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

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Two-phase liquid argon time projection chambers (LAr TPCs) are prime candidates for the ambitious program to explore the nature of dark matter. The large target, high scintillation light yield and good spatial resolution in all three cartesian directions concurrently allows also a high precision measurement of solar neutrino fluxes via elastic scattering. We studied the cosmogenic and radiogenic backgrounds affecting solar neutrino detection in a 100 tonne fiducial LAr TPC operating at LNGS depth. Such a detector has the potential to measure the CNO neutrino rate with 5 σ sensitivity, and to significantly improve the precision on the measured ^{7}Be and *pep* neutrino fluxes.

1 Introduction

The study of solar neutrinos has given a fundamental contribution to both astroparticle and elementary particle physics, offering an ideal test of solar models and, at the same time, relevant indications on the fundamental interactions among particles. Radiochemical (Homestake [1], GALLEX/GNO [2, 3], SAGE [4]) and real-time experiments (Kamiokande [5], SuperKamiokande [6], SNO [7] and Borexino [8]) have already measured the solar neutrino components from the ^{7}Be, ^{8}B, *pep*, and *pp* reactions, all belonging to the dominant mechanism for the energy production in the Sun: the proton-proton chain. At the same time, no neutrino from the ^{13}N, ^{15}O, and ^{17}F reactions, from the CNO cycle, has been yet observed. The CNO cycle has 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 solar-like stars. In addition, constraining the chemical composition of the Sun will improve astrophysical models like for star formation and Super Nova explosion.

CNO neutrinos may also solve the long-standing and well–known solar metallicity problem. The abundance of the heavy elements, Z (aka metals) in the Sun is a critical parameter in the SSM, since it affects the radiative opacity, and the boundary definition of the convective zone. In particular, abundances of oxygen, carbon, and nitrogen have a direct impact on the energy production of the Sun via the CNO cycle. The SSM predicts different neutrino fluxes if assuming either high–Z [9] or low–Z [10] chemical compositions in the Sun. The largest discrepancy in the prediction of solar neutrino fluxes resides in the CNO component: a measurement of the CNO neutrino flux at 10-20% accuracy has the potential to solve the metallicity problem.

The most stringent experimental limit on the CNO neutrino rate is from Borexino [8] using elastic neutrino-electron scattering. They obtained an upper limit for the interaction rate of

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}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}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 1: Expected solar neutrino rates in cpd/100 tonne of LAr active mass, comparing the low-metallicity [11] and high-metallicity [12] predictions using the Standard Solar Model and neutrino oscillation parameters from the MSW-LMA [13] region with $\Delta m^2 = 7.54{\times}10^{-5}$ eV^2 and $\sin^2(\theta_{12}) = 0.307$.

7.9 counts per day per 100 tonnes (cpd/100 tonne) at the 95% C.L., which corresponds to a flux limit of $<7.9{\times}10^{6}$ cm^{-2} s^{-1} [8]. Despite the contamination from ^{210}Bi in the active mass of Borexino is exceptionally low ($\sim$20 cpd/100 tonne), its spectral shape is very similar to the expected CNO signal, precluding a positive observation of CNO neutrinos.

Liquid argon (LAr) may represent the ideal target for measuring the CNO neutrino component from the Sun. LAr, in fact, is a powerful scintillator, 4-5 times brighter than organic liquid scintillators and, as a liquefied noble element, does not react and does not bond with chemical species. In addition, the use of a two-phase time projection chamber (TPC) technique can further abate the background. In a two-phase TPC, a thin gas layer above the LAr target volume converts the ionization electrons, once extracted and accelerated by an electric field, in a secondary light signal by gas proportional scintillation. LAr TPC can determine the position of energy deposit events in the liquid to within a few mm in the drift direction, and $\sim$1 cm or better in the two transverse directions, removing backgrounds from surfaces with a sharp definition of a fiducial volume. Moreover, the identification of multiple-Compton scatter events and other events having multiple energy deposition sites.

