10}C, ^{11}Be
- isotopes with $0.5\text{s} < T_{1/2} < 1$s as ^{8}B, ^{8}Li, ^{6}He
- isotopes with 100ms $< T_{1/2} <$ 200ms as ^{9}C, ^{9}Li, ^{8}He

5.3.1 The Isotopes ^{10}C, ^{11}Be

The cross section of ^{10}C was determined by an exponential fit to the SGL-mode data in time intervals, in which the muon spill was interrupted for at least 200s (see Fig. 4).

To suppress the contribution of the dominant ^{11}C in the counting rate, a threshold of E_{thr} = 1MeV has been chosen for the ^{10}C analysis. With a detector efficiency of $\epsilon = (61.79 \pm 2.57)\%$ we evaluated the following cross sections:

$$E_\mu = 100\text{GeV}: \quad \sigma(^{10}\text{C}) = \quad (77.43 \pm 4.9)\,\mu barn$$
$$E_\mu = 190\text{GeV}: \quad \sigma(^{10}\text{C}) = \quad (115.4 \pm 14.6)\,\mu barn$$

In the error propagation the statistical uncertainties of the experimental data as well as the error in the muon intensity have been taken into account. The lateral production of the short-lived isotopes was assumed to be equal to the measured ^{11}C distribution. The values quoted here are valid under this assumption.

The contribution of the isotope ^{11}Be in this data set could be neglected since the cross section for the production of ^{11}Be via (n,2p)-reaction is much smaller than the cross section for the production of ^{10}C (as will be shown in the following section) while the detector efficiencies for both isotopes are almost equal. Therefore $\sigma(^{11}\text{Be})$ had to be determined by a different method, described in chapter 5.3.2.

5.3.2 The Isotopes ^{8}B, ^{8}Li, ^{6}He

For the analysis of the isotopes with 0.5s $<T_{1/2}<$1s, the counting rates $\tilde{a}_n(t_i)$ of the i-th time bin t_i (with $t_i = 0; 0.1; 0.2; \ldots; 10$s), recorded after muon spill n, have been integrated over the total number of muon spills N:

$$\tilde{A}(t_i) = \sum_{spill\, n=1}^{N} \tilde{a}_n(t_i) \tag{5}$$

The activity $A_{isotope}(t_0)$ of the isotope in demand, at a certain counting time t_0, can be derived from an exponential fit to the data $\tilde{A}(t_i)$. The cross section σ for the muon induced production of the isotope is given in equation 3. The only difference is, that for the analysis of the short-lived isotopes, the effective muon number $N_\mu^{eff}(t_0)$ at t_0 is defined as:

$$N_\mu^{eff}(t_0) = \sum_{t_j=0}^{2.4s} \frac{N_\mu \Delta t}{2.4s} \cdot e^{-\frac{(t_0 - t_j)}{\tau}};\ t_j = 0, 0.1, ..., 2.4s \tag{6}$$

with the spill duration time of 2.4s and the total, integrated muon number N_μ.

The different muon induced short-lived isotopes in the data set can be distinguished due to their different decay modes (β^+ or β^-), half lifes and $\beta-$endpoint energies. Therefore the radio instable isotopes have been divided into several analysis groups from which the cross sections of the muon produced nuclides can be determined one after the other following the order given in Table 3 and 4. Table 3 lists the three analysis groups for the data set with $\Delta t = 1/10$s counter read-out timing in order to evaluate $\sigma(^8\text{B})$, $\sigma(^{11}\text{Be})$, $\sigma(^8\text{Li})$ and $\sigma(^6\text{He})$.

To determine the cross sections for the β^+-emitters ^{10}C and ^{8}B, the TFC-mode with energy thresholds of 110keV and 1MeV has been chosen. Since ^{9}C, with a very short half life of 130ms, has already decayed at the counting time t_0 and ^{11}C and ^{7}Be contribute only to a constant background in the time window of 10sec, ^{10}C and ^{8}B can be distinguished very well due to their different half lifes. The cross section, calculated for the two data sets with E>110keV and E>1MeV and for the different runs agree very well within the error bars. For $\sigma(^8\text{B})$ one obtains the following mean values including $\epsilon = (6.23 \pm 0.30)\%$ (E>110keV) and $\epsilon = (5.93 \pm 0.28)\%$ (E>1MeV), respectively:

$$\begin{aligned} E_\mu = 100\text{GeV}: \quad \sigma(^8\text{B}) = \quad & (4.16 \pm 0.81)\mu barn \\ E_\mu = 190\text{GeV}: \quad \sigma(^8\text{B}) = \quad & (7.13 \pm 1.46)\mu barn \end{aligned}$$

The cross sections of the β^--emitters ^{11}Be and ^{8}Li can be calculated from a fit to the SGL-mode data in the energy interval 4MeV<E<12MeV (see Fig. 5). Since ^{6}He

