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D. Franco, C. Giganti, P. Agnes, L. Agostino, B. Bottino, et al.. Solar neutrino detection in a large volume double-phase liquid argon experiment. *Journal of Cosmology and Astroparticle Physics*, 2016, 08, pp.017. <10.1088/1475-7516/2016/08/017>. <hal-01554275>

HAL Id: hal-01554275

<https://hal.science/hal-01554275v1>

Submitted on 12 Jul 2022

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To cite this article: D. Franco *et al* JCAP08(2016)017

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Solar neutrino detection in a large volume double-phase liquid argon experiment

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Received April 26, 2016

Revised July 5, 2016

Accepted August 1, 2016

Published August 9, 2016

Abstract. Precision measurements of solar neutrinos emitted by specific nuclear reaction chains in the Sun are of great interest for developing an improved understanding of star formation and evolution. Given the expected neutrino fluxes and known detection reactions, such measurements require detectors capable of collecting neutrino-electron scattering data in exposures on the order of 1 ktonne-yr, with good energy resolution and extremely low background. Two-phase liquid argon time projection chambers (LAr TPCs) are under development for direct Dark Matter WIMP searches, which possess very large sensitive mass, high scintillation light yield, good energy resolution, and good spatial resolution in all three cartesian directions. While enabling Dark Matter searches with sensitivity extending to the “neutrino floor” (given by the rate of nuclear recoil events from solar neutrino coherent scattering), such detectors could also enable precision measurements of solar neutrino fluxes using the neutrino-electron elastic scattering events.

Modeling results are presented for the cosmogenic and radiogenic backgrounds affecting solar neutrino detection in a 300 tonne (100 tonne fiducial) LAr TPC operating at LNGS depth (3,800 meters of water equivalent). The results show that such a detector could measure the CNO neutrino rate with $\sim 15\%$ precision, and significantly improve the precision of the ${}^7\text{Be}$ and *pep* neutrino rates compared to the currently available results from the Borexino organic liquid scintillator detector.

Keywords: neutrino astronomy, neutrino detectors, neutrino experiments, solar and atmospheric neutrinos

ArXiv ePrint: [1510.04196](https://arxiv.org/abs/1510.04196)

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1 Introduction

Fifty years of experimental study has yielded detailed information on neutrinos from the Sun, with profound implications for our understanding of nature. The Davis chlorine experiment [1] was the first to detect solar neutrinos, giving the historic proof that the Sun’s energy is indeed produced by nuclear fusion reactions in its interior. Further study of the “solar neutrino problem” (the overall deficit of solar neutrinos detected on Earth by Davis and subsequent experiments [GALLEX/GNO [2, 3], SAGE [4], Kamiokande [5], and SuperKamiokande [6]]) led to the paradigm-changing 2001 discovery of “neutrino flavor oscillations,” which imply nonzero neutrino masses. This occurred as the Sudbury Neutrino Observatory (SNO) experiment [7] showed that the solar neutrino problem was explained by electron-type neutrinos from the Sun changing in transit into the other two active neutrino flavors (muon- and tau-type), which cannot undergo the low energy charged-current detection reactions used by all preceding experiments. Soon after, the LMA-MSW [14, 15] oscillation paradigm for the neutrino oscillation phenomenon was confirmed by the KamLAND experiment using reactor electron-antineutrinos [8]. In 2007, the Borexino experiment [9–13] began a new phase of solar neutrino measurements intended to make precision tests of the Standard Solar Model (SSM) [16] and important astrophysics [17] and geophysics [18] measurements.

To date, spectral features corresponding to almost all solar neutrino production reactions have been observed, with the notable exception of neutrinos produced in the ^{13}N , ^{15}O , and ^{17}F reactions of the CNO cycle. The CNO cycle plays a key role in astrophysics, since it is the dominant source of energy in stars more massive than the Sun and in advanced evolutionary stages of Sun-like stars. Solar CNO neutrino measurements would constrain the chemical composition of the Sun, leading to improved models for star formation and supernova explosions. A direct measurement of the CNO neutrino components could also solve the long-standing and well-known “solar metallicity problem”. The solar metallicity (fraction of elements with $Z > 2$) is an important parameter in the SSM. The metallicity is inferred from spectroscopy, and when input to SSM calculations its value affects the predicted sound speed radial profiles within the Sun (accurately measured via helioseismology), and also changes some neutrino fluxes [19, 20]. Two ranges of metallicity, known as the low-metallicity [21] and high-metallicity solutions [22], have been derived from spectroscopic measurements of the

Neutrino Source	Unit	GS98			AGSS09			Δ
		Flux	$+\sigma$	$-\sigma$	Flux	$+\sigma$	$-\sigma$	
pp	$\times 10^{10}$	5.97	+0.006	-0.006	6.03	+0.005	-0.005	-1.0%
pep	$\times 10^8$	1.41	+0.011	-0.011	1.44	+0.010	-0.010	-2.1%
hep	$\times 10^3$	7.91	+0.15	-0.15	8.18	+0.15	-0.15	-3.3%
${}^7\text{Be}$	$\times 10^9$	5.08	+0.06	-0.06	4.64	+0.06	-0.06	9.1%
${}^8\text{B}$	$\times 10^6$	5.88	+0.11	-0.11	4.85	+0.12	-0.12	19.2%
${}^{13}\text{N}$	$\times 10^8$	2.82	+0.14	-0.14	2.07	+0.14	-0.13	30.2%
${}^{15}\text{O}$	$\times 10^8$	2.09	+0.16	-0.15	1.47	+0.16	-0.15	34.8%
${}^{17}\text{F}$	$\times 10^6$	5.65	+0.17	-0.16	3.48	+0.17	-0.16	47.5%

Table 1. Solar neutrino fluxes predicted by the GS98 high-metallicity [22] and AGSS09 low-metallicity [21] solutions with the Standard Solar Model. Units are in $\text{cm}^{-2} \text{s}^{-1}$. The discrepancy Δ is evaluated as: $2 \times (GS98 - AGSS09)/(GS98 + AGSS09)$.

Sun. The newest and recommended range (that of ref. [21]) results in a stark disagreement between predicted and observed sound speed profiles [20]. As shown in table 1, the CNO neutrino flux predictions discriminate between the two abundance ranges. A direct measurement of the CNO neutrino flux with a 10–20% uncertainty could solve the solar metallicity problem.

The most stringent experimental limit on the CNO neutrino rate is from Borexino [16] using elastic neutrino-electron scattering. They obtained an upper limit for the interaction rate of 7.9 counts per day per 100 tonnes (cpd/100 tonne) at the 95% C.L., which corresponds to a flux limit of $<7.9 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$, nearly double the expectations from table 1. Borexino is a large organic liquid scintillation detector with excellent intrinsic radio-purity. Although the ${}^{210}\text{Bi}$ activity in the active mass of Borexino is exceptionally low (~ 20 cpd/100 tonne), its spectral shape is very similar to the expected CNO signal. This precludes a positive neutrino signal from being extracted. For this reason, the Borexino collaboration is planning a new purification campaign, mainly focused on ${}^{210}\text{Bi}$ removal.

Liquid argon (LAr) presents an excellent alternative for observing CNO neutrinos via neutrino-electron elastic scattering. LAr is a powerful scintillator, 4-5 times brighter than organic liquid scintillators. In addition LAr, as a liquefied noble element, does not react and does not bond with chemical species, and can be maintained with very high purity in either the liquid or the gas phase. The ultimate impurity levels of ${}^{238}\text{U}$ and ${}^{232}\text{Th}$ achievable in LAr are lower than those achieved in organic liquid scintillators [16]. The main impurity background is dissolved radon, emanating from vessels, pipes, and filters. But thanks to the low normal boiling temperature of LAr, it has been demonstrated that radon can be removed to a level of $\sim \mu\text{Bq}/\text{m}^3$ gas by cryogenic adsorption on activated carbon [23].

Two-phase LAr TPCs have an LAr target volume and a thin gas layer at the top, where the ionization electrons surviving recombination are extracted and accelerated to produce a secondary light signal by gas proportional scintillation (GPS). LAr TPCs can determine the position of energy deposit events in the liquid to within a few mm in the drift direction, and ~ 1 cm or better in the two transverse directions. For a program of precision measurements on solar neutrinos, use of an LAr TPC with fiducial mass of several hundred tonnes would bring a number of important advantages. The fiducial volume could be sharply defined, removing backgrounds from surfaces and eliminating the largest source of systematic error

currently affecting ${}^7\text{Be}$ measurements. It would also allow strong suppression of gamma-ray background by identifying and rejecting multiple-Compton scatters and other events having multiple energy deposition sites.