The overall solar neutrino-electron scattering rate expected in LAr is $\sim$150 cpd/100 tonne, as shown in table 1. However, the spectral range below 0.6 MeV is inaccessible due to the intrinsic contamination of ^{39}Ar, a β–decay (Q = 0.565 MeV) produced by cosmic ray spallation of $^{\mathrm{nat}}$Ar. Argon extracted from underground gas wells (UAr) has been shown by the Darkside collaboration to contain only $\sim$0.7 mBq/kg of ^{39}Ar [14]. But even this level would prevent extraction of solar neutrino signals in the low energy region, which is dominated by *pp* neutrinos. However, ^{7}Be neutrino interactions, whose Compton-like edge is expected at $\sim$0.66 MeV, would be accessible thanks to the excellent energy resolution achievable in LAr.

Assuming a light yield of 6,000 photoelectrons / MeV, as measured by MicroCLEAN [15], the number of expected CNO neutrinos, interacting via elastic scattering in 400 tonne$\times$year exposure of LAr and above 0.6 MeV, is between $\sim$900 and 1,300 events, depending on the metallicity model, as shown in figure 1. The main limitation to their detection is the background from *in situ* produced cosmogenic isotopes, radon emanated from the detector inner walls and distributed throughout the purification/recirculation loop, and from the external background. In the following sections, we will review the impact of each contaminant on the solar neutrino detection with a 100 ton fiducial mass two-phase LAr TPC .

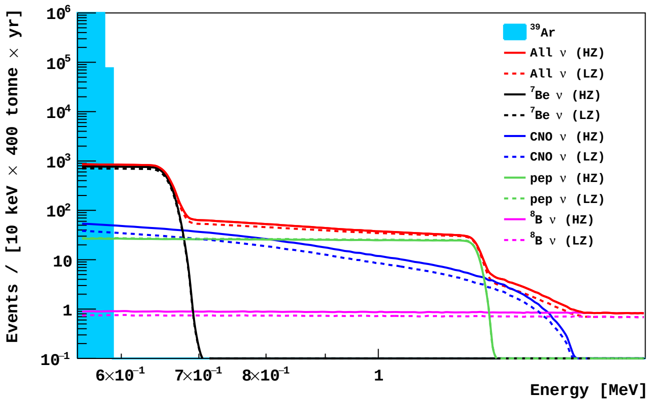

Figure 1: Simulated solar neutrino spectra in a 400 tonne-yr LAr TPC exposure, assuming σ =1.3% energy resolution at 1 MeV, corresponding to a PE yield of 6 PE/keV. The blue shaded area represents the tail of the ^{39}Ar contamination, intrinsic to underground LAr.

2 The background

The detector is assumed to be located at the Gran Sasso Laboratory, shielded by 1,400 m of rock. Despite the deep underground location, the residual muon flux may still produce measurable amounts of radioactive isotopes by muon–induced spallation on argon. These can produce dangerous, delayed electron-recoil background in the solar neutrino energy window. The cosmogenic radionuclide production was simulated with FLUKA assuming a cylindrical TPC of 3.3 m radius and 3 m height. 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 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 diamater) filled with water. Cosmic muons were generated 3 m above the cylindrical water tank, crossing 0.7 m rock layer, in order to fully develop the hadronic showers.

The simulation resulted in the production of more than 80 isotopes by muon spallation on argon, each of them handled by a GEANT4-based simulation, which generated decays and tracked the products in the full detector geometry. This allowed to estimate the efficiency of the multiple scattering cut. The predicted single scatter background induced by cosmogenic isotopes is evaluated in 0.733 cpd/100 tonne a factor ∼7 lower than the overall neutrino signal in the energy region of interest between 0.7 and 1.3 MeV. The dominant contribution comes from ^{32}P, ^{38}Cl, and ^{32}P, with a decay rate of 0.332, 0.147, and 0.106 cpd/100 tonne respectively [16].