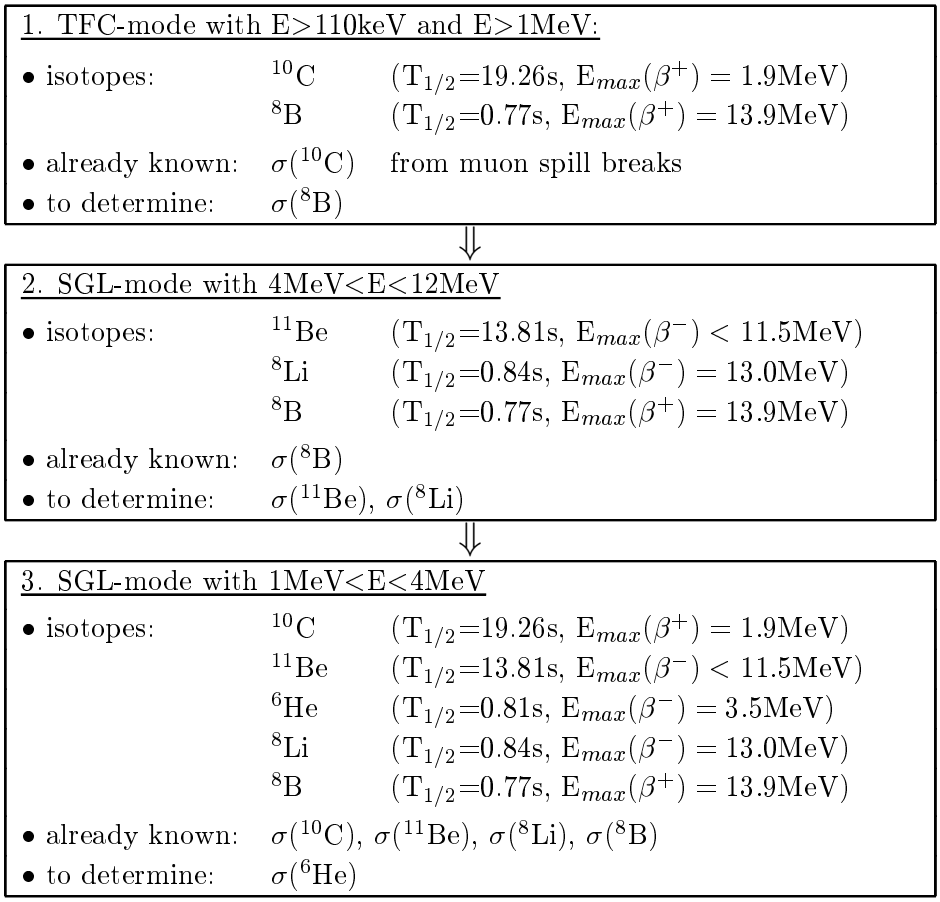

Table 3: *The data set with $\Delta t = 1/10s$ counter read out timing was divided into three analysis groups from which the cross sections for the muon produced nuclides could be determined one after the other. In the first step, $\sigma(^8B)$ could be evaluated by a fit to the TFC-mode data. Afterwards, $\sigma(^{11}Be)$ and $\sigma(^8Li)$ could be determined from the SGL-mode data by including the known $\sigma(^8B)$ in the fit. With the cross sections evaluated in the previous steps, the remaining cross section $\sigma(^6He)$ could be extracted by a fit to the SGL-mode data in the energy interval 1MeV< E <4MeV.*

and ^{10}C do not appear in this energy interval and $\sigma(^8\mathrm{B})$ is already known from the analysis described above, $\sigma(^{11}\mathrm{Be})$ and $\sigma(^8\mathrm{Li})$ can be determined unambiguously. With $\epsilon = (57.34 \pm 0.49)\%$ the mean values of $\sigma(^8\mathrm{Li})$ are:

$$\begin{aligned} E_\mu = 100\mathrm{GeV}: \quad \sigma(^8\mathrm{Li}) = \quad (2.93 \pm 0.80)\mu barn \\ E_\mu = 190\mathrm{GeV}: \quad \sigma(^8\mathrm{Li}) = \quad (4.02 \pm 1.46)\mu barn \end{aligned}$$

In comparison to $\sigma(^8\mathrm{Li})$, only an upper limit could be obtained for $\sigma(^{11}\mathrm{Be})$ with this method. The actual value for $\sigma(^{11}\mathrm{Be})$ is smaller than the calculated one since the summation of the counting rates in Eq. 5 does not consider the fact that ^{11}Be atoms that have been produced in muon spill n, still contribute to the counting rate after muon spill $n+1$ due to a half life that is greater than the spill repetition time of 14.4s. The calculated upper limit for the cross section of ^{11}Be with a detector efficiency of $\epsilon = (56.28 \pm 0.51)\%$ is:

$$\begin{aligned} E_\mu = 100\mathrm{GeV}: \quad \sigma(^{11}\mathrm{Be}) < \quad 1.22\mu barn\ (68\%CL) \\ E_\mu = 190\mathrm{GeV}: \quad \sigma(^{11}\mathrm{Be}) < \quad 2.34\mu barn\ (68\%CL) \end{aligned}$$

The last remaining cross section for the short-lived isotopes with 0.5s$< T_{1/2} <$20s is $\sigma(^6\mathrm{He})$. This cross section can be determined by applying a fit to the SGL-mode data in the energy interval 1MeV<E<4MeV with a detector efficiency of $\epsilon = (59.56 \pm 0.45)\%$. Including the already calculated cross sections from the isotopes ^{10}C, ^{11}Be, ^{8}Li and ^{8}B one obtains:

$$\begin{aligned} E_\mu = 100\mathrm{GeV}: \quad \sigma(^6\mathrm{He}) = \quad (10.15 \pm 1.0)\mu barn \\ E_\mu = 190\mathrm{GeV}: \quad \sigma(^6\mathrm{He}) = \quad (16.02 \pm 1.6)\mu barn \end{aligned}$$

5.3.3 The Isotopes ^{9}C, ^{9}Li, ^{8}He

For the very short-lived isotopes with half lifes inbetween 100ms and 200ms, the time interval for the counter read-out was set to $\Delta t = 1/100$s. Since this change in the data aquisition has only been performed during the beam time with a muon energy of E_μ=190GeV, the cross sections for ^{9}C, ^{9}Li and ^{8}He could only be evaluated for this muon energy.

As displayed in Table 4, $\sigma(^9\mathrm{C})$ could be determined from the TFC-mode data with an energy threshold of E_{thr}=1MeV (in order to reduce the background contributions from ^{11}C) and a detector efficiency $\epsilon = (6.0 \pm 0.6)\%$.

