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SciPost Phys. Proc. 12, 032 (2023)

Background suppression in the COSINUS experiment: Active muon veto and radiopure materials selection

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14th International Conference on Identification of Dark Matter
Vienna, Austria, 18-22 July 2022
doi:10.21468/SciPostPhysProc.12

Abstract

For over twenty-five years the DAMA/LIBRA experiment has reported an annual modulation signal that is consistent with a dark matter explanation. This signal is, currently, in tension with the null results observed by other searches that utilize different target detectors. The COSINUS experiment will perform a model-independent cross-check of the DAMA/LIBRA result by using the same target material, NaI crystals, operated as scintillating calorimeters. By measuring both temperature and light the NaI crystals in COSINUS will be able to distinguish between electron and nuclear recoils on an event-by-event basis. However, background events induced by cosmic-rays, environmental radioactivity or the intrinsic contamination of the materials used in the crystal, shielding and infrastructure can pose an issue to any analysis and must be fully understood. We report on the status of the development of the simulation for an active water Cherenkov muon veto, as well as the results of the beginning radiogenic material screening.

Received 27-09-2022
Accepted 28-04-2023
Published 04-07-2023
doi:10.21468/SciPostPhysProc.12.032

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1 Introduction

The particle nature of dark matter is one of the largest unsolved mysteries in particle-astrophysics. It is responsible for 26% of the mass-energy content of the universe and its existence is evident through the gravitational impact it has on astronomical observations [1]. Over the past twenty-five years the DAMA/LIBRA (formerly DAMA/NaI) experiment [2–5] has observed an annual modulation signal that is consistent with a dark matter explanation. However, in a standard halo scenario, the signal is contradicted by the null-results of numerous experiments that utilize a different target material [6]. In order to perform a truly model-independent investigation of the DAMA/LIBRA result an experiment with the same target material is required. Planned or currently active experiments of this type include: SABRE [7], PICO-LON [8], COSINE [9], ANAIS [10] and the focus of this work COSINUS.

The COSINUS (Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches) experiment [11–14] will use NaI crystals operated as cryogenic scintillating calorimeters to cross-check the DAMA/LIBRA result. These detectors will be cooled to milli-Kelvin temperatures and provide a measurement of both the phonon and light signal caused by particle interactions. This allows differentiation between nuclear recoils (from large neutral particles such as dark matter or neutrons) and electron recoils (charged particle backgrounds and photons) on an event-by-event basis. Phonon data directly from the NaI crystals will be readout using the novel *remoTES* setup [15] and the crystals will be surrounded by a silicon detector to absorb the scintillation light. This is the first cryogenic measurement of NaI detectors used for a dark matter search.

Construction of the experimental apparatus has begun in Hall B at the INFN Gran Sasso National Laboratory (LNGS) and physics data taking is expected to begin around the summer of 2023. The experiment consists of a dry dilution refrigerator housing the target crystals surrounded by a large tank filled with ultra-pure water. Further details about the experimental setup can be found in Ref. [14]. The first phase, called COSINUS-1π, aims for an exposure of 100 kg·days which, if the design threshold stated in Ref. [16] is achieved, will exclude a spin-independent dark matter scattering off Na and/or I as an explanation of the DAMA/LIBRA result. The second phase, called COSINUS-2π, will aim to achieve 1000 kg·days exposure for a fully model-independent cross-check of a nuclear-recoil origin of the DAMA/LIBRA signal.

It is important for the COSINUS experiment that environmental, material and cosmogenic backgrounds be reduced as much as possible. Neutrons interacting in the target crystal can mimic a dark matter recoil signal and is one of the most dangerous types of backgrounds. As well, at low energies the discriminating power of the COSINUS experiment is weaker and gamma radioactivity must be properly accounted for. In Ref. [14], a study of passive shielding configurations was performed to optimize the design of the COSINUS experiment to significantly reduce the flux of ambient and radiogenic neutrons and gammas. This study also showed that the passive shielding is insufficient for handling the background from cosmogenic neutrons, and thus an active water Cherenkov veto is required for the removal of these muon-induced events. Section 2 details the current results of a simulation program whose goal is to optimize the detector parameters (photomultiplier (PMT) arrangement, trigger conditions and dead layer optimization) to maximize the muon detection efficiency. Additionally, the intrinsic radioactive contamination of the NaI crystals and materials within close proximity will be create a background regardless of shielding. Careful material selection is then required to reduce the background contribution from these materials. Section 3 details the material assay results of selected, important materials. Finally, section 4 will detail future goals of the work presented herein.

2 Active water Cherenkov muon veto

Cosmogenic neutrons can be produced through muon-induced spallation processes or from hadronic or electronic cascades generated from muons. As shown in Ref. [14] these neutrons will be the dominant contribution to the COSINUS nuclear recoil background and an active Cherenkov muon veto is required to reduce this rate. As a charged particle enters the water tank, if the velocity of that particle is faster then the speed of light in that volume, Cherenkov radiation will be produced. The veto system will employ an arrangement of PMTs along the bottom and side of the water tank to detect this radiation and allow for the muon event to be tagged.