DarkSide-50 [24] is a 50 kg two-phase LAr TPC designed to search for nuclear-recoil events from galactic WIMP scattering. Recent DarkSide-50 results demonstrate the excellent performance of this technology for discriminating nuclear-recoil from electron-recoil events, and in radio-purity of the detector and active medium. On the basis of these results, the DarkSide collaboration is proposing a roadmap for the construction of an LAr WIMP Dark Matter search detector able to reach the so-called “neutrino floor”. This is the Dark Matter sensitivity level set by the irreducible nuclear-recoil background from coherent nuclear scattering of solar and atmospheric neutrinos on argon nuclei [25]. The projected exposure of 1,000 tonne yr would allow more than 10,000 CNO neutrino-electron scattering events to be collected. Such a detector would also have the capability of observing other components of the solar neutrino spectrum, such as ${}^7\text{Be}$ and pep , with a more favorable signal-to-background ratio than Borexino. These neutrino-electron scattering events would not be a background problem for the WIMP search, due to the excellent particle identification capability of the LAr TPC.

The present work explores the potential for solar neutrino measurements from the large mass LAr detectors being designed for direct Dark Matter searches. In particular, we investigate the expected measurement precision for neutrino rates as a function of the background contaminations, taking into account the detector response and associated systematics.

2 Neutrino signal and backgrounds

The overall solar neutrino-electron scattering rate expected in LAr is ~ 150 cpd/100 tonne. However, the spectral range below 0.6 MeV is inaccessible, due to background from ${}^{39}\text{Ar}$, ($Q(\beta^-) = 0.565$ MeV, $t_{1/2} = 269$ y) produced by cosmic ray spallation of ${}^{\text{nat}}\text{Ar}$. Atmospheric argon with its $\sim 9 \times 10^9$ cpd/100 tonne (~ 1 Bq/kg) of ${}^{39}\text{Ar}$ is prohibitively radioactive for use in any large LAr TPC. Argon extracted from underground gas wells (UAr) has been shown by the Darkside collaboration to contain only $\sim 6 \times 10^6$ cpd/100 tonne (0.7 mBq/kg) of ${}^{39}\text{Ar}$ [26]. But even this level would prevent extraction of solar neutrino signals in the low energy region, which is dominated by pp neutrinos. However, ${}^7\text{Be}$ neutrino interactions, whose Compton-like edge is expected at ~ 0.66 MeV, would be accessible (particularly with UAr) thanks to the excellent energy resolution achievable in LAr.

The 3-D event localization available in an LAr TPC allows the pulse height of single-site events to be fully position corrected, which should result in an energy resolution limited by photoelectron statistics. With a scintillation photon yield of $\sim 40,000$ photons/MeV [27], LAr is approximately a factor 4 brighter than organic liquid scintillators. DarkSide-50 [24] has already demonstrated a photoelectron yield of ~ 7000 photoelectrons (PE)/MeV at a 200 V/cm field (~ 8500 pe/MeV at zero field), albeit in a relatively small detector. MicroCLEAN [28], a small, single-phase LAr detector, measured a yield of ~ 6000 PE/MeV at zero field, constant within 2% in the $[0.04, 0.66]$ MeV energy range. Such yields are approximately 12–14 times that achieved in Borexino (~ 500 PE/MeV), the solar neutrino experiment with the best resolution ever reached.

Light yield, however, can be strongly affected when scaling LAr target masses from a few tens of kilograms (DarkSide-50 and MicroCLEAN) to hundreds of tons. Optical effects in the UV range, like Rayleigh scattering and light absorption, can, in fact, reduce the light yield when photon travels long distances. Different techniques were used to estimate the Rayleigh

scattering length: by calculation (90 cm [29]), direct measurement (66 ± 3 cm [30]), and by extrapolation from measurements at higher wavelengths (55 ± 5 cm [31]). The absorption length is expected to be much larger, but, since the light propagation is dominated by the Rayleigh effect, a direct measurement is extremely challenging. Theoretically, it has been estimated [32] that, as a consequence of the Stokes' shift, a LAr dimer should be in a vibrational excited state almost 1 eV above the ground state to re-absorb the emitted photon. Such a state can be formed only during atom collisions, making the LAr self-absorption negligible. The dominant process in the light absorption in LAr is expected then to be strongly dependent on the presence of chemical impurities or noble gases like nitrogen, which can affect the attenuation length already at the ppb level [33]. Such impurities can be efficiently removed via adsorption or via distillation. The DarkSide collaboration is building the 350 m tall ARIA [34] cryogenic distillation column to assess the feasibility of isotopic separation of ^{39}Ar from ^{40}Ar . This facility will have unprecedented capabilities for removal of chemical impurities and could have a significant impact in improving the optical properties of LAr.

Assuming photoelectron-statistics-limited resolution with 6000 PE/keV, and an ^{39}Ar specific activity of 0.7 mBq/kg, no event from ^{39}Ar is expected to appear above 0.6 MeV due to resolution smearing in a 400 tonne-year exposure (see figure 1). The present paper will therefore consider the energy range of interest for solar neutrinos to have a threshold at 0.6 MeV.

Other possible background sources are ^{42}Ar ($Q(\beta^-) = 0.599$ MeV, $\tau_{1/2} = 33$ yr), and its daughter ^{42}K ($Q(\beta^-) = 3.52$ MeV, $\tau_{1/2} = 12.4$ hr). Recent measurements by the GERDA collaboration [35] with atmospheric argon gave a ^{42}Ar specific activity of $\sim 8 \times 10^5$ cpd/100 tonne (94.5 ± 18.1 $\mu\text{Bq/kg}$), which would presumably be in equilibrium with the ^{42}K daughter at the same level. ^{42}Ar can be produced by two sequential neutron captures on ^{40}Ar (mostly during atmospheric nuclear tests) or from spallation by cosmic ray α -particles ($^{40}\text{Ar}(\alpha, 2p)^{42}\text{Ar}$) [36]. (Cosmic α 's amount to 14% of the cosmic proton flux.) Underground argon is not subject to either of these mechanisms, and so would be expected to contain a much lower level of ^{42}Ar than atmospheric argon.

Table 2 shows the expected solar neutrino rates in LAr from ^7Be , ^8B , pep , and CNO neutrinos in the [0.6, 1.3] MeV energy range, comparing the low-metallicity (LZ) solution [21] with the high-metallicity (HZ) solution [22]. Rates for both solutions are calculated with the SSM and the neutrino oscillation survival probabilities from the MSW-LMA (large mixing angle) solution, using $\Delta m^2 = 7.54 \times 10^{-5}$ eV² and $\sin^2(\theta_{12}) = 0.307$ [14, 15]. For the LZ solution the total neutrino rate is 4.63 ± 0.22 cpd/100 tonne, which increases to 5.14 ± 0.25 cpd/100 tonne for the HZ solution. The main contribution (~ 3 cpd/100 tonne) is from ^7Be , even though this contributes only in the range [0.6, 0.7] MeV, as shown in figure 1. The HZ solution predicts almost equal contributions from pep and CNO neutrinos above 0.7 MeV, while in the LZ model the pep rate in this range is expected to be twice as large as that from CNO neutrinos. The ^8B component is not measurable in the [0.6, 1.3] MeV energy range, since its contribution is very small and featureless. ^8B may be observable at high energies (> 5 MeV) where radioactive backgrounds and other contributions are negligible, but this is beyond the scope of this work and will be not treated.

Aside from the argon isotopic impurities discussed above, the main backgrounds in the [0.6, 1.3] MeV energy range for a detector operating at LNGS depth are expected to be:

- cosmogenic radionuclides produced in the running detector, by the interaction of cosmic rays with LAr;

Neutrino Source	Low Metallicity (LZ)		High Metallicity (HZ)	
	All	[0.6–1.3] MeV	All	[0.6–1.3] MeV
pp	107.9 ± 2.0	0	107.0 ± 2.0	0
pep	2.28 ± 0.05	1.10 ± 0.02	2.23 ± 0.05	1.07 ± 0.02
${}^7\text{Be}$	36.10 ± 2.60	2.85 ± 0.21	39.58 ± 2.85	3.13 ± 0.23
CNO	3.06 ± 0.30	0.64 ± 0.06	4.28 ± 0.44	0.90 ± 0.09
${}^8\text{B}$	0.30 ± 0.04	0.035 ± 0.005	0.36 ± 0.06	0.042 ± 0.007
Total		4.63 ± 0.22		5.14 ± 0.25

Table 2. Expected solar neutrino rates in cpd/100 tonne of LAr active mass, comparing the low-metallicity [21] and high-metallicity [22] predictions using the Standard Solar Model and neutrino oscillation parameters from the MSW-LMA [14, 15] region with $\Delta m^2 = 7.54 \times 10^{-5} \text{ eV}^2$ and $\sin^2(\theta_{12}) = 0.307$.