For ^{9}Li and ^{8}He only a combined cross section $\sigma(^9\mathrm{Li} + ^8\mathrm{He})$ could be evaluated from the SGL-mode data in the energy interval 4MeV<E<12MeV with a combined efficiency of

1. TFC-mode with E>1MeV:		
• isotopes:	^{10}C	($T_{1/2}$=19.26s, $E_{max}(\beta^+)$ = 1.9MeV)
	^{8}B	($T_{1/2}$=0.77s, $E_{max}(\beta^+)$ = 13.9MeV)
	^{9}C	($T_{1/2}$=0.13s, $E_{max}(\beta^+)$ < 16.0MeV)
• already known:	$\sigma(^{10}\mathrm{C})$, $\sigma(^{8}\mathrm{B})$	
• to determine:	$\sigma(^{9}\mathrm{C})$	

⇓

2. SGL-mode with 4MeV<E<12MeV		
• isotopes:	^{8}Li	($T_{1/2}$=0.84s, $E_{max}(\beta^-)$ = 13.0 MeV)
	^{8}B	($T_{1/2}$=0.77s, $E_{max}(\beta^+)$ = 13.9 MeV)
	^{9}Li	($T_{1/2}$=0.18s, $E_{max}(\beta^-)$ < 13.6 MeV)
	^{8}He	($T_{1/2}$=0.12s, $E_{max}(\beta^-)$ = 10.6 MeV)
• already known:	$\sigma(^{8}\mathrm{Li})$, $\sigma(^{8}\mathrm{B})$	
• to determine:	$\sigma(^{9}\mathrm{Li} + ^{8}\mathrm{He})$	

Table 4: *For the determination of the cross sections for the very short-lived isotopes (100ms $< T_{1/2} <$ 200ms) the data set with Δt = 1/100s counter read-out timing was divided into two analysis groups. $\sigma(^9C)$ could be evaluated by a fit to the TFC-mode data including the already known cross sections for ^{10}C and ^{8}B. For ^{9}Li and ^{8}He only a combined cross section $\sigma(^{9}\mathrm{Li}+^{8}\mathrm{He})$ could be evaluated from the SGL-mode data with 4MeV<E<12MeV.*

$\epsilon = (54.04 \pm 0.50)\%$ (see Fig. 6). The half lifes of $T_{1/2}$ =180ms (^{9}Li) and $T_{1/2}$ =120ms (^{8}He) are too close together to be distinguished in a fit to the data. The values that we obtained averaging over all runs are:

$$E_\mu = 190\text{GeV}: \quad \begin{aligned} \sigma(^9\text{C}) &= (4.83 \pm 1.51)\mu barn \\ \sigma(^9\text{Li} +^8\text{He}) &= (2.12 \pm 0.35)\mu barn \end{aligned}$$

A summary of the cross sections σ for the radioactive isotopes that can be produced by muons and their secondaries in a liquid scintillator (^{12}C) target are given in Table 5. The cross section of the isotope ^{12}B with a half life of only 20ms could not be determined. The time intervals of 1/100s for the counter read-out were not sufficient to resolve the decay of this isotope.

	σ in $\mu barn$ for E_μ		energy dependence
Isotopes	100 GeV	190 GeV	exponent α
^{11}C	576 ± 45	905 ± 58	0.70 ± 0.16
^{7}Be	127 ± 13	230 ± 23	0.93 ± 0.23
^{11}Be	$< 1.22(68\%CL)$	$< 2.34(68\%CL)$	
^{10}C	77.4 ± 4.9	115.4 ± 14.6	0.62 ± 0.22
^{8}Li	2.93 ± 0.80	4.02 ± 1.46	0.50 ± 0.71
^{6}He	10.15 ± 1.0	16.02 ± 1.60	0.71 ± 0.22
^{8}B	4.16 ± 0.81	7.13 ± 1.46	0.84 ± 0.45
^{9}C		4.83 ± 1.51	
^{9}Li+ ^{8}He		2.12 ± 0.35	

Table 5: *Cross sections σ and energy dependences α for all muon induced radioactive isotopes which can be produced in a scintillator (^{12}C) target. The cross sections (given in μbarn) have been measured at two different muon beam energies, E_μ=100GeV and E_μ=190GeV, respectively. The weighted mean value of the exponent α is $\langle\alpha\rangle = 0.73 \pm 0.10$.*

6 Energy Dependence of the Total Cross Section

The radioactive isotopes mentioned above are produced in nuclear- and electromagnetic showers, triggered by muons penetrating the concrete and water absorber. Two muon energies 100GeV and 190GeV were available during our beam time at CERN. Based on the calculated cross sections obtained for each of the two muon energies, the energy dependence of the total cross section for all muon produced radio isotopes in the scintillator

target was evaluated assuming the power law

$$\sigma_{tot}(E_\mu) \propto E_\mu^\alpha \qquad [10]. \tag{7}$$

From the ratio of the measured cross sections for 100GeV and 190GeV the exponent α was calculated via

$$\alpha = \frac{ln\,(\,\frac{\sigma(190GeV)}{\sigma(100GeV)}\,)}{ln\,(\,\frac{190GeV}{100GeV}\,)} \quad . \tag{8}$$

Tab. 5 lists the values of the exponent α for each muon induced isotope in the scintillator. As one can deduce from Tab. 5, α varies from 0.50 to 0.93 with an weighted mean value $\langle\alpha\rangle = 0.73 \pm 0.10$.

This value agrees very well within the error bars with other experimental results , obtained from the irradiation of ^{71}Ga (α = 0.7 - 0.8 [5]) at energies of 100GeV, 200GeV and 280GeV and measurements performed with Pb-targets (α = 0.62-0.91 [13]) and Fe-, Ni-, Cu-targets [8]. The calculated value from reference [10] $\alpha = 0.75$ agrees also very well with our experimental result.

7 The Muon Induced Background in BOREXINO and KamLAND

The measurements at CERN were carried out with the objective to measure the cross sections for the production of cosmic ray induced isotopes and finally to calculate the muon induced background rates for low-level counting experiments using liquid scintillator targets, such as BOREXINO and KamLAND.

