nature portfolio

Peer Review File

Upgrading the COSINE-100 Experiment for Enhanced Sensitivity to Low-Mass Dark Matter Detection

Corresponding Author: Dr Hyun Su Lee

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This paper provides a detailed description of how the COSINE-100 experiment was decommissioned and the parts reused for an upgraded experiment, COSINE-100U, in the new Yemilab underground lab. The procedure for preparing the COSINE-100 crystals for re-use, and the new improved encapsulation design, are carefully explained, followed by the qualification tests done to characterise the new crystal assemblies.
The improvement to the crystal lightyield is substantial, and no significant radioactive impurities seem to have been introduced during the refurbishing. Together with the placement of the experiment in a lab with better muon shielding, and improved operating conditions, this will allow the new experiment to perform a competitive search for light WIMPs, in addition to the continued test of the DAMA/LIBRA claim.
The upgrade procedure and the performance of the crystal assemblies is of interest to the community, so are the projections for the WIMP sensitivity.

A number of comments/suggestions regarding specific parts of the text follow:
L82: I was confused about what ‘crystal-6’ meant until reading the next section. Maybe you can explain here already that there are 8 crystals of slightly different dimensions, as shown in Tab 1, and that you will be using the crystal labelled C6 as an example.
L96: grammar - eliminating, minimising
Fig1: The teflon wrapper is not shown?
Tab 1: The light yield is abbreviated as PEs/keV in the table and NPE/keV in the text (L98). I think it is common to just use “PE/keV”. Any way, please chose a consistent label (also for later in the text)
L206: the part of the comma doesn’t really fit into the sentence unless the LY with the old encapsulation is also given. However, since the table has all the numbers, it would suffice in the text to just leave out the part “from the mean … C6”, so it reads “ … provides an average light yield increase of approximately 35%. Results for each crystal are summarised in Table 1”.
Fig 9: It is hard to tell from this figure how much of the sea-level spectrum comes from muon-induced background and how much might be from new internal background (due to the closer placement of the PMTs, and any possible contamination introduced during assembly). The figure is therefore difficult to interpret. It is also not clear to me what the origin of the peaks at 33 keV and 47 keV is. Since those peaks are used for stability measurement, I feel it is important to explain them a bit more.
Fig 10 : I assume that the two peaks in the spectrum are the 5.5 and 6 MeV Rn222 chain alphas, and that they appear at 2.5-3 MeV because of some quenching effect. I suggest adding an explanation in the text about why the Rn222 alphas show up at the ‘wrong’ energy.
L269: The two week stability monitoring period was already explained at the beginning of the section.
L318 ‘room temperature’ is confusing here, because this term usually refers to ~20C, while here I believe it refers to -30C. Maybe the information can be added to the sentence in L313 “… warehouse-type refrigerator with a 10kW cryocooler to serve as the … “
L321/322 I was confused because the wording implies that the recycling of the shielding is what prevents radiation from external sources, and I was thinking along the lines of the shielding material itself having decreased radioactivity due to being underground for a long time or something like that. However I now think that the part about recycling the material is just an aside, and the rest is just an explanation of why the shielding is needed in the first place. Please re-organize the first two sentences to make this clear. Also ‘prevent’ -> ‘block’.

L350 'remained' -> 'remaining'
L367 The table gives just 238U and 232Th, but no individual isotopes further down the chain. Do you assume secular equilibrium in the simulations then? If so, it is worth mentioning in the text.

Reviewer #3

(Remarks to the Author)
We applaud the work by the COSINE collaboration to improve the detector performance and analysis that will increase the overall sensitivity of the apparatus to measure interactions with dark matter candidates.

What are the major claims of the paper? Are they novel and will they be of interest to others in the community and the wider field?

The overall improvement of the crystal design seems to be the point of the paper and not just the encapsulation, though the encapsulation process is highly emphasized and discussed in detail.
While about 60% of the paper focuses on the encapsulation upgrade and the subsequent tests, the remaining 40% presents the decommissioning and installation of the upgrade, the expected backgrounds, simulations and sensitivity studies.