- ${}^{222}\text{Rn}$ dissolved in the LAr after being emanated from the detector walls or from the recirculation system;
- external background, i.e. γ -rays from radioactive contaminants in the detector construction materials.

Most of these backgrounds produce γ -rays, which allows them to be strongly suppressed by the multi-site interaction discrimination available in an LAr TPC. If an event produces two or more interactions (multiple Compton scatters, etc.) separated by just a few millimeters along the drift direction, the ionization electrons from each interaction reach the gas layer several microseconds apart, generating secondary gas proportional scintillation pulses well separated in time. For instance, assuming an electric field of 200 V/cm, the drift velocity in LAr is $\sim 1 \text{ mm}/\mu\text{s}$. Two interactions occurring 1 cm apart along the drift direction will generate GPS light pulses separated by about 10 μs . The characteristic scintillation emission times of gaseous argon ($\tau_{fast} \sim 6 \text{ ns}$ and $\tau_{slow} \sim 1.6 \mu\text{s}$) allow the start times of pulses to be measured with a precision of tens of nanoseconds, thus easily allowing identification of events with even rather closely-spaced multiple interactions. The resulting discrimination factors are estimated by Monte Carlo codes developed and benchmarked in connection with the DarkSide-50 experiment.

Another possible source of background would be ${}^{85}\text{Kr}$ ($Q(\beta^-) = 0.687 \text{ MeV}$, $\tau_{1/2} = 10.75 \text{ yr}$) in the LAr fill. The DarkSide collaboration has measured a ${}^{85}\text{Kr}$ contamination in underground argon of $\sim 1.7 \times 10^7 \text{ cpd}/100 \text{ tonne}$ (2 mBq/kg [26]). ${}^{85}\text{Kr}$ in UAr can originate from atmospheric leaks or deep underground natural fission processes [26], which are known to give ${}^{85}\text{Kr}$ activity in deep underground water reservoirs [37].

Despite the fact that only $\sim 1\%$ of ${}^{85}\text{Kr}$ decay events have an energy above 0.6 MeV, a contamination of the order of that measured in UAr by DarkSide-50 would seriously compromise the ${}^7\text{Be}$ neutrino rate measurement. However, it would not affect the measurement of higher energy CNO neutrinos. The DarkSide collaboration is planning to fill the planned multi-ton detector using argon purified by cryogenic distillation in columns with thousands of equilibrium stages [39], a technique that can reduce the ${}^{85}\text{Kr}$ activity well below 10 cpd/100 tonne (100 $\mu\text{Bq}/(100 \text{ tonne})$ [38]). This would effectively eliminate the ${}^{85}\text{K}$ interference with the ${}^7\text{Be}$ measurement.

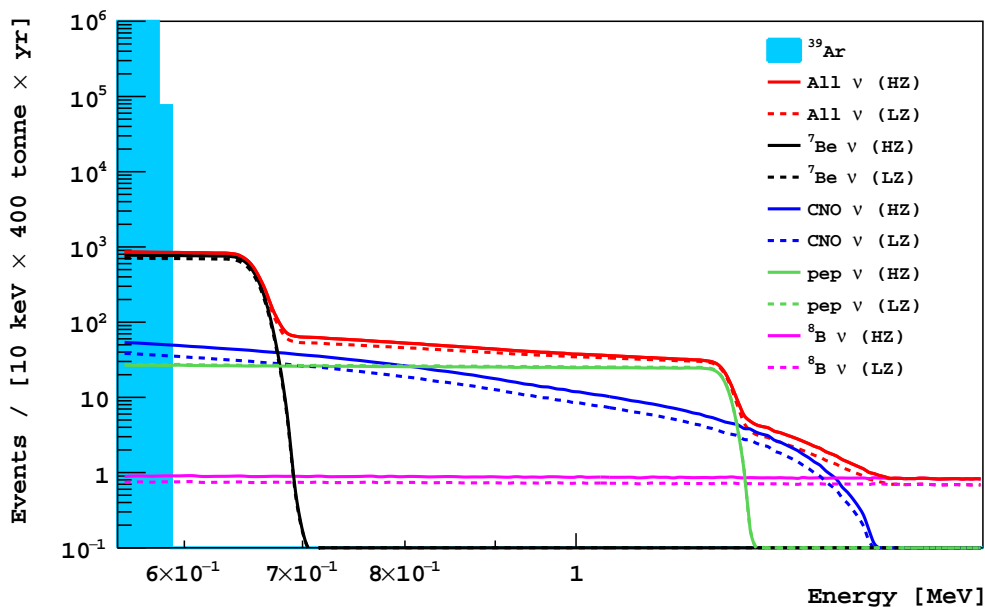


Figure 1. Simulated solar neutrino spectra in a 400 tonne-yr LAr TPC exposure, assuming $\sigma = 1.3\%$ energy resolution at 1 MeV, corresponding to a PE yield of 6 PE/keV. The blue shaded area represents the tail of the ^{39}Ar contamination, intrinsic to underground LAr.

In the next subsections, the contamination from each background source, and the associated residual rate after the multiple scattering cut, will be discussed in detail.

2.1 Cosmogenic background

Direct dark matter search experiments are located deep underground in order to be shielded against the cosmic rays and their interaction products. At moderate depths however, the residual muon flux may still produce measurable amounts of radioactive isotopes by muon-induced spallation on the argon. These can produce dangerous, delayed electron-recoil background in the solar neutrino energy window.

Radiochemical and scintillator experiments for solar neutrino physics, like GALLEX and Borexino, have investigated muon-induced radionuclide production using dedicated setups exposed to muon beams at CERN [40, 41]. Further, radionuclide production models in simulation packages like GEANT4 [42, 43] and FLUKA [44, 45] have been greatly improved in recent years. Predictions now typically agree within a factor of ~ 2 with measured values, as shown by the Borexino in [46] and KamLAND collaborations [47]. The present work uses FLUKA for evaluating the cosmogenic production rates, since it has been found to be in better agreement with the Borexino measurements [46].

The detector geometry simulated in the present FLUKA code was a cylindrical TPC of 3.3 m radius and 3 m height, corresponding to a ~ 150 tonne LAr active mass. The TPC sidewall is a 3 cm thick teflon layer, and the top and bottom ends are covered with 2 mm thick silicon layers, representing silicon photomultiplier arrays. The 2 cm thick gaseous argon region sits just below the upper silicon layer. The TPC is contained in a 3 mm thick cylindrical stainless steel cryostat with 3.5 m radius and 3.2 m height. Gaseous argon is also present in the cryostat, outside the TPC region and above the LAr level. The cryostat is

Isotope	Half Life	Decay Mode	Q-value [MeV]	Rate	
				Entire Range	[0.6–1.3] MeV
^{41}Ar	109.61 min	β^-	2.492	0.213	0.054
^{38}Cl	37.230 min	β^-	4.917	0.815	0.147
^{39}Cl	55.6 min	β^-	3.442	0.173	0.051
^{32}P	14.268 d	β^-	1.711	0.636	0.332
^{34}P	12.43 s	β^-	5.383	0.145	0.021
^{31}Si	157.36 min	β^-	1.492	0.229	0.106
Others				1.897	0.022
Total				4.108	0.733

Table 3. Rate (cpd/100 tonne) of single scattering background events from in situ produced cosmogenic isotopes, in the whole spectrum and in the region of interest for solar neutrinos [0.6–1.3] MeV.

housed in a Borexino-like veto detector consisting of a 6 m radius stainless steel sphere filled with liquid scintillator placed within a larger cylindrical tank (17 m height, 16 m diameter) filled with water. In this work, the veto is considered as a passive shield only, despite the fact that the detection of light in the scintillator can provide a powerful rejection tool against external backgrounds. As in the cosmogenic simulation study for Borexino described in [46], we used as input the cosmic ray muon flux measured by MACRO at Gran Sasso laboratory ($\langle E_\mu \rangle = 283 \text{ GeV}$, $1.14 \mu/(\text{hr m}^2)$ [48]), and a $\frac{\mu^+}{\mu^-}$ ratio of 1.38, as measured by the OPERA experiment [49].

Cosmic muons were generated 3 m above the cylindrical water tank with an intervening 0.7 m rock layer, in order to fully develop the hadronic showers. The radionuclide production rates were then converted to specific activities, taking into account the mean life of each isotope. The simulation resulted in the production of more than 80 isotopes by muon spallation on argon, as shown in the tables in appendix A. Cosmogenic isotopes produced in the other materials of the detector are taken into account in this analysis, but do not significantly contribute to the overall background.