The muon induced background $R_{isotope}$ of a certain isotope depends on the differential muon energy spectrum $\frac{dN_\mu}{dE_\mu}$ at the experimental site at depth h, the number of target atoms $N_{^{12}C}$ and the cross section σ_0 that referrs to a muon energy of 1GeV.

$$R_{isotope} = N_{^{12}C} \cdot \sigma_0 \cdot \int_0^\infty \left(\frac{E_\mu}{1GeV}\right)^\alpha \frac{dN_\mu}{dE_\mu}\, dE_\mu \tag{9}$$

The production rate can also be written in dependence on the mean muon energy $\langle E_\mu\rangle$ at depth h:

$$R_{isotope} = \beta_\alpha \cdot N_{^{12}C} \cdot \sigma(190GeV) \cdot \left(\frac{\langle E_\mu\rangle}{190GeV}\right)^\alpha \cdot \Phi_\mu \tag{10}$$

where Φ_μ is the total muon flux at the experimental site and β_α is the correction factor for the averaging of E_μ

$$\beta_\alpha = \frac{\langle E_\mu^\alpha\rangle}{\langle E_\mu\rangle^\alpha} \tag{11}$$

For the following calculations we used our measured mean value of $\alpha = 0.73 \pm 0.10$ with a corresponding correction factor of $\beta_{0.73} = 0.87 \pm 0.03$.

For the determination of the different nuclide production rates in the solar neutrino experiment BOREXINO, we used the average muon energy measured by the MACRO-Collaboration [11] at the Gran Sasso Underground Laboratory where BOREXINO is located, too. The mean muon energy was found to be $\langle E_\mu \rangle = 320 \pm 4(stat.) \pm 11(syst.)$ GeV [11].

The total muon flux at the detector $\Phi_\mu = (1.16 \pm 0.09)\mu/(h \cdot m^2)$ is taken from reference [5]. With the number of $N_{^{12}C} = 4.51 \cdot 10^{30}$ in 100t fiducial volume, we calculate the counting rates of the muon induced isotopes in BOREXINO, that are summarized in Tab. 6. In addition to the total counting rates, Tab. 6 lists the muon background rates in the different energy regions that are relevant for the detection of ^{7}Be-neutrinos (250keV<E<800keV), pep-neutrinos (0.8MeV<E<1.4MeV) and ^{8}B-neutrinos (2.8MeV<E<5.5MeV).

	Muon-induced background rates in BOREXINO given in counts/(d·100t) for the different energy regions :			
Isotopes	full energy range	250keV<E<800keV ^{7}Be-ν region	0.8MeV<E<1.4MeV *pep*-ν region	2.8MeV<E<5.5MeV ^{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

Table 6: *Muon-induced background rates in* BOREXINO, *calculated for different energy regions that are relevant for solar neutrino physics. The rates are given in counts/d normalized to 100 tons of target mass.*

Also of great interest is the estimation of the muon induced background in the other forthcoming low-level counting neutrino experiment, KAMLAND [15, 22], located 2700mwe underground in the Kamioka mine in Japan. The detector set-up, aimed to detect reactor anti neutrinos and solar neutrinos in 1200m^3 of liquid scintillator, is similar to the

Borexino experiment.

The scintillator target of KamLand consists out of 80% Isoparaffin and 20% Pseudocumene (PC) enriched with PPO, with a normalized number of $N_{^{12}C} = 4.31 \cdot 10^{30}$ in 100t target mass. The mean total muon energy at a depth of 2700mwe was calculated to be $\langle E_\mu \rangle \sim 285$GeV using a zenith angle distribution of the muon flux well approximated by $cos^2\theta$ [9]. The overall muon flux at Kamioka should be ∼8 times higher than the muon flux at Gran Sasso [9].

According to these numbers one estimates the production rates for muon induced isotopes $R_{isotope}$ in KamLand in comparison to Borexino. Normalized to 100 tons of target mass one obtains

$$\frac{R_{isotope}^{Borexino}}{R_{isotope}^{Kamland}} = \frac{N_{^{12}C}^{Borexino}}{N_{^{12}C}^{Kamland}} \cdot \left(\frac{\langle E_\mu^{Borexino} \rangle}{\langle E_\mu^{Kamland} \rangle} \right)^{0.73} \cdot \frac{\Phi_\mu^{Borexino}}{\Phi_\mu^{Kamland}} = 0.14 \qquad (12)$$

what results in a ∼7 times higher muon induced background rate for KamLand compared to Borexino.

8 Discussion of the Results

As one can deduce from Tab. 6, the largest background contribution in the energy region 250keV<E<800keV results from the isotope ^{7}Be. The background in Borexino and KamLand for low energy solar neutrino detection due to this cosmogenic produced nuclide is present via the 478keV gamma emission. In Borexino the solar $\nu(^7\text{Be})$ flux is measured taking the integral over the event rate from 250keV up to 800keV to cover the compton-like edge from the electron recoil at 660keV. The expected energy resolution at 660keV is ≈ 6%. Although the 478keV gammas don't coincide with the compton edge the cosmogenic produced ^{7}Be nuclei contribute to the integral counting rate in this so-called $\nu(^7\text{Be})$-window (250keV<E<800keV).

Compared with an expected ^{7}Be-ν rate of ≈ 50 counts/(d·100t) (according to the SSM) a total cosmic ray induced background rate of ≈ 0.4 counts/(d·100t) in Borexino is tolerable. Even for total neutrino flavour conversion the signal rate of ≈ 10 counts/(d·100t) exeeds this background contribution significantly. For KamLand the expected background is ≈ 3 counts/(d·100t).

The production rate of ^{7}Be at sea level during the storage and transportation of the scintillator is another serious issue. For Borexino it is foreseen to purify the scintillator underground.