The optimization of the muon veto design is being performed through a detailed Monte Carlo simulation based on GEANT4 [17, 18] version 10.2.3. and ImpCRESST [19]. The goal of this study is to evaluate attainable veto efficiencies by testing different trigger conditions of the detector. The geometry that was used was a simplified version of option 4 from Ref. [14]. A reflective foil (95% reflectivity) on the inner surface of the tank was added and the optical package of GEANT4 was implemented.

To acquire the energy, flux, position and angular distribution of muons entering the water volume at the underground laboratory a simulation using the MUSUN [20] code was performed. The output of the MUSUN code on a cuboid of $12\times12\times13$ m^3 generated a muon flux of 2.3×10^6 $year^{-1}$, with an average energy of 270 GeV. This result profile was then used to generate thirty-million muons that impinge on the COSINUS geometry. To ensure proper account of particle showers each muon must traverse 2.5 m of rock shielding placed around the detector. As optical simulations are computationally time intensive only muons that create a neutron that makes it into the dry-well,[1] called *dangerous events*, are simulated with the optical package on. For the purposes of this work 1000 of these dangerous events were simulated on the COSINUS geometry.

Neutron events were classified into *muon events*, which are generated from a muon crossing the water tank, and *shower events* where the neutrons alone or with some electromagnetic shower cross the water tank. For each of these type of events a photon hit map can be created around the surface of the water tank. Fig. 1 shows the photon map of the bottom of the water tank for 949 muon events and 51 shower events. The binning is chosen to be equivalent to the surface area of a 20 cm diameter PMT, about which 28 are likely to be deployed by COSINUS. The black squares in Fig. 1 represent an example scenario where 18 PMTs are placed along the bottom of the water tank. Additionally, in this scenario 10 PMTs are placed in two evenly

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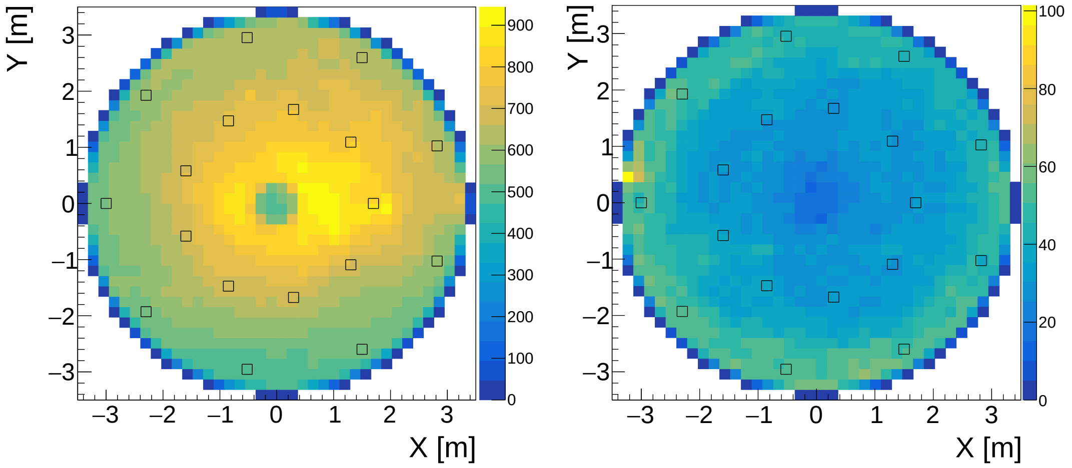
[1] Stainless steel tube, 70 cm in diameter, in the centre of the water tank that contains the cryostat and detectors.



(a)

(b)

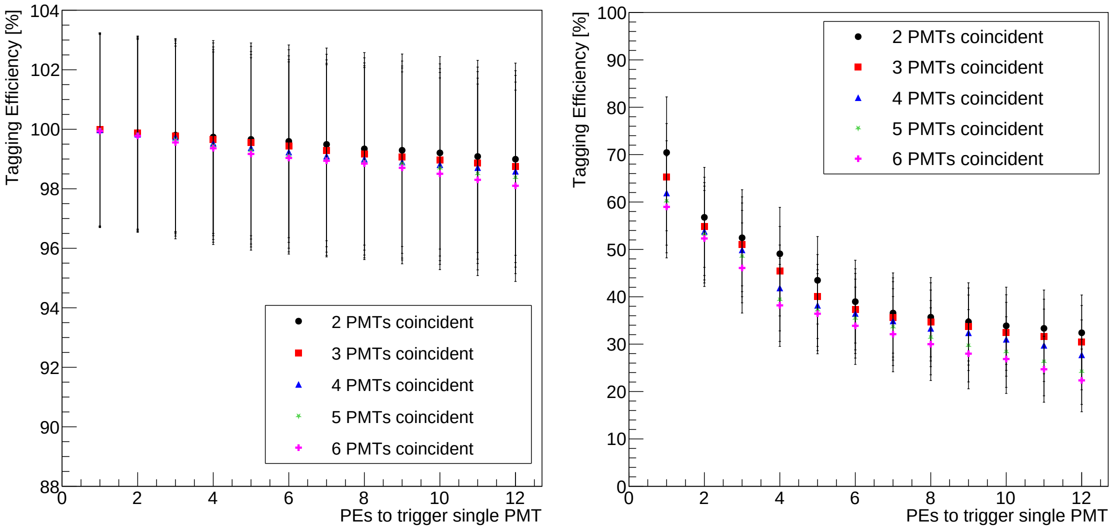
Figure 1: Photon illumination map of the bottom of the COSINUS water Cherenkov detector for (a) Muon and (b) Shower events. The black squares represent a potential placement of PMTs. The color band is the average number of photons produced per muon event and the binning was selected to match a PMT window of 324 cm^2.