The produced isotopes were then handed off to a GEANT4 simulation, which generated decays and tracked the decay products in the full detector geometry. This allowed the efficiency of the multiple scattering cut to be estimated. Multiple scattering events were conservatively defined as events producing at least two energy deposits exceeding 10 keV, with a vertical separation exceeding 1 cm. Rejecting such events is extremely effective in eliminating β^+ decays, which have a high probability for multiple interactions due to positron annihilation γ -rays, and also those β^- decays accompanied by gamma emission. The energy region for solar neutrinos, however, is mostly populated by pure β -decay and so the multiple scattering cut rejects only $\sim 20\%$ of the cosmogenic background, as shown in figures 3 and 2.

Additional rejection power would be expected by applying a delayed veto to events following a crossing muon detected in the vetoes. However, this has not been done in the present analysis, since its efficiency depends on parameters such as the muon rate and on the event acquisition gate length of the experiment.

The final predicted overall rate of events due to cosmogenic activities, summarized in table 3, corresponds to 4.1 cpd/100 tonne in the entire energy range, and 0.733 cpd/100 tonne in the [0.6 - 1.3 MeV] energy region of interest for solar neutrinos. The neutrino signal-

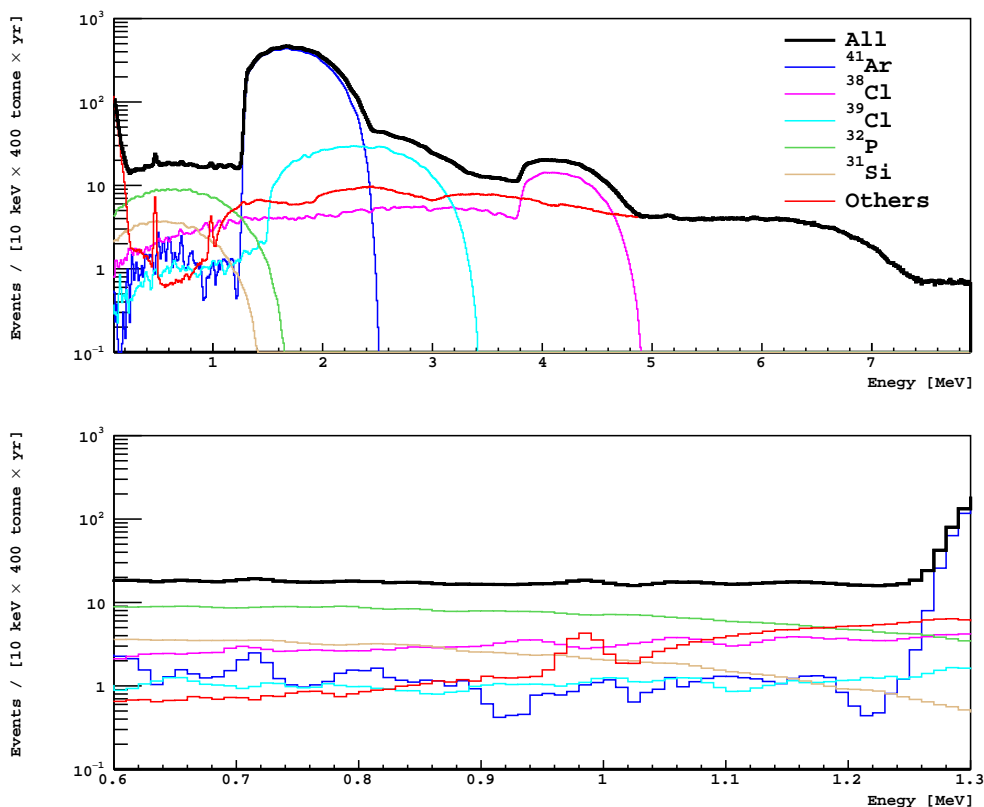


Figure 2. Spectra of cosmogenic-isotope induced backgrounds, before the multiple scattering cut, in the full energy range (top) and in the solar neutrino energy window [0.6, 1.3] MeV (bottom).

to-background ratio in the region of interest is thus estimated to be 6.3 (7), assuming the low (high) metallicity model. Even if we arbitrarily increase all production rates by a factor of two to allow for uncertainties of the FLUKA production model, the signal-to-background ratio will be larger than 3. This is ample to allow an accurate measurement of the solar neutrino components. The systematic uncertainties induced by the uncertainties on the cosmogenic isotope activities will be discussed in the next section.

As a general remark, even if the cosmogenic background does not represent a main obstacle to the solar neutrino rate measurement, as demonstrated in the next sections, a deeper experimental location, with the muon flux potentially reduced, could make this background negligible.

2.2 Radon contamination

Contamination of the target argon mass by ^{222}Rn may represent the most serious background problem for the solar neutrino measurements. ^{222}Rn emanated into the active argon from anywhere in the detector system will be distributed throughout the LAr fill by the purification/recirculation loop. One of the goals of this work is to quantify the maximum contamination of ^{222}Rn that could be tolerated in a CNO neutrino experiment.

^{222}Rn α -decay has a half life of 3.8 days, and is followed by two α - (^{218}Po , and ^{214}Po) and two β -decays (^{214}Pb and ^{214}Bi). The ^{222}Rn chain segment effectively stops at the ^{210}Pb

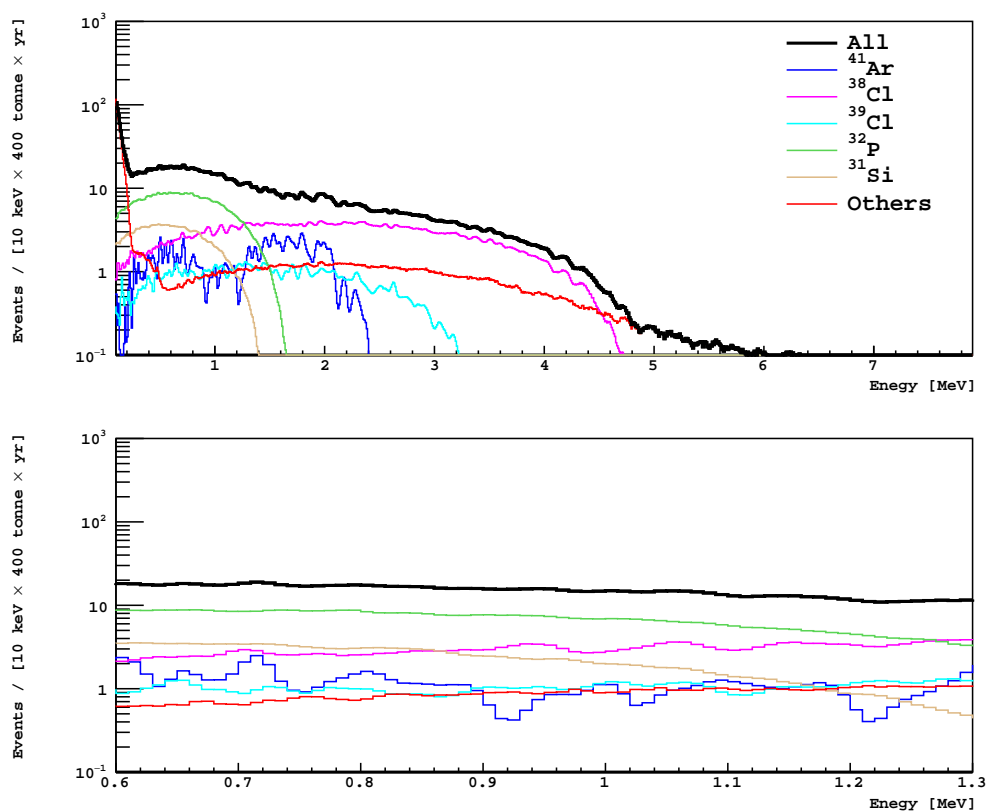


Figure 3. Spectra of cosmogenic-isotope induced backgrounds, after the multiple scattering cut, in the full energy range (top) and in the solar neutrino energy window [0.6, 1.3] MeV (bottom).