For the detection of the solar pep-neutrinos the situation is more critical. Since ^{11}C

is a β^+−emitter, the deposited energy in the liquid scintillator volume is shifted towards energies above 1.022MeV due to the annihilation of the positron. Thus, 50.61% of all ^{11}C decays coincide with the energy region 0.8MeV<E<1.4MeV, accounting for a background rate of ≈ 8 counts/(d·100t) in Borexino. This large background contribution jeopardizes the detection of the solar pep-neutrinos, with an event rate of 1.5 counts/(d·100t) in this energy interval in Borexino according to the SSM. In MSW scenarios the signal to background rate due to ^{11}C production is expected to be well below 0.1.

The third listed energy region 2.8MeV<E<5.5MeV is of interest too, since Borexino, KamLand and Lens are the only solar neutrino experiments capable to detect the ^{8}B-neutrino spectrum with an energy threshold less than 5.5MeV, which is the region that is most sensitive to a spectral distortion according to the MSW effect [17]. Above energies of ≈3MeV no background contributions are to expect from primordial radio nuclides originating from the decay chains of ^{238}U, ^{232}Th, ^{40}K etc., besides the beta and gamma decay of ^{208}Tl ($T_{1/2}$ = 3.03min, and E_{max} = 5MeV)[2]. However, the ^{208}Tl signals may be tagged via delayed coincidence measurement taking into account the spatial correlation between the preceeding monoenergetic alpha decay of ^{212}Bi and the ^{208}Tl event itself. Therefore, cosmogenic background with a rate of 0.6 counts/(d·100t) in Borexino, especially from the long lived ^{10}C, plays a dominant role in this energy regime of the solar ^{8}B neutrino branch.

Although the background rate is of the same order as the neutrino event rate in this energy interval (R_ν=0.53 ν/(d·100t)), it seems to be possible to determine the ^{8}B-ν-rate by using the method of statistical subtraction. The signal to background ratio can be improved drastically if one restricts the energy interval to 3.8MeV<E<5.5MeV in which the contribution of ^{10}C, that has a maximal energy release of 3.7MeV, is negligible.

Lens [19, 20] is aiming for charged current low-energy solar neutrino spectroscopy using ^{160}Gd, ^{176}Yb or ^{82}Se as target nuclei. In the configuration as a doped liquid scintillator the mass concentration of these nuclei will be in the regime of about 10%. Therefore the target nuclei may give a non negligible, additional contribution to the cosmogenic background production discussed in this paper. We intent to perform comprehensive measurements by irradiating Gd, Yb and Se in the near future.

[2] Alpha decays with energies well above 3MeV are quenched in an organic liquid scintillator by a factor of roughly 10.

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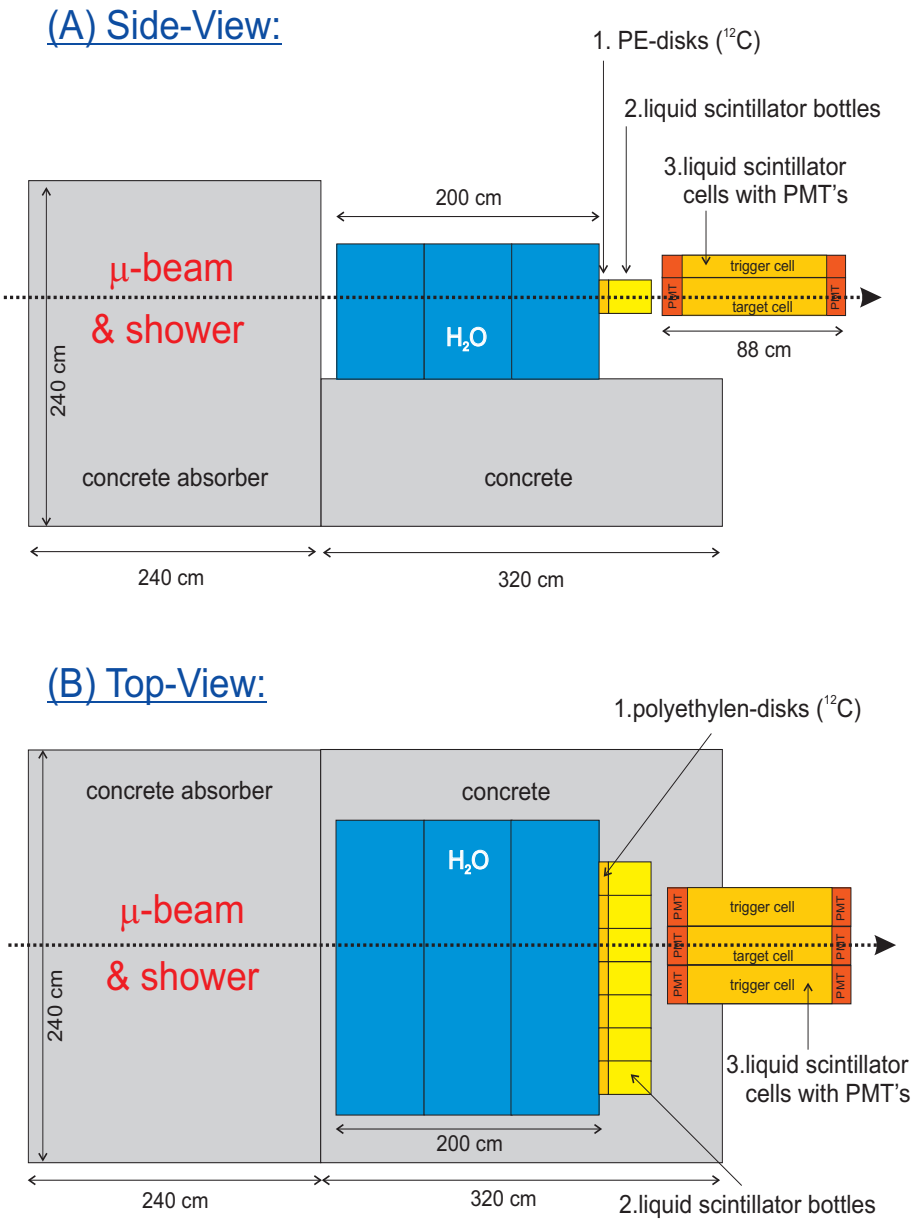

