TECHNICAL REPORT

Muon detector for the COSINE-100 experiment

The COSINE-100 collaboration

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Abstract: The COSINE-100 dark matter search experiment has started taking physics data with
the goal of performing an independent measurement of the annual modulation signal observed
by DAMA/LIBRA. A muon detector was constructed by using plastic scintillator panels in the
outermost layer of the shield surrounding the COSINE-100 detector. It detects cosmic ray muons in
order to understand the impact of the muon annual modulation on dark matter analysis. Assembly
and initial performance tests of each module have been performed at a ground laboratory. The
installation of the detector in the Yangyang Underground Laboratory (Y2L) was completed in the
summer of 2016. Using three months of data, the muon underground flux was measured to be
$328 \pm 1\text{(stat.)} \pm 10\text{(syst.)} \text{muons/m}^2/\text{day}$. In this report, the assembly of the muon detector and the
results from the analysis are presented.

Keywords: Large detector systems for particle and astroparticle physics; Dark Matter detectors
(WIMPs, axions, etc.); Particle identification methods

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1 Introduction

When a primary cosmic ray particle interacts with a molecule in the atmosphere, a shower of energetic hadrons including pions ($\pi^\pm$) and kaons ($K^\pm$) are generated. They quickly decay and produce relativistic muons [1, 2] that are highly boosted with a lifetime long enough to reach the surface and deep underground laboratories. Therefore, they can be a significant background source in underground physics experiments. Because muons can produce spallation neutrons that can produce detector signals and mimic those from dark matter particles, it is essential to understand muon and muon-induced events in direct dark matter search experiments [3, 4].

Phenomena attributed to dark matter could be explained as being due to the effects of previously unseen particles such as weakly interacting massive particles (WIMPs), which are strongly motivated by theory [5, 6]. Numerous experiments have searched for WIMPs by directly detecting nuclei recoils from WIMP-nucleon interactions in low background detectors located deep underground [7–9]. A positive signal of annual modulation would be a signature for dark matter due to changes in its relative motion of against the Earth orbits the Sun in the galaxy cluster. Among various dark matter search experiments, the DAMA/LIBRA experiment using a NaI(Tl) crystal array [10–12] is extremely interesting because an annual modulation was observed, which can be interpreted as WIMP-nucleon interactions [13].

Because of annual variations of temperature and density in the atmosphere, it is well known that the muon rate is modulated annually [14–16]. This fact motivated the consideration of muons as a possible source to explain the DAMA/LIBRA signal [17–19]. However, this possibility remains unresolved because there is a phase difference between the muon and the WIMP-induced modulations [20], and the rates for muon-induced neutrons predicted in simulation-based studies [21, 22] are too low to explain the modulation observed by the DAMA/LIBRA experiment.

The COSINE-100 experiment is a collaboration between the Korea Invisible Mass Search (KIMS) [23–25] and DM-Ice [15, 16] experiments to confirm or refute the annual modulation signal observed by the DAMA/LIBRA experiment. The COSINE-100 experiment was commissioned and has been taking physics data since September 2016 with a 106 kg array of low-background NaI(Tl) crystals in the Yangyang Underground Laboratory (Y2L) in Korea [26]. One of its features is the outermost plastic scintillator panels surrounding the main detector, which are used to tag muon events. In this paper, the assembly and the initial performance of the muon detector are described as well as a measurement of the cosmic ray flux.
The muon detector for COSINE-100 consists of 37 panels of 3-cm thick Eljen EJ-200 plastic scintillator. Twenty seven of the panels are 40 cm wide, ten are 33 cm wide in order to fit into the shielding structure. The array forms a near cubic structure with sides labeled as top, bottom, front, back, left, and right. The top-side panels are 282 cm long and are read out by a photomultiplier tube (PMT) at both ends. The panels on the other sides are approximately 200 cm long and their signals are read out by one PMT. Table 1 lists dimensions of the muon panels for the six sides. Each panel is polished and coupled to an acrylic light guide using BC-600 optical cement from Saint-Gobain. Two-inch H7195 PMTs from Hamamatsu Photonics are mounted with the optical cement at the end of the light guides. The optical coupling was visually inspected, as shown in figure 1 (a). To increase the light collection, a Vikuiti reflector film is attached with optical grease at one end of the scintillator for the 200-cm-long panels. The muon panels are wrapped with a TYVEK reflector to collect light efficiently, as shown in figure 1 (b). Then, the panel is covered with a 50-µm-thick aluminum foil [figure 1 (c)] and a black vinyl sheet [figure 1 (d)] to prevent external light from leaking inside and physical damage. A schematic of the muon panel used for the left or right side is shown in figure 2.