The external background contribution is due to radioactive contaminants in the detector materials. The largest contributions are expected to have origin in the photosensors and in the cryostat. Gamma-rays are the only events able to reach the active mass and to produce

a signal that can mimic a neutrino event. The strategy to abate this class of background is primarily based on the multiple scattering cut and on the fiducialization of the active volume. We estimated that the attenuation lengths for γ's induced by ^{40}K, ^{214}Bi, and ^{208}Tl originating in the photosensors are of the order of $\sim$4 cm. As a consequence, a 30 cm cut from the TPC walls in combination with the multiple scattering cut, would reduce such contamination by a factor $\sim 10^6$.
In the present work we assume 2 mm thick silicon photomultipliers (SiPM) as photosensors, on the top and bottom of the TPC, corresponding to $\sim$300 kg of silicon. A recent measurement by I. Ostrovskiy *et al.* [17] quoted an overall contamination in SiPM from ^{40}K, and the ^{238}U and ^{232}Th smaller than 0.1 mBq/kg. In the here–proposed detector, this activity corresponds to an upper limit of 30 mBq. After the selection cuts, the external background contribution from the SiPM's of $\sim 2.6\times 10^{-3}$ cpd/100 tonne, negligible with respect to the solar neutrino rate.
The dominant contribution for the external background is expected coming from the cryostat, whose mass is of the order of the tonne–scale. Stainless steel cryostats are contaminated in ^{60}Co at the level of tens of mBq/kg. The correspondent activity in the LAr target was estimated to be of the same order of the solar neutrino interaction rate in the energy window of interest, assuming a fiducial volume of 30 cm from the TPC walls. 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 [18]. Further, an external active veto as in DarkSide-50 [19] would further reduce the ^{60}Co background by vetoing events with ^{60}Co gammas detected in coincidence by the TPC and the veto. In the sensitivity study described in this work, we then assume negligible the background from external sources.

Contamination of the target argon mass by ^{222}Rn represents the most critical background for the solar neutrino measurements. ^{222}Rn can be emanated into the active argon from the TPC materials in contact with the LAr target and/or distributed throughout the LAr fill by the recirculation loop. The main goal of this work is to evaluate the maximum contamination of ^{222}Rn not preventing the CNO neutrino measurement. In particular, only the ^{214}Pb and ^{214}Bi isotopes of the ^{222}Rn decay segment can provide a signal that could mimic the neutrino one. In fact, α's can be efficiently discriminated by the use of the LAr scintillation pulse shape discrimination, which has a rejection power at the 10^7–10^8 level [20]. β–decays with simultaneous emission of γ-rays produce multi-site energy deposits, that can be identified and rejected by means of the multiple scattering cut. The simulations indicate that only 6.9% (5.9%) of ^{214}Pb (^{214}Bi) decays will produce a single site deposit in the solar neutrino energy region. However, despite most of the ^{222}Rn induced events can be rejected, the residual contamination represents a serious background: we estimated that 45 μBq/(100 tonne) of ^{222}Rn contamination would introduce a background rate equivalent to the expected solar neutrino signal. The overall spectrum, including all the contaminations, is shown in figure 2.

3 Sensitivity study

The measurement of the rate of each solar neutrino component relies on the identification of the individual spectral shapes. To study the sensitivity of a large LAr TPC we exploited a toy Monte Carlo approach. The data sample was produced by generating the neutrino signal and the background components discussed in the previous section, assuming a 400 tonne$\times$yr statistics. The data sample was generated for each metallicity model and for a given radon

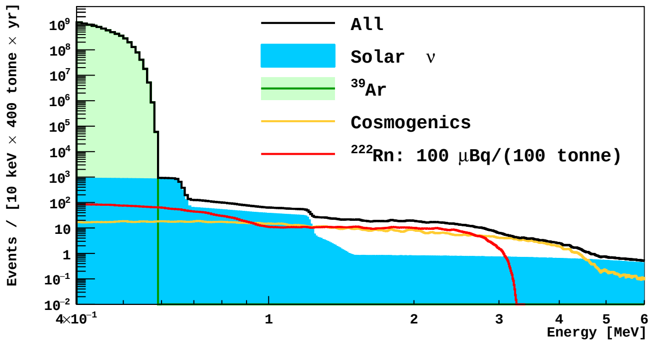

Figure 2: Components of the electron recoil energy spectrum, simulated for a 4 year exposure of 100 tonnes of LAr (see legend), assuming a radon contamination in LAr of 100 μBq/(100 tonne) .