Figure 1: *Schematical drawing of the side-view (A) and top-view (B) of the experimental set-up at the SPS-muon beam at* CERN. *The muon shower builds up in the concrete and water absorber placed in front of the three different* ^{12}C *targets: (1) Polyethylene disks and (2) bottles filled with the liquid scintillator Pseudocumene. Both targets are positioned perpendicular to the muon beam in order to measure the lateral activation profile. (3) scintillator cells for the in-situ-scintillation spectroscopy measurement of the short- lived isotopes.*

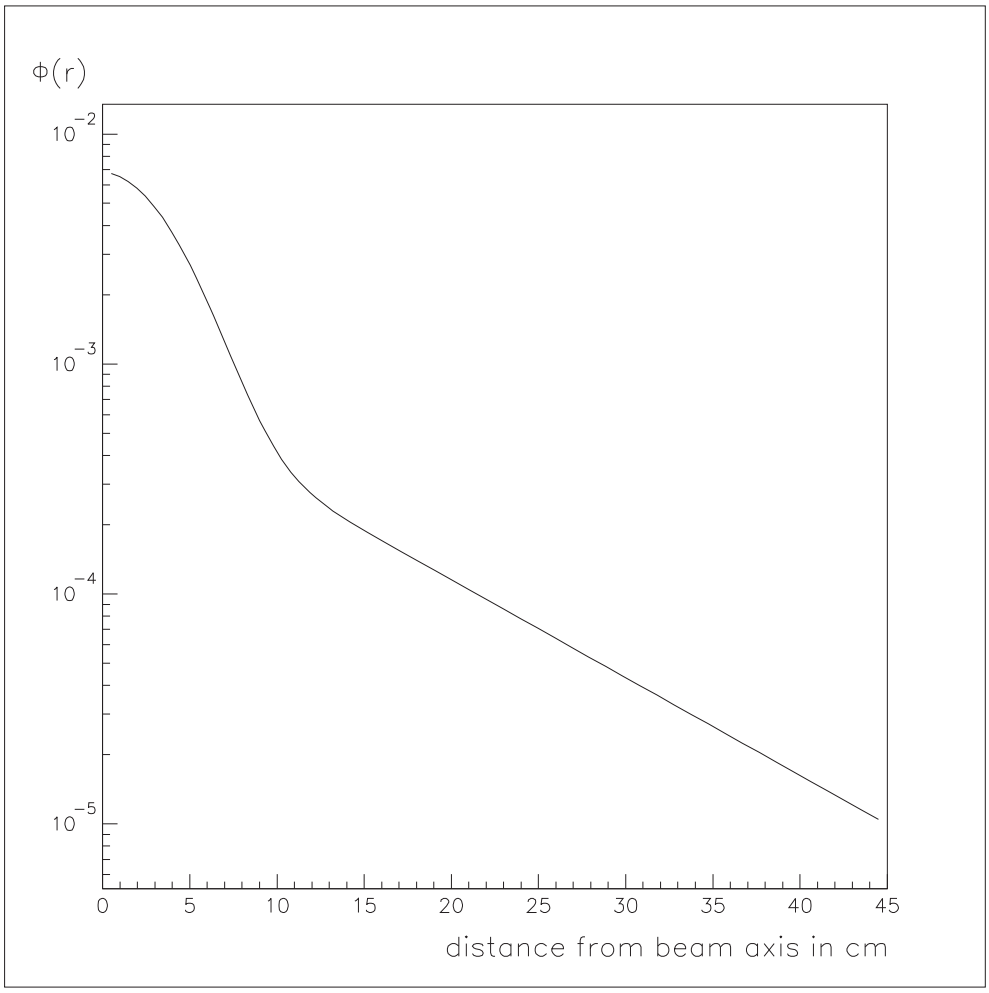

Figure 2: *Lateral activation profile $\Phi(r)$, which describes the probability that an isotope is produced at a given distance r perpendicular to the muon track.*