![Figure 1. Assembly procedure of the plastic scintillator panels. (a) The light guide with PMT is attached with BC-600 optical cement. (b) A panel is being wrapped with a TYVEK reflector. (c) A panel is being wrapped with an aluminum foil. (d) Muon panels stacked after being wrapped with a black vinyl sheet.](image)

Various tests were performed with the muon panels in a ground laboratory where the cosmic ray muon flux is reasonably high. A small trigger counter made of the same plastic scintillator was placed above the muon detector panel as shown in figure 3. Coincident signals from the muon panel and the trigger counter are used to select muon candidates. With a sufficiently high energy threshold for the signals in the trigger counter, muon candidate events in the panel can be selected as shown in figure 4 (a). The muon candidate signals in the panels are well modeled by a Landau distribution.  

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1http://www.eljentechnology.com.  
2http://www.crystals.saint-gobain.com.  
3http://www.hamamatsu.com.
| Position | Length (cm) | Width (cm) | Thickness (cm) | Panels | PMTs |
|----------|-------------|------------|----------------|--------|------|
| Top      | 282         | 40         | 3              | 5      | 2    |
| Front    | 205         | 40         | 3              | 5      | 1    |
|          | 207         | 33         | 3              | 2      | 1    |
| Back     | 202         | 40         | 3              | 5      | 1    |
|          | 202         | 33         | 3              | 2      | 1    |
| Right    | 204         | 40         | 3              | 5      | 1    |
| Left     | 204         | 40         | 3              | 5      | 1    |
| Bottom   | 207         | 33         | 3              | 6      | 1    |
|          | 205         | 40         | 3              | 2      | 1    |

Table 1. Plastic scintillator panels in the muon detector for the COSINE-100 experiment.

Figure 2. Schematic view of a right or left muon panel with assembly parts.

Figure 3. Experimental setup to test the performance of the muon panels.

The most probable value (MPV) of a Landau function fit to the distribution is used to estimate the relative light collection efficiency of each panel from muons and found to be approximately 250 photoelectrons with 20% panel to panel deviations. To study the position dependence of the light collection, the trigger counter was placed in three different positions: 15 cm (the closest), 102 cm (center), and 189 cm (the farthest) from the PMT. As shown in figure 4(b), the light collection strongly depends on the distance between the muon hit and the PMT; the maximum difference in the light collection was 45%. Nonetheless, muon candidate events far from the PMT were well separated from background events. The muon selection threshold for each panel is determined from the data accumulated at the lowest light yield location.
\[ \chi^2 / \text{ndf} = 82.61 / 71 \]

| Constant | 14.9 ± 267.8 |
|----------|--------------|
| MPV      | 97.5 ± 8637  |
| Sigma    | 53.7 ± 1189  |

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Figure 4. (a) Muon candidate events selected by the trigger counter and modeled by a Landau distribution. (b) Position-dependent charge distributions from three different trigger positions for a 204 cm long muon panel.

Figure 5. Schematic view of the muon tagging efficiency setup.

Figure 6. (a) Charge distributions of the two trigger panels in the setup of figure 5. Charge distributions of channel 3 (b) and channel 4 (c) after applying muon selection requirements for channel 1 (>4800) and channel 2 (>5400).