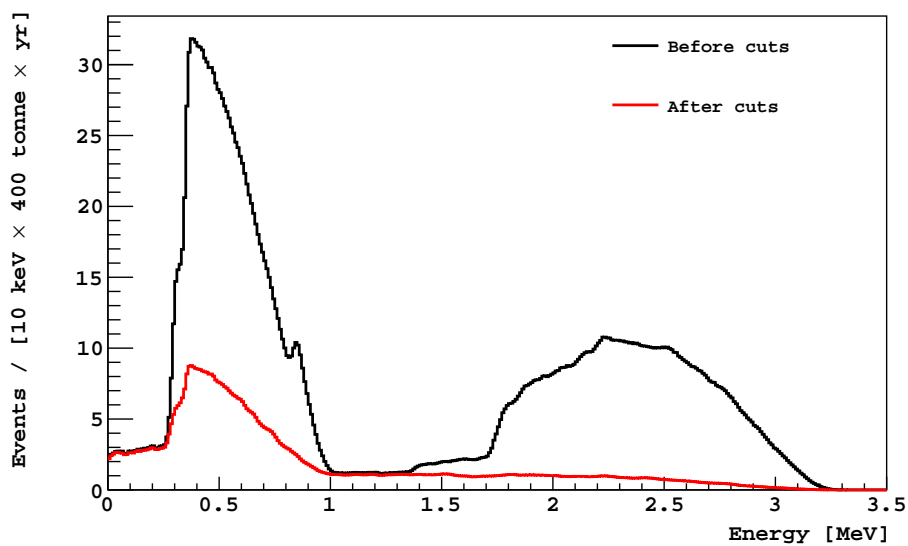


Figure 4. Simulated energy spectra from the ^{222}Rn daughters ^{214}Pb and ^{214}Bi , showing the effect of the multiple interaction cut. ^{222}Rn activity of $10 \mu\text{Bq}/(100 \text{ tonne})$ ($0.9 \text{ cpd}/100 \text{ tonne}$) is assumed.

level, due to its relatively long half life (22.3 y). In LAr, the heavily ionizing α events are very strongly suppressed by the pulse shape discrimination: having nuclear-recoil-like pulse shape parameters [51], the α/β discrimination factor is of the order of 10^7 – 10^8 [24]. Further, α events fall above the energy range for neutrino observation, since in LAr almost all ($\sim 85\%$ [51]) of the α -energy is converted into light, contrary to organic scintillators where only a small fraction ($<10\%$) is converted.

The isotopes ^{214}Pb and ^{214}Bi decay by β -emission without coincident γ -rays 6.3% and 18.2% of the time, respectively. Those decays with coincident γ -rays can be suppressed in a two-phase LAr TPC by eliminating events with multiple interaction sites. The effect of this cut on the total spectrum from the ^{222}Rn decay chain, simulated with GEANT4, is shown in figure 4. The simulations indicate that 6.9% (5.9%) ^{214}Pb (^{214}Bi) decays will remain with energy deposits in the solar neutrino energy region, after the multiple-interaction cut. As a result, 45 $\mu\text{Bq}/(100\text{ tonne})$ (3.8 cpd/100 tonne) of ^{222}Rn contamination would introduce a background rate equivalent to the expected solar neutrino signal. Simulated experimental spectra for ^{222}Rn contaminations ranging from 10 $\mu\text{Bq}/(100\text{ tonne})$ (0.8 cpd/100 tonne) to 10 mBq/(100 tonne) (800 cpd/100 tonne) are shown in figure 5.

The ^{222}Rn decay rate can at least be directly measured with the LAr TPC itself, by looking at the delayed coincidence between the ^{214}Bi β -decay and the ^{214}Po α decay ($\tau_{1/2} = 163\ \mu\text{s}$), a technique widely used by several low background experiments (e.g. [16]). Selecting ^{214}Bi events in the [0.6, 3.3] MeV region will give a sample free of ^{39}Ar contamination, and containing $\sim 96\%$ of the ^{214}Bi decays. An accurate constraint on the ^{222}Rn activity will allow the identification of the neutrino spectral shape even with high ^{222}Rn contaminations, as discussed in the next section.

2.3 External background

The term “external background” is used here for events from decays from radioactivity in the detector materials, such as the cryostat and the photosensors. Only the γ -rays from such activities can reach the active mass and produce an electron recoil. For the solar neutrino measurements, nuclear recoils from radio- or cosmogenic neutron scattering can be identified and discarded using the pulse shape discrimination, with discrimination power for β/γ vs. nuclear recoils known to be larger than 10^7 in LAr [24].

To evaluate the background induced by external gamma rays affecting a solar neutrino measurement, a GEANT4 simulation was performed using ^{40}K , ^{214}Bi and ^{208}Tl originating in the photosensors, and ^{60}C from the cryostat. The contaminations of ^{40}K , and the ^{238}U and ^{232}Th parents of ^{214}Bi and ^{208}Tl in SiPM photosensors have been reported to be smaller than 0.1 mBq/kg [50]. In the present work 2 mm thick silicon photosensors were simulated on the top and bottom of the TPC, corresponding to ~ 300 kg of silicon. This gives an upper limit on the activity from the photosensors of 30 mBq. Assuming a conservative rejection factor of 10^5 , we expect ~ 0.02 cpd in the [0.6–1.3] MeV energy range, negligible with respect to the solar neutrino fluxes.

The ^{60}Co activity in stainless steel typical of that to be used for the cryostat has been measured by Koehler et al. [52] and by Maneschg et al. [53], for different samples, with results in the range of [6.6, 45.5] mBq/kg. Assuming a 1 tonne cryostat mass with the lowest ^{60}Co value in the range, the overall expected ^{60}C event rate is 570 cpd/100 tonne, with 1.7 cpd/100 tonne remaining after the fiducial volume cut. The latter rate is comparable with the expected solar neutrino signal, making ^{60}Co the most dangerous background among the external sources. Several solutions can be adopted to further reduce the ^{60}Co contribution,

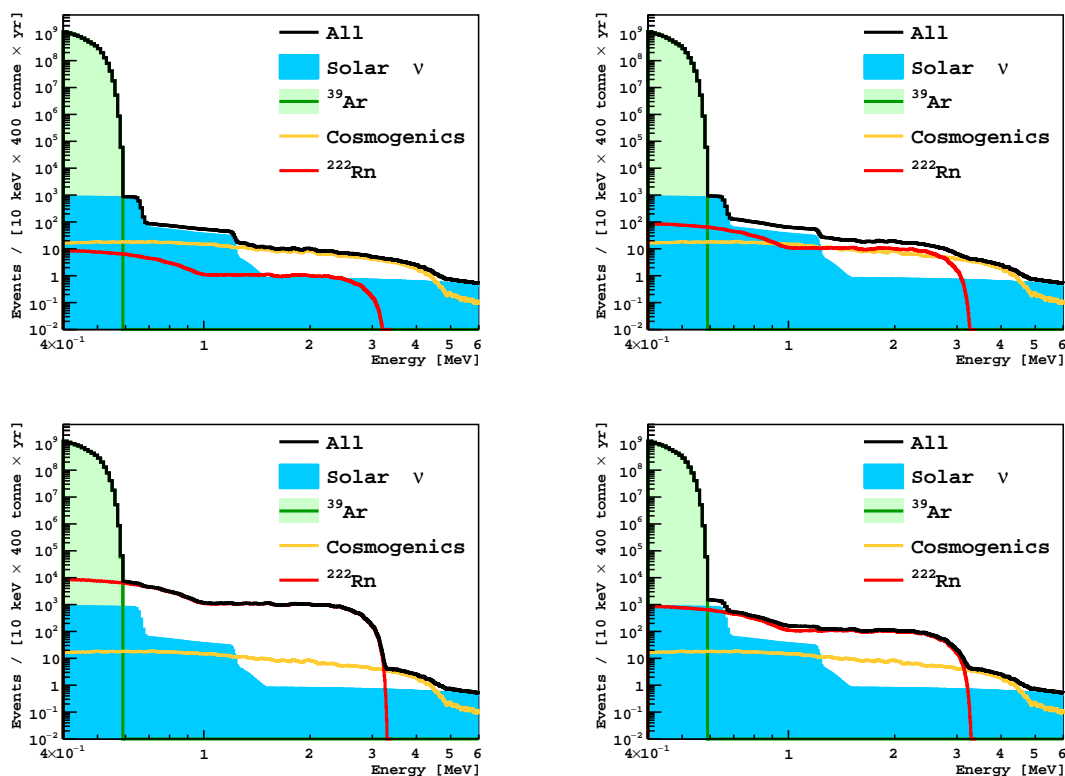


Figure 5. Components of the electron recoil energy spectrum, simulated for a 4 year exposure of 100 tonnes of LAr (see legend). Each panel shows a different assumed radon level in the LAr (clockwise from top left: 10, 100, 1,000, 10,000 $\mu\text{Bq}/(100 \text{ tonne})$, corresponding to a range between 0.8 and 800 cpd/100 tonne).

such as a stronger fiducial cut, an active liquid scintillator detector surrounding the TPC working as an anti-coincidence veto (like in DarkSide-50 [57]), or the identification of a stainless steel batch with lower ^{60}Co contamination. A titanium cryostat is a possible solution to this problem, since Ti may be produced with less radioactive contamination than stainless steel, particularly for the case of ^{60}Co [54].