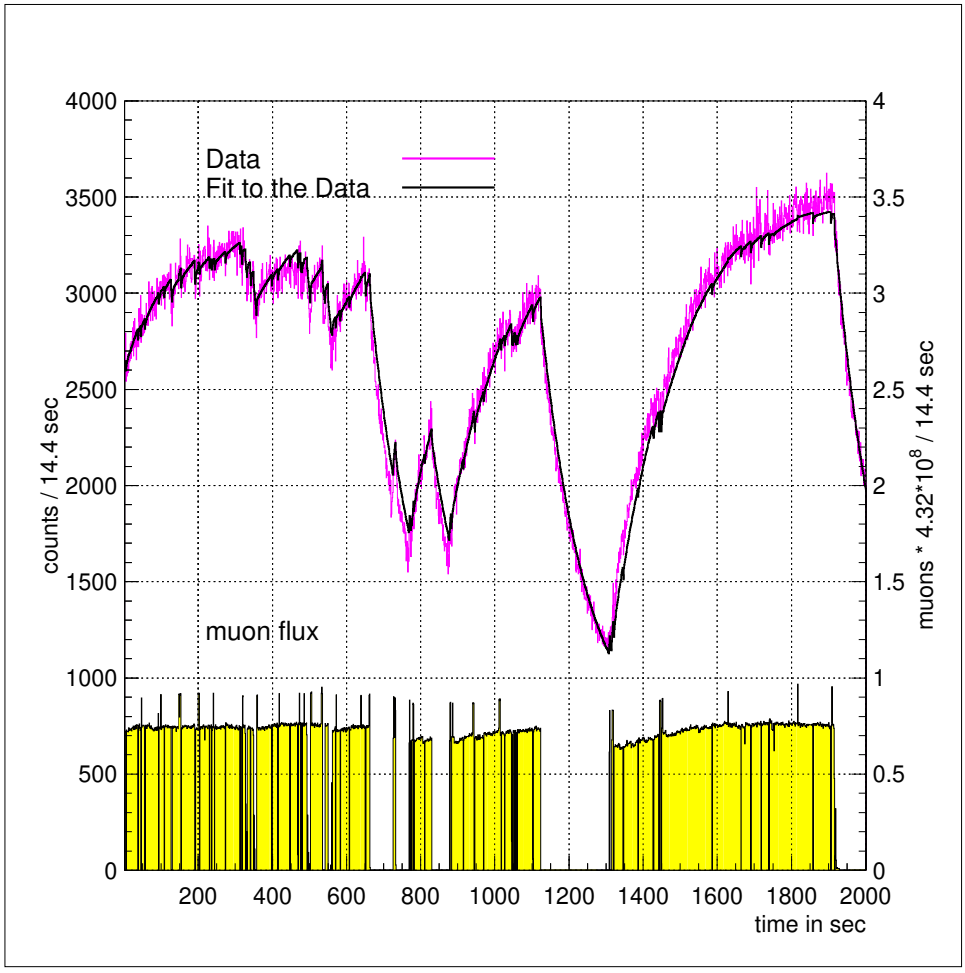

Figure 3: *Time variation of the ^{11}C counting rate in the scintillator target cell with respect to the muon flux. The black line depicts a fit to the data in the 3-fold coincidence mode.*

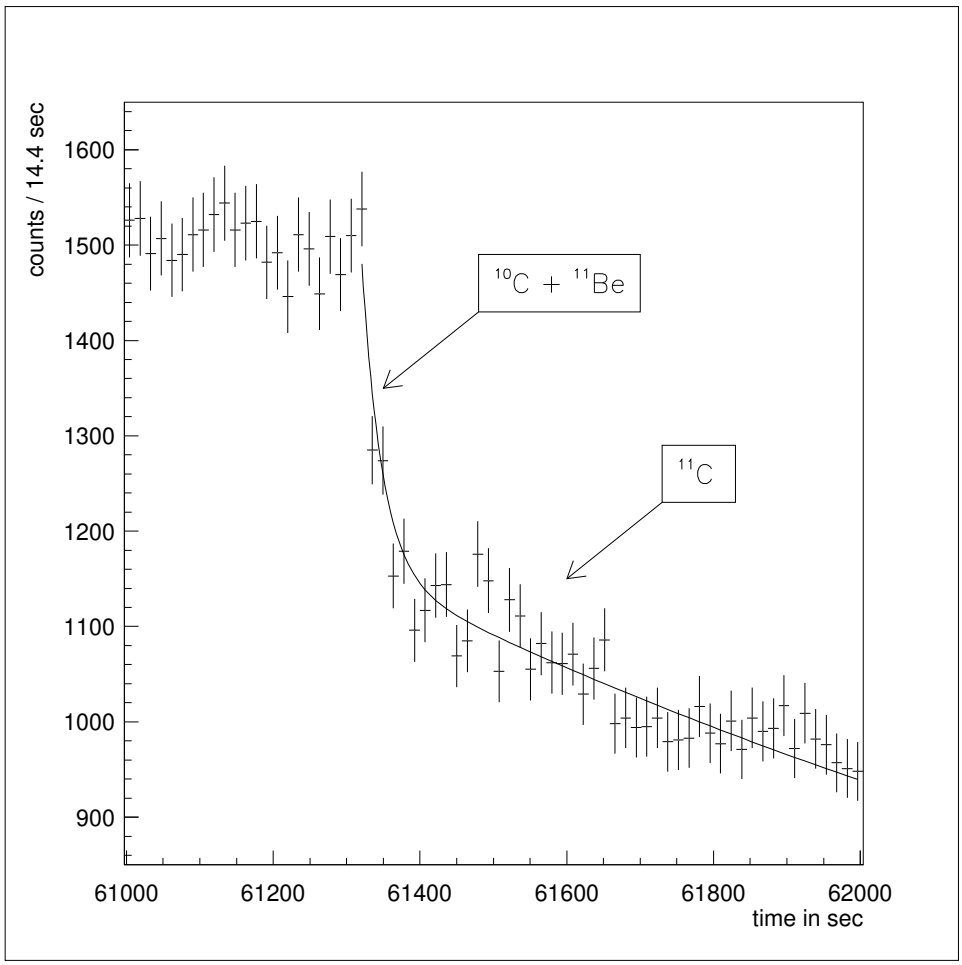

Figure 4: *Determination of the muon induced cross section of* ^{10}C *in a time interval in which the muon spill was interrupted for more than 200sec. The exponential fit to the Single mode data with an energy threshold E>1MeV is displayed.*