The paper reports on the implementation of the encapsulation upgrade for the COSINE-100U detectors, background and contamination tests, and discusses the sensitivity calculations. The NaI[Tl] crystal upgrade process and outcomes are of interest to people engaged in detecting low-energy signals. The paper contributes to the understanding of the potential physics reach for the NaI detector technology as it is right now. There are not many studies on the background contributions in NaI based detector experiments measuring low-energy signals, so this information is beneficial to the community.

In reading the paper, questions arose that were not addressed or there was confusion that needed some calculations to clarify. Explanations of these items would be helpful for the reader.

The following are suggested clarifications or overall considerations. Specific questions or suggestions at a line in the text are given below.

In the introduction, the encapsulation improvement paper is referenced [24] which describes"the development of an encapsulation technique that simplifies the overall design by attaching the photo sensors directly to the crystal so that light losses are minimized. The light yield of a NaI(Tl) crystal encapsulated with this technique was improved by more than 30%, and as many as 22 photoelectrons per keV have been measured." as written in the abstract.
It is mentioned in the paragraph above section 2.1 that changes were made for an inner and outer structure.

There were many details described in that paper [24] including the cutting down and beveling, and it would be helpful to understand if there were major differences in the process for the COSINE crystals. For example, is section 2.2 redundant or can it be reduced as several of the details and pictures seem similar to the referenced NIM paper.

The paper provides much detail on the encapsulation, and not as much detail on the analysis for example for the light yield and energy resolution. In section 3.2 lines 208 through 211, the paper states that Figure 8b 'clearly demonstrates improved energy resolution' as a result of the increased light yield and similar improvements were seen in other crystals. This analysis is not described, and the quantitative improvement that was achieved is not provided.
In Figure 8b, there is an asymmetry to the peak shape for the COSINE-100 peak response to the 241Am source. Was that asymmetry characteristic of the detector crystals? Could that be accounted for in the analysis? The improved peak is more symmetric which leads to a better energy resolution. Is this correction understood considering the new configuration?

The paper emphasizes the encapsulation upgrade and provides background testing and then sensitivity calculations in a few pages. If the paper is to be balanced, then perhaps the details of the encapsulation process might be moved to an appendix. For the overall sensitivity presentation of the new set-up, the encapsulation details and figures interrupt the flow. These details have their importance for someone wanting to repeat the process, so removal is not recommended, but an appendix may be the right place.

The 30 keV peak discussed in lines 240-246, is referenced to paper [34]. This paper also discusses the 210Pb (210Bi*) decay to produce the '46.5 keV' line that is seen at 49 keV. The reference and explanation for the peak around 48-49 keV in Figure 9 (but around 46 keV in Figure 11a) referred to as the 46.5 keV peak is not explained.

The paragraph lines 349 through 354 discusses the installation and testing of the crystals with the process to be completed in about a month after the writing of the paper. The conclusion of the hardware part of the upgrade process would be stronger with a definitive statement. This information should be updated.

The paragraph on the sensitivity calculation mentions including the increased light yield values. The threshold is taken as the project analysis value with added tools of 5 NPE. With an increased light yield, wouldn't the threshold be able to be reduced below the COSINE-100, 8 NPE threshold? This would involve a calculation and assumptions about quenching factors as given in the reference that produced the 8 NPE threshold.
The authors could consider showing the impact of the increased light yield without the projected lowering of the threshold through analysis techniques.

The following are specific editorial suggestions:

Line 59: a clarification of what “detector performance” refers to would be helpful to the reader. For example, what improvement is the most important?

Line 66, 105: coherent neutrino-nucleus scattering → coherent elastic neutrino-nucleus scattering

Figure 1 - are the Teflon sheets included in the drawing and if so, could they be indicated. If possible, thicker arrows would be helpful for seeing the place being referenced.