spaced rows along the wall of the water tank but the photon maps are not shown here. Fig. 1 shows that shower events do not penetrate far into water tank while muon events create a large amount of light. These distinguishing patterns can be used to optimize PMT placement to maximize veto efficiency. For example, the shower events will have a higher chance of being detected by PMTs that are placed closer to the wall of the tank.

The veto efficiency was evaluated for the PMT arrangement presented above. A flat quantum efficiency of 30% was assumed, based off Hamamatsu R5912-100 PMTs [21], along with a 90% collection efficiency. A PMT is considered triggered if the number of photons that impinge on the given surface area and pass the efficiency cuts surpass the set photoelectron threshold. An event is considered vetoed if the number of PMTs that trigger during an event equal or exceed the required amount. Fig. 2 shows the veto efficiency for muon and shower events under different trigger conditions. The error bars in the figure correspond to the statistical uncertainty. Muon events show an almost 100% veto efficiency that is relatively independent of the trigger conditions. This is expected from the large amount of Cherenkov radiation they create. The veto efficiency of the shower events is significantly lower at ∼60% and can reduce to less then 30% depending on the trigger conditions. The optimization of the shower event efficiency through different PMT arrangement is a primary goal of these simulations.

3 Material assay

A detailed material assay program has begun on important components used in the COSINUS experiment. Presented here are selected results for stainless steel, copper and astrograde NaI powder. The stainless steel is the holder for the cryostat in the water tank known as the dry-well. The copper is a measurement of cleaned samples from Poligrat and is used as shielding in the COSINUS cryostat, see Ref. [14]. The NaI astrograde powder is from the MERCK company which will be used by SICCAS to grow the crystals. Both high purity germanium (HPGe) and High resolution Inductively Coupled Plasma Mass Spectrometry (HR-ICP-MS) measurements were performed at the STELLA (SubTErranean Low Level Assay) [22] and Chemical



(a)

(b)

Figure 2: Veto efficiency of the COSINUS water Cherenkov detector for (a) Muon and (b) Shower events. Efficiency is shown as a function of photoelectron threshold and by the number of PMTs required to trigger.

Table 1: Material screening results of selected elements of the COSINUS experiment. All units are in mBq/kg unless otherwise stated. For the HPGe measurements upper limits are given with a 95% C.L. and uncertainties with 68% C.L. For the HR-ICP-MS evaluation the upper limit is defined as three times the standard deviation of a blank measurement.

Material	Method	^{232}Th		^{238}U			^{235}U	^{40}K
		^{228}Ra	^{228}Th	^{226}Ra	^{234}Th	^{234m}Pa		
Stainless Steel	HPGe	< 1.1	< 1.3	0.9(4)	< 84	< 26	< 1.5	< 5
Copper	HPGe	< 0.2	< 0.11	0.15(4)	< 7.2	< 3.8	< 0.14	< 1.7
NaI Powder	HR-ICP-MS	Th: < 10 ppt		U: < 10 ppt				< 15 ppb

services plant at LNGS respectively. The results of the measurements are shown in Table 1. The stainless steel was found to be adequate and ultimately was used for the construction of the dry-well. The copper was found to be too contaminated and alternative products and cleaning methods will be utilized. The ^{40}K content of the NaI powder was found to be consistent with the DAMA/LIBRA experiment [2]. These results represent the beginning of a material assay program that will be continued to inform the selection of materials for the COSINUS experiment.

4 Conclusion and future work

For dark matter searches, understanding the backgrounds involved in the experiment is of upmost importance. In this work we have a simulated a water Cherenkov muon veto that will be used to reduce the cosmogenic neutron backgrounds. Current simulations show that a veto efficiency of >99% for muon events and 60(12)% for shower events is achievable for the COSINUS experiment. Future work will simulate a higher number of muon events in order to reduce the statistical uncertainty and these high statistics simulations will test multiple configurations of PMTs to optimize the veto efficiency. It is known that ambient and radiogenic gammas will contribute to the overall PMT trigger rate and as they do not correspond to any muon events they act as false positive signals. Future simulations will include these events in order to study placing the PMTs away from the water tank walls, creating an effective dead layer, and how this dead layer will effect overall veto efficiency power and trigger rate. Finally, this work has also discussed the commencement of a material screening program that is being carried out for different materials in COSINUS. This program will allow for stringent selection and placement of low background materials in the experiment and the results are expected to provide input for the upcoming COSINUS Monte Carlo simulations and sensitivity estimates.

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