To estimate the muon detection efficiency as well as measure the muon flux, four panels were stacked as shown in figure 5. A trigger for muon candidate events requires coincident signal in top (channel 1)–bottom (channel 2) pair. When the trigger condition is satisfied, data are recorded from all four channels. If muons are passing through the top-bottom pair, these muons should also pass the middle two panels. An offline selection signal threshold for muon candidates is applied for the top and bottom panels to remove the environmental \( \gamma \)-or \( \beta \)-induced backgrounds as shown in figure 6 (a). The charge distributions of the middle two panels after the offline selection cuts to the top and bottom panels are shown in figures 6 (b) and 6 (c). A total of 425,824 events are selected.
as muon candidates from the top-bottom pairs. From this result, muon detection efficiency for the muon panels is measured approximately to be 99.6%; the 0.4% loss could include a systematic uncertainty due to minor misalignments of the panels. Muon candidate events selected by coincident signals from the two middle panels are used to estimate the muon flux at the ground laboratory, which is $136 \pm 7$ muons/m$^2$/s.

2 Underground measurement

After the ground laboratory measurement, the muon panels were subsequently installed in the COSINE-100 room at Y2L as an active muon shield. The entire array of 37 panels surrounds the detector with a full $4\pi$ solid angle coverage. The general layout of the COSINE-100 muon detector and a photograph of the installed detector are shown in figure 7.

![Figure 7](image)

Figure 7. (a) Schematic of the COSINE-100 shielding structure, (b) Photograph of the installed muon detector captured from the corner between the front and the right side.

A total of 42 PMT signals are digitized by charge-sensitive 62.5 Megasamples per second (MS/s) ADCs from Notice Korea that are called SADC. One SADC module contains 32 channels with field-programmable gate arrays for signal processing and trigger generation. The dynamic range is 2 V with 12-bit resolution. Two modules are dedicated for muon detection. The SADC continuously calculates the integrated charges using a 192 ns integration time window with 16 ns time bin. The trigger thresholds are set to be approximately one-third of the typical muon selection threshold. At least two PMTs from independent panels should exceed the trigger threshold at 4000 ADC within a 400 ns coincident time window. If this trigger condition is satisfied, each SADC channel records the maximum value of the 192 ns integrated charges and its time position within a $4\mu$s search window (a range of approximately $-2$ to $2\mu$s from the trigger position). Information for the six sides is calculated by combining the information of the panels constituting each side. The charges of all panels from one side are added for a given side, but the timing is selected from the one which has the maximum charge.

http://www.noticekorea.com.
Muon fluxes in underground laboratories show significantly reduced rates [27]. Because the surviving muons at deep underground places still have high energies, most of the muons penetrate through all of the detector materials while leaving relatively large energy depositions. Energetic muons should deposit energies that are greater than the minimum ionization energy, which is approximately 6 MeV for a 3-cm-thick plastic scintillator [2] and is much larger than the typical γ or β energies produced by environmental background components. In addition, because the muon detector provides 4π coverage of the COSINE-100 detector, muon signals can be observed in at least two sides of the detector. Therefore, muon candidate events can be selected according to their energy deposits and coincidence requirements.

The two-dimensional charge distribution of coincident events on two sides are analyzed. As an example, a scatter plot from the top and bottom sides is shown in figure 8 (a). Time differences (ΔT) between the bottom-side and top-side signals are shown in figure 8 (b), where muon candidate events exhibit a clear coincidence, while the γ/β background events have a random distribution as shown in figure 8 (c). On the basis of the time correlation observed for the muon candidate events, an additional selection criterion of ΔT is applied containing a 5σ range of signal events, in this example \(-100 \text{ ns} < \Delta T < 115\) ns as shown in figure 8 (b).