contamination, and then fitted with an analytical model. The procedure was repeated 10,000 times for each set of parameters. An example of fit is shown in figure 3

The cosmogenic spectrum was observed to be rather flat after the multiple scattering cut, with the exception of the contribution from ^{32}P, as shown in figure 3. Cosmogenics have been then modeled with a linear energy function plus the beta shape from ^{32}P. The systematics associated to this model choice was deeply investigated and, as shown in reference [16], can be assumed negligible.
The CNO spectral shape is similar to that of the low energy radon component. At radon contamination levels above 200 μBq/(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 systematic deviations were observed for ^{7}Be and *pep*, whose spectral shapes have clear characteristic features.

4 Conclusions

The final results are summarized in figure 4. Assuming to be able to contain the radon contamination below 200 μBq/(100 tonne), a LAr TPC with an exposure of 400 tonne×years exposure, has the power to observe (>5 σ) CNO neutrinos and to measure ^{7}Be and *pep* neutrinos with a statistical accuracy of ∼2% and ∼10%, respectively. At the same time, the associated systematics connected to the definition of the fiducial volume and to the determination of the energy scale were evaluated to be less than 1%, thanks to the exception resolution in the position reconstruction and to the light yield, more than 10 times larger than in an organic liquid scintillator (more details can be found here: [16]).
In conclusion, a large volume LAr TPC, designed for direct dark matter WIMP search, has also the potential to experimentally observe the CNO neutrinos from the Sun, and, more in general, to provide a rich set of physics results for solar neutrinos.

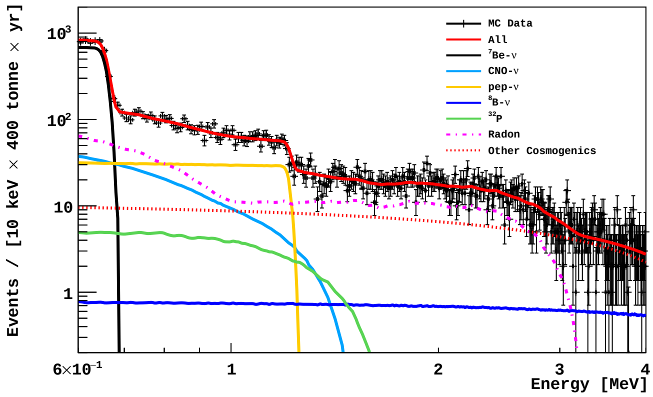

Figure 3: Example of simulated spectra and fit, assuming radon contaminations of 100 μBq/(100 tonne), assuming the low–metallicity SSM The cosmogenic component is modeled with a first degree polynomial, with the exception of an explicit spectrum for ^{32}P.

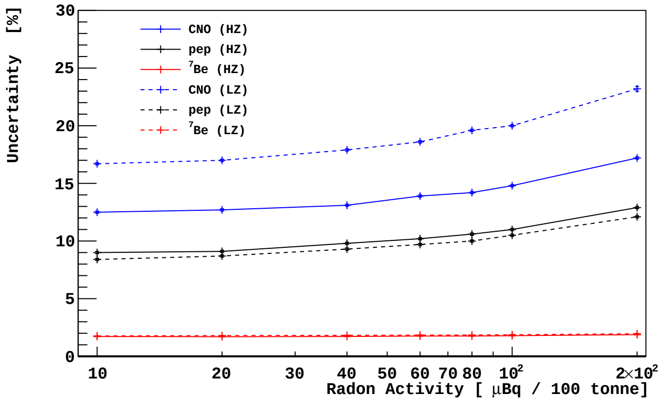

Figure 4: Statistical uncertainties on the solar neutrino components, as a function of the radon activity.

5 Acknowledgments

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