Simulating the source levels just described, and after rejecting multi-sited events as discussed previously, the fraction of surviving external background events is of the order of a few tenths of a per cent as shown in table 4. In addition, the surviving events are located close to the TPC walls. The simulated distributions of surviving events fit exponential attenuation from the boundaries inward, with attenuation lengths varying from 3.6 to 5.1 cm depending on the source and position. As shown in table 4, a fiducial volume cut placed 30 cm from the TPC wall would provide a rejection factor of 10^5 , effectively suppressing the single-scatter component of external background.

In the sensitivity study described in the next section, we assume that the background from external sources is negligible.

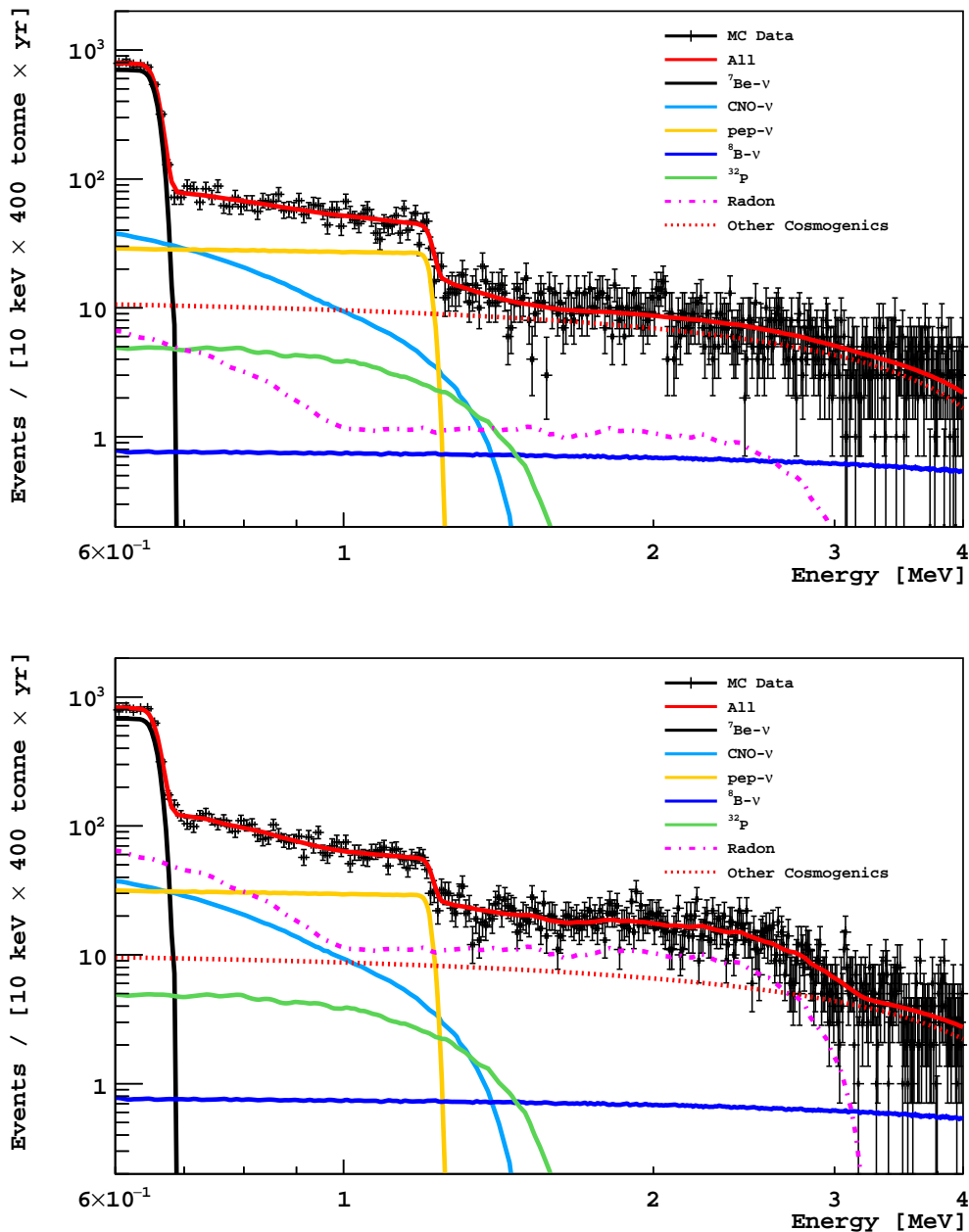


Figure 6. Examples of simulated spectra and fits, assuming radon contaminations of 10 (top) and 100 (bottom) $\mu\text{Bq}/(100 \text{ tonne})$ (0.8 and 8 cpd/100 tonne). The calculations assume the low-metallicity SSM, and the cosmogenic component is modeled with a first degree polynomial, with the exception of an explicit spectrum for ^{32}P .

Source	Origin	Attenuation length [cm]	Survived Fraction	
			without FV	with FV
^{40}K	Photosensors	3.9	0.3×10^{-2}	1×10^{-6}
^{214}Bi	Photosensors	4.2	1.1×10^{-2}	9×10^{-6}
^{208}Tl	Photosensors	3.6	0.7×10^{-2}	2×10^{-6}
^{60}Co	Cryostat	5.1	0.1×10^{-2}	3×10^{-6}

Table 4. Fraction of events producing only a single energy deposition in the [0.6, 1.3] MeV energy range. The last column includes a fiducial volume cut applied at 30 cm from the TPC walls.

3 Sensitivity to solar neutrinos

A measurement of the solar neutrino spectral components relies on identification of the spectral shapes of the individual components. We attempt to estimate the sensitivity of a 100 tonne two-phase LAr TPC to solar neutrinos using a toy Monte Carlo approach. For each solar metallicity model we sampled GEANT4-generated energy spectra for the various signal and background components, to produce simulated data samples. Ten thousand samples were generated with Poisson statistics corresponding to a 400 tonne yr exposure, and assuming PE-statistics-limited detector resolution with a light yield of 6000 pe/MeV. The external background was neglected, since, as discussed above, it can be completely suppressed by multi-site and fiducial volume cuts. The radon contribution in the generated data samples was varied from 10 to 200 $\mu\text{Bq}/(100 \text{ tonne})$ (0.8 - 16 cpd/100 tonne).

The simulated spectra were then fit with a model designed to account for the large uncertainty of the cosmogenic background shape. For the present work, only the most abundant cosmogenic contribution from ^{32}P (see table 3 and appendix A) has been explicitly included in the fit function. The aggregate electron recoil spectrum from the remaining cosmogenics was modeled with a linear function of energy. The parameters of the function were left free to vary in the fit which was performed with a maximum likelihood method using the RooFit package [55].

The radon level in the fitting model was not freely varied, but was determined from the simulated number of $^{214}\text{Bi-Po}$ events in each simulated sample. Conservatively assuming a $^{214}\text{Bi-Po}$ tagging efficiency of 60%, the intensity of the radon-daughter spectral component of the fitting model was selected with a statistical uncertainty based on the number of $^{214}\text{Bi-Po}$ events seen. The fit range extended from 0.6 to 5 MeV, so as to better constrain the background contributions. Examples of simulated spectra and fits are shown in figure 6 for radon contaminations between 10 and 100 $\mu\text{Bq}/(100 \text{ tonne})$ (0.8 - 8 cpd/100 tonne). The resulting fitted values and uncertainties of the neutrino signal components are given in table 5.

The CNO spectral shape is similar to that of the low energy radon component. At radon contamination levels above 200 $\mu\text{Bq}/(100 \text{ tonne})$ (16 cpd/100 tonne), the fit shows a systematic deviation from the central value of the simulated CNO component (SSM-LZ) by a few percent, implying that to guarantee a correct CNO measurement, the radon activity must be reduced below this level. No such systematic deviations are observed for ^7Be and pep , whose spectral shapes have clear characteristic features.