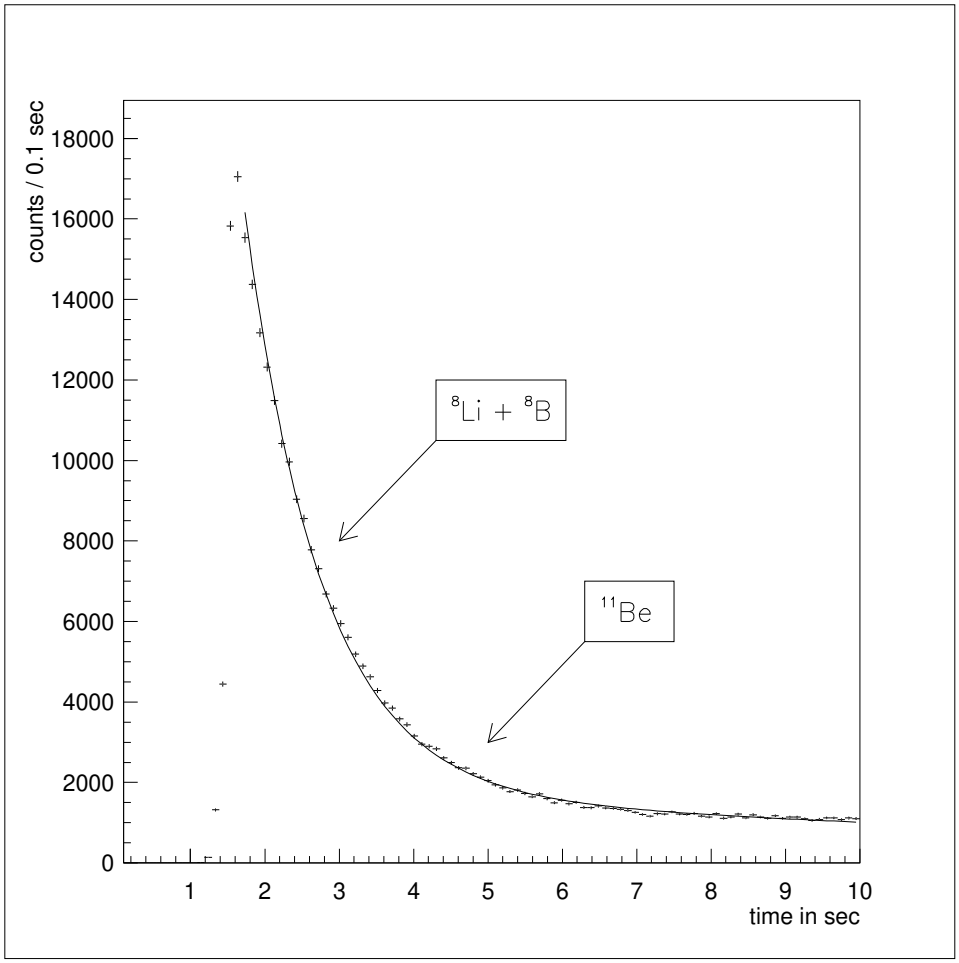

Figure 5: *Determination of the muon induced cross section of ^{11}Be and ^{8}Li from a fit to the SGL-mode data in the energy interval 4MeV<E<12MeV. In order to avoid any damage to the target cell in the muon beam, the high voltage (HV) was switched on some milliseconds prior to the end of the muon spill. Here in this data set, the HV was not fully applied when the first 3 data points were recorded.*

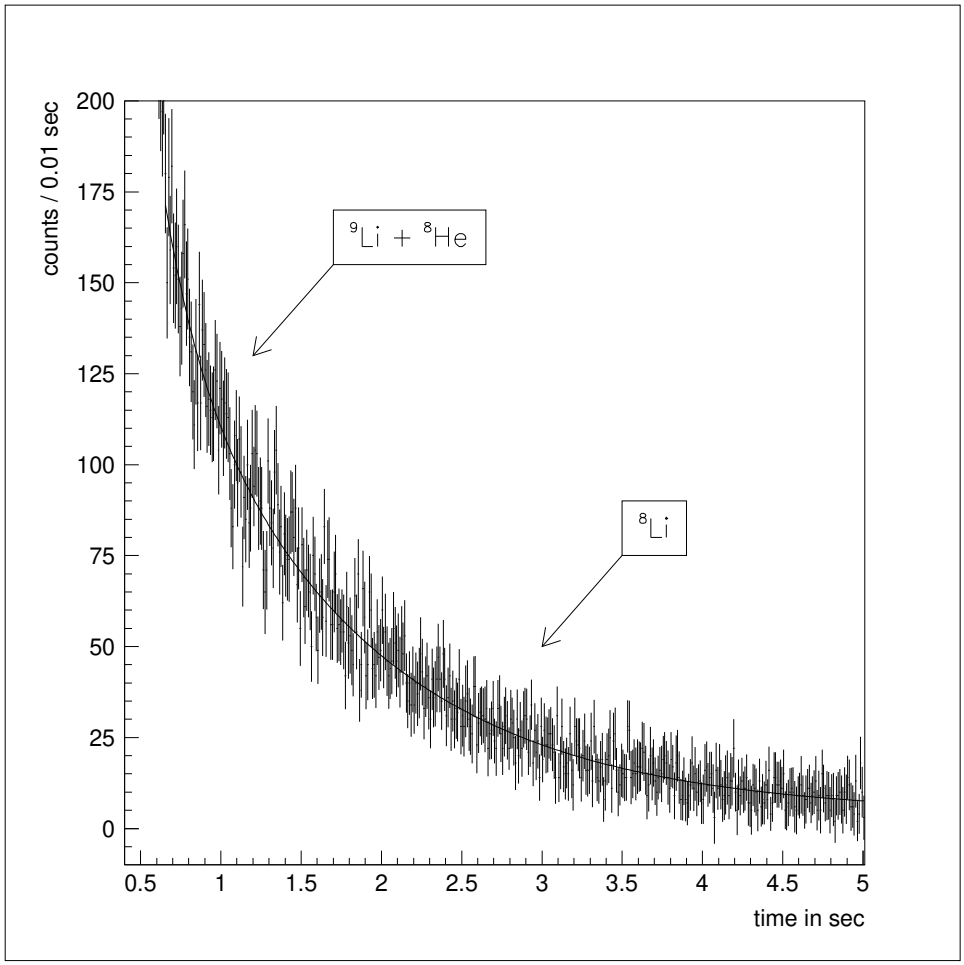

Figure 6: *Determination of the combined muon induced cross section of* ^{9}*Li and* ^{8}*He from a fit to the SGL-mode data in the energy interval 4MeV<E<12MeV.*