![Figure 8](image_url)

**Figure 8.** (a) A scatter-plot of the signal distributions for top- and bottom-side coincident events. The red lines represent the selection criteria for muon candidate events. Time differences (ΔT) between top-side and bottom-side hits for muon candidate events (b) and non-muon candidate events (c).

Using the ΔT distribution of the signal events, the background contamination in the signal region can be estimated. The number of events outside the signal region (\(-200 \text{ ns} < \Delta T < -100 \text{ ns}\) or \(115 \text{ ns} < \Delta T < 215 \text{ ns}\)) is counted in figure 8 (b). Considering the background distribution in figure 8 (c), the background contamination in the signal region is calculated to be 0.2%.

The muon selection criteria discussed above were applied to determine the charge distribution of the top-side panels. Here, the muon selection threshold for the top side is ignored to reveal the background shape as shown in figure 9. Muon candidate events are fitted with the expected signal shape, Landau distributions, together with an exponential background component. Because the muons induce spallation that makes multiple hits on the top-side, two Landau distributions are considered for signal modeling. From this fit, the background contribution in the signal region can be estimated as approximately 0.3%, which is consistent with the background contamination rate estimated with the ΔT distribution. Furthermore, the muon selection efficiency was estimated to be 99.9 ± 0.1% when the charge threshold cuts mentioned previously are applied. A similar muon selection technique is applied for all pairs of different sides to tag muon candidate events.
Figure 9. The charge spectrum of muon candidate events in the top-side panels with the charge threshold trigger requirement relaxed. An exponentially decaying background component and Landau-function shaped muon signal component is used to model the data. Here we consider two Landau functions to take into account events with two hits, visible by the second peak around $44 \times 10^3$ ADC counts. The fit results indicate that the normally required threshold for the top-side charge rejects a negligible number of signal muon events (<0.1%).

The muon flux at the COSINE-100 experimental site is determined from all of two-side hit events including signals in the top-side panel array. A muon event with hits in more than two sides are also counted as a single muon event. To normalize the muon rate, the effective area of the top-side is calculated as $A_d = 5.48 \pm 0.16 \text{m}^2$, where the uncertainty reflects the area of the top-side panels that extend beyond the sides of the array and its muon tagging is not fully active. This uncertainty is expected to be reduced with simulation-based studies.

A total number of 144,325 muon candidate events ($N_\mu$) were observed during a period of approximately three months. Because the non-muon contribution is negligible, the muon flux $\Phi_\mu$ can be calculated as follows:

$$\Phi_\mu = \frac{N_\mu}{t_d \cdot A_d \cdot \epsilon_\mu},$$

(2.1)

where $\epsilon_\mu$ is the muon selection efficiency, and $t_d$ is the total data acquisition time. This returns a measured muon flux at the COSINE-100 experimental site of $328 \pm 1 \text{(stat.)} \pm 10 \text{(syst.) \text{muons/m}^2\text{/day}}$, where the systematic uncertainty is dominated by the top-side area calculation. This is slightly higher than that at the KIMS experimental site [28], which is consistent with an expectation based on the surface geometry of the Y2L and an approximately 200 m horizontal distance between two sides. This rate is approximately $2.8 \times 10^{-5}$ times the muon rate of the ground laboratory measurement. The muon rates measured during a three-month period were very stable as shown in figure 10. A muon-induced event study with the NaI(Tl) crystals has started while the data taking is ongoing.
3 Summary

An array of plastic scintillator muon counters was installed around the outer detector shielding of the COSINE-100 experiment. The purpose is to tag and study the correlations between crystal and muon events that can mimic WIMP-like signals. Several tests were performed to validate the performance of the detector. The muon selection efficiency was found to be 99.9 ± 0.1 %, with only approximately 0.3% fake muon events. This detection efficiency is sufficient for the COSINE-100 experiment. Using three months of data, the muon flux at the experimental site was measured to be 328 ± 1(stat.) ± 10(syst.) muons/m²/day. Currently, data acquisition is ongoing to obtain sufficiently large statistics for the modulation analysis.

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