The impact of a ^{85}Kr contamination was also tested by adding 1, 10, and 100 $\mu\text{Bq}/(100 \text{ tonne})$ (corresponding to 0.09, 0.9, and 9 cpd/100 tonne) of ^{85}Kr events to the toy MC samples, assuming a radon contamination of 10 $\mu\text{Bq}/(100 \text{ tonne})$ (0.8 cpd/100 tonne). These contamination levels resulted in an overall ^7Be rate precision of $\sim 2\%$, 3.5% , and 5% , respectively. As expected, extraction of the other neutrino components was unaffected by the ^{85}Kr

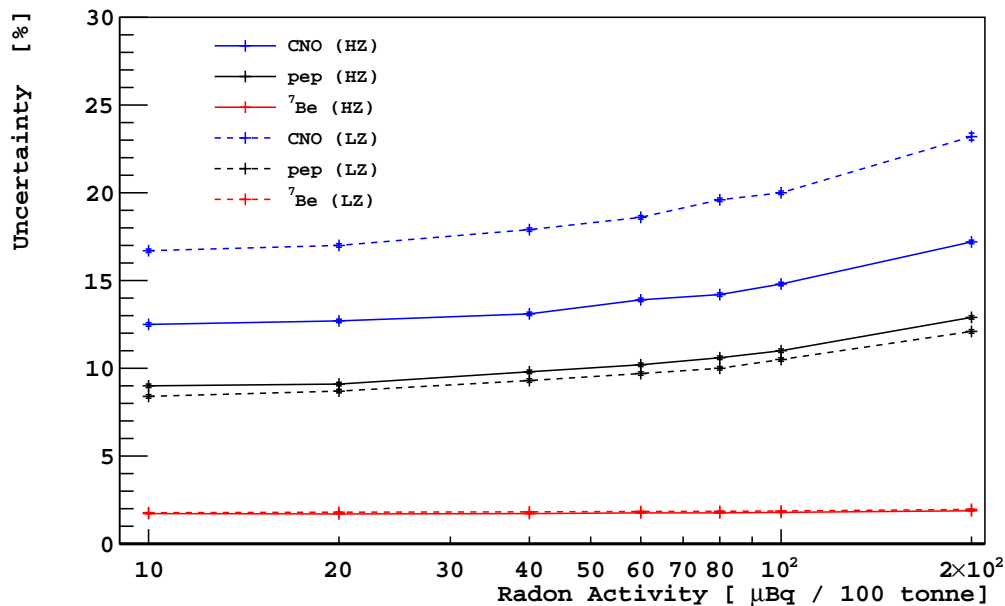


Figure 7. Statistical uncertainties on the solar neutrino components, as a function of the radon activity.

^{222}Rn Activity	Low Metallicity			High Metallicity		
	$\sigma(^7\text{Be})$	$\sigma(\text{pep})$	$\sigma(\text{CNO})$	$\sigma(^7\text{Be})$	$\sigma(\text{pep})$	$\sigma(\text{CNO})$
10	1.77 ± 0.01	8.4 ± 0.1	16.7 ± 0.1	1.72 ± 0.01	9.0 ± 0.1	12.5 ± 0.1
20	1.80 ± 0.01	8.7 ± 0.1	17.0 ± 0.1	1.70 ± 0.01	9.1 ± 0.1	12.7 ± 0.1
40	1.82 ± 0.01	9.3 ± 0.1	17.9 ± 0.1	1.72 ± 0.01	9.8 ± 0.1	13.1 ± 0.1
60	1.84 ± 0.01	9.7 ± 0.1	18.6 ± 0.1	1.76 ± 0.01	10.2 ± 0.1	13.9 ± 0.1
80	1.85 ± 0.01	10.0 ± 0.1	19.6 ± 0.1	1.76 ± 0.01	10.6 ± 0.1	14.2 ± 0.1
100	1.87 ± 0.01	10.5 ± 0.1	20.0 ± 0.1	1.79 ± 0.01	11.0 ± 0.1	14.8 ± 0.1
200	1.96 ± 0.01	12.1 ± 0.1	23.2 ± 0.2	1.88 ± 0.01	12.9 ± 0.1	17.2 ± 0.1

Table 5. Solar neutrino rate uncertainties [%] as a function of the ^{222}Rn contamination [$10 \mu\text{Bq}/(100 \text{ tonne}) = 0.8 \text{ cpd}/100 \text{ tonne}$]

contamination. In the fitting model, the amplitude of the ^{85}Kr contribution was left as a free parameter, rather than attempting to constrain it by exploiting the ^{85}Kr - ^{85m}Rb delayed coincidence as was done in ref. [26].

The systematic uncertainty associated with the linear model of the cosmogenic background shape was also studied. For this purpose, toy MC samples were generated while uniformly varying each cosmogenic isotope activity, based on the table in appendix A, by a factor between 0.5 and 2, with respect to its nominal activity. These samples were produced assuming radon contaminations of 10 and 100 $\mu\text{Bq}/(100 \text{ tonne})$ (0.8 - 8 cpd/100 tonne). The resulting variations in the extracted solar neutrino signals lie within the uncertainties reported in table 5, showing that the systematic uncertainty from the linear model assumption is unimportant.

Other important sources of systematic uncertainty are expected to be the method for determining the energy scale, and the definition of the fiducial volume cut used to reject external background.

The energy scale can be expected to be almost linear. In this range, ref. [56] reported a linear energy response of the LAr ionization signal using a ^{207}Bi source with a gridded ionization chamber. The scintillation signal is expected to behave in the same way, being complementary to the ionization signal. In addition, the intrinsic ^{39}Ar contamination with endpoint at 0.565 MeV, offers a precise calibration feature to constrain the energy scale at the sub-percent level.

Systematic uncertainty in the fiducial volume cut along the drift direction is small, since the drift velocity is known with high accuracy and precision, giving a corresponding spatial precision at the sub-millimeter level. The dominant source of systematic uncertainty is expected to be related to the radial volume cut, since the position reconstruction in the plane orthogonal to the drift field is more complicated. This systematic uncertainty is expected to contribute a few percent, still not affecting the CNO and *pep* measurements, which are dominated by their statistical uncertainty. It can, however, be the limiting uncertainty for ^7Be , due to the high statistical precision ($\sim 1.7\%$) achievable for this component of the rate.

4 Conclusions

The present work exhibits background and signal extraction simulations indicating that a two-phase LAr TPC with 100 tonne fiducial mass has the necessary accuracy and precision to measure so-far unknown components of the solar neutrino spectrum.

The two most important sources of background relevant to the proposed solar neutrino measurement are ^{60}Co contamination in the cryostat metal, and ^{222}Rn contamination within the active volume.

The ^{60}Co issue could be solved by either applying stronger fiducial volume cuts or by making the cryostat of titanium, which is almost free of ^{60}Co [54]. Further, an external active veto as in DarkSide-50 [57] would further reduce the ^{60}Co background by vetoing events with ^{60}Co gammas detected in coincidence by the TPC and the veto.

The required limit on the circulating ^{222}Rn contamination, less than $200 \mu\text{Bq}/(100 \text{ tonne})$, represents the most difficult challenge. DarkSide-50 has measured a ^{222}Rn contamination at the level of $\sim 100 \text{ mBq}/(100 \text{ tonne})$ [58], about 3 orders of magnitude larger than what is required. However, the ^{222}Rn emanation rate from the detector materials and the purification loop components is expected to provide a relatively lower contribution in a larger detector: its rate approximately scales with the ratio of the detector material surface over the LAr mass. LAr can also be efficiently purified via adsorption with activated carbon columns in both gaseous and liquid phases, as done in DarkSide-50. However, available Rn assay systems do not have the sensitivity to monitor or verify the required level of radio-purity [23].

With 400 tonne \times years exposure, precisions at the level of $\sim 2\%$, $\sim 10\%$, and $\sim 15\%$ for the ^7Be , *pep* and CNO neutrino rates, respectively, are possible. These expectations can be compared to the best present measurements of the first two components (4.6% and 21.6% from Borexino), and the best upper limit for the CNO [16] neutrinos.

A CNO measurement, in particular, would provide the first direct observation of neutrinos from the CNO cycle, with the potential to discriminate between the two solar metallicity solutions. Following the same approach used in [59], a measurement of the CNO rate with 15% precision would improve upon the current knowledge of the C and N content in the Sun ($\pm 25\%$), to the 16.5% level.

The simulations indicate an attainable precision for the measured ${}^7\text{Be}$ rate which would be equivalent to an 8% measurement of the S17 nuclear cross section (${}^7\text{Be}(p,\gamma){}^8\text{B}$), which is an important input parameter in the SSM. This is similar to the precision achieved in the direct beam-target measurement [60], and would improve upon the current S17 determination from Borexino using solar neutrino rates ($\pm 12\%$) [59].

In conclusion, a large volume LAr TPC designed for a direct dark matter WIMP search, can also provide a rich set of physics results for solar neutrinos. Both the precision on the ${}^7\text{Be}$ and pep components could be significantly improved, and potentially a first measurement of the CNO component can be achieved, if stringent ${}^{222}\text{Rn}$ suppression levels were reached.

Acknowledgments

We acknowledge the financial support from the UnivEarthS Labex program of Sorbonne Paris Cité (ANR-10-LABX-0023 and ANR-11-IDEX-0005-02).