Line 98: Here it is mentioned that there is an approximate 50% light yield improvement over COSINE-100 crystals. Later in line 204 it is stated there is an approximate 35% increase in light yield. The indication of the approximate increase is different in each case. One needs to go to Table 1 to calculate the 33% increase for C6 crystal and separately to see that the 22 PE/keV is overall about 50% higher than the originals around 15 PEs/keV compared to 22 PEs/keV. Clarification here would be very helpful to not confuse the reader and necessitate extra study of Table 1.

Line 106: Not clear from the text at this place; how is the liquid scintillator involved? Only for NEON or also COSINE? Overall it seems like a few more details about the experiment would be good before discussing the upgrade. A drawing of the overall design would be useful to not have to refer to a previous reference.

Line 109: typo We→ we

Line 121: Why was 45 degrees for the beveling chosen? Would a larger angle than 45 degrees be even better? What was the trade-off for the decision?
After reading that the crystal was machined, the question arises, how large is the loss of active mass due to this? Table 1 shows about a 1 kg loss in each case, or less than 1 kg for most crystals. A brief phrase with reference to Table 1 would quickly answer that question for the reader.

Fig 2: In figure c the optical pad is mentioned. Where is the optical pad in the drawing? Is it the same optical pad as before?

Line 204: The use of NPE/keV (number of photoelectrons per keV) is not consistent with Table 1 which has PEs/keV.

Line 155: It is mentioned that Figure 5a shows the crystal with mineral oil on it. Looking at 5a, it looks like the crystal is inside of a bag of some sort. The caption says that the crystal is moved to a glovebox but it is not clear in the picture that the crystal is in a glovebox. The caption does not mention the mineral oil coating.

Fig. 6a: It would be helpful to have some information on which color represents which material, in particular the Pb and liquid scintillator

Line 191: “Inside the container, an acrylic table was used to install one NaI(Tl) crystal for the first characterization, as shown in Figure 6.” What is the ‘first characterization’? The first one described is the Am source runs. Later in line 290, the background measurements were in the shield setup as shown in Fig.6. Would that be Fig.6 a? So either the crystals were in the 6b set up for the Am run or in 6a in the shielded configuration for the background run? Please specify either a or b for the Figure 6 reference.

Line 197 What is the total length of a waveform? Where do the 2.6-4.6 and 3.6-5.6 mus numbers come from?

Line 263: Using the data in Table 2, the bulk alpha decreases range from 3.5% to 6.6%. Considering The increases are larger than the stated error, but considering the long 22 year half-life of 210Pb, are these decreases significant? Is there a ‘clear decrease’ as stated?

Figure 11: The wording in the figure caption needs to be revisited as it is not well constructed and not clear.
Figure 13: It would help the reader if the location of the COSINE hall is indicated more clearly on the figure. The writing in the figure is very small.

Line 291: Is there also a number in meters of water equivalent for the depth of the Yemilab? Should be around 2400 m.w.e. from the muon flux, which is pretty good.
How does that depth (in m.w.e.) compare to the previous location?

Line 315: Were there tests already with cooled down crystals to determine the light yield? Is that part of the detector characterization? Was the liquid scintillator also tested at this temperature? (line 344 says that the individual components were all tested)

Line 350: grammar remained → remaining
Line 353: grammar with a month → within a month

Figure 15 caption typo shieling → shielding

Table 3: Were the optical pad and the quartz also studied and the radiopurity determined?

line 389: What about 40K from PTFE? Would this contamination impact at low energies? What about (alpha,n) reactions, are they simulated (is this discussed in a previous publication)?

Line 399: What is the impact of improved light yield on the improved sensitivity? Can that be clarified more, maybe a plot with a signal expectation for the old and new light yield?

Fig 17: Inclusion of sensitivity in comparison to COSINE-100 results would be helpful to see the improvement in sensitivity for the upgrade.

Reviewer #4

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Communications Physics initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts

Version 1:

Reviewer comments:

Reviewer #3

(Remarks to the Author)
Overall, the authors have greatly improved the manuscript from the first version. As mentioned previously, we applaud the work by