A Cosmogenic isotope production table

Isotope	Half life	Decay Mode	Q-value [keV]	Activity [cpd/(100 × tonne)]
${}^6\text{He}$	806.7 ms	β^-	3507.8	$1.28\text{e-}01 \pm 1.25\text{e-}02$
${}^8\text{He}$	119.1 ms	β^-	9670.2	$9.68\text{e-}03 \pm 3.42\text{e-}03$
${}^8\text{Li}$	839.9 ms	β^-	12975.2	$9.55\text{e-}02 \pm 1.07\text{e-}02$
${}^9\text{Li}$	178.3 ms	β^-	13606.7	$2.06\text{e-}02 \pm 4.99\text{e-}03$
${}^{11}\text{Li}$	8.75 ms	β^-	20231.2	$1.21\text{e-}03 \pm 1.21\text{e-}03$
${}^7\text{Be}$	53.22 d	EC	861.815	$1.02\text{e-}01 \pm 1.08\text{e-}02$
${}^{11}\text{Be}$	13.76 s	β^-	11509.2	$8.47\text{e-}03 \pm 3.20\text{e-}03$
${}^{12}\text{Be}$	21.3 ms	β^-	11708	$2.42\text{e-}03 \pm 1.71\text{e-}03$
${}^8\text{B}$	770 ms	β^+	14949.8	$9.68\text{e-}03 \pm 3.42\text{e-}03$
${}^{12}\text{B}$	20.20 ms	β^-	13369.3	$3.39\text{e-}02 \pm 6.40\text{e-}03$
${}^{13}\text{B}$	17.36 ms	β^-	13437.2	$7.26\text{e-}03 \pm 2.96\text{e-}03$
${}^{14}\text{B}$	12.5 ms	β^-	20644	$1.21\text{e-}03 \pm 1.21\text{e-}03$
${}^9\text{C}$	126.5 ms	β^+	16494.8	$4.84\text{e-}03 \pm 2.42\text{e-}03$
${}^{10}\text{C}$	19.290 s	β^+	2929.62	$8.47\text{e-}03 \pm 3.20\text{e-}03$
${}^{11}\text{C}$	1221.8 s	β^+	1982.4	$5.44\text{e-}02 \pm 8.11\text{e-}03$
${}^{14}\text{C}$	5700 y	β^-	156.475	$8.42\text{e-}06 \pm 1.11\text{e-}06$
${}^{15}\text{C}$	2.449 s	β^-	9771.7	$1.21\text{e-}02 \pm 3.82\text{e-}03$
${}^{16}\text{C}$	0.747 s	β^-	7891.58	$1.21\text{e-}03 \pm 1.21\text{e-}03$
${}^{12}\text{N}$	11.000 ms	β^+	17338.1	$1.21\text{e-}03 \pm 1.21\text{e-}03$
${}^{13}\text{N}$	9.965 min	β^+	2220.49	$3.63\text{e-}03 \pm 2.09\text{e-}03$
${}^{16}\text{N}$	7.13 s	β^-	10419.1	$3.87\text{e-}02 \pm 6.84\text{e-}03$

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Isotope	Half life	Decay Mode	Q-value [keV]	Activity [cpd/(100 × tonne)]
¹⁷ N	4.173 s	β^-	8680	1.21e-02 ± 3.82e-03
¹⁸ N	624 ms	β^-	11916.9	1.21e-03 ± 1.21e-03
¹⁴ O	70.606 s	β^+	5143.04	1.21e-03 ± 1.21e-03
¹⁵ O	122.24 s	β^+	2754	2.06e-02 ± 4.99e-03
¹⁹ O	26.88 s	β^-	4819.6	1.09e-02 ± 3.63e-03
²⁰ O	13.51 s	β^-	2757.45	6.05e-03 ± 2.70e-03
¹⁷ F	64.49 s	β^+	2760.8	3.63e-03 ± 2.09e-03
¹⁸ F	109.77 min	β^+	1655.5	4.11e-02 ± 7.05e-03
²⁰ F	11.163 s	β^-	7024.53	3.99e-02 ± 6.95e-03
²¹ F	4.158 s	β^-	5684.2	1.57e-02 ± 4.36e-03
²² F	4.23 s	β^-	9543.42	2.42e-03 ± 1.71e-03
¹⁹ Ne	17.22 s	β^+	3238.4	2.42e-03 ± 1.71e-03
²³ Ne	37.24 s	β^-	4375.81	8.47e-03 ± 3.20e-03
²⁴ Ne	3.38 min	β^-	1994.39	4.84e-03 ± 2.42e-03
²¹ Na	22.49 s	EC	3547.6	8.47e-03 ± 3.20e-03
²² Na	2.6027 y	β^+	2842.3	1.99e-02 ± 3.03e-03
²⁴ Na	14.997 h	β^-	4146.78	8.34e-02 ± 1.00e-02
²⁵ Na	59.1 s	β^-	3835	3.99e-02 ± 6.95e-03
²⁶ Na	1.077 s	β^-	7503.27	3.63e-03 ± 2.09e-03
²³ Mg	11.317 s	EC	4056.1	1.21e-03 ± 1.21e-03
²⁷ Mg	9.458 min	β^-	1766.84	7.01e-02 ± 9.21e-03
²⁸ Mg	20.915 h	β^-	859.42	1.33e-02 ± 4.01e-03
²⁵ Al	7.183 s	β^+	4276.7	4.84e-03 ± 2.42e-03
²⁸ Al	2.2414 min	β^-	2862.77	2.23e-01 ± 1.64e-02
²⁹ Al	6.56 min	β^-	2406.31	1.40e-01 ± 1.30e-02
³⁰ Al	3.62 s	β^-	6325.68	2.78e-02 ± 5.80e-03
³¹ Al	644 ms	β^-	5205.97	2.42e-03 ± 1.71e-03
³² Al	33.0 ms	β^-	13020	1.21e-03 ± 1.21e-03
²⁷ Si	4.16 s	EC	4812.36	4.84e-03 ± 2.42e-03
³¹ Si	157.36 min	β^-	1491.5	2.33e-01 ± 1.68e-02
³² Si	153 y	β^-	227.2	1.26e-03 ± 1.15e-04
³³ Si	6.11 s	β^-	5845	1.69e-02 ± 4.53e-03
³⁴ Si	2.77 s	β^-	4592	1.21e-03 ± 1.21e-03
²⁹ P	4.142 s	EC	4942.5	2.42e-03 ± 1.71e-03
³⁰ P	2.498 min	EC	4232.4	1.08e-01 ± 1.14e-02
³² P	14.268 d	β^-	1710.66	6.52e-01 ± 2.79e-02

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Isotope	Half life	Decay Mode	Q-value [keV]	Activity [cpd/(100 × tonne)]
³³ P	25.35 d	β^-	248.5	$6.29\text{e-}01 \pm 2.72\text{e-}02$
³⁴ P	12.43 s	β^-	5382.96	$2.06\text{e-}01 \pm 1.58\text{e-}02$
³⁵ P	47.3 s	β^-	3988.4	$8.10\text{e-}02 \pm 9.90\text{e-}03$
³⁶ P	5.6 s	β^-	7122.1	$4.84\text{e-}03 \pm 2.42\text{e-}03$
³⁰ S	1.178 s	EC	6138	$1.21\text{e-}03 \pm 1.21\text{e-}03$
³¹ S	2.5534 s	EC	5398.02	$3.63\text{e-}03 \pm 2.09\text{e-}03$
³⁵ S	87.37 d	β^-	167.33	$9.74\text{e-}01 \pm 3.28\text{e-}02$
³⁷ S	5.05 min	β^-	4865.13	$2.87\text{e-}01 \pm 1.86\text{e-}02$
³⁸ S	170.3 min	β^-	2937	$8.95\text{e-}02 \pm 1.04\text{e-}02$
³⁹ S	11.5 s	β^-	5338.78	$1.21\text{e-}03 \pm 1.21\text{e-}03$
³⁴ Cl	1.5266 s	EC	5491.63	$7.98\text{e-}02 \pm 9.83\text{e-}03$
³⁸ Cl	37.230 min	β^-	4916.5	$1.71\text{e+}00 \pm 4.55\text{e-}02$
³⁹ Cl	55.6 min	β^-	3442	$2.61\text{e+}00 \pm 5.62\text{e-}02$
⁴⁰ Cl	1.35 min	β^-	7480	$5.35\text{e-}01 \pm 2.54\text{e-}02$
³⁵ Ar	1.7756 s	EC	5966.1	$3.63\text{e-}03 \pm 2.09\text{e-}03$
³⁷ Ar	35.011 d	EC	813.87	$1.48\text{e+}00 \pm 4.16\text{e-}02$
³⁹ Ar	269 y	β^-	565	$4.02\text{e-}02 \pm 4.84\text{e-}04$
⁴¹ Ar	109.61 min	β^-	2491.61	$2.23\text{e+}01 \pm 1.64\text{e-}01$
³⁸ K	7.636 min	EC	5913.86	$7.26\text{e-}03 \pm 2.96\text{e-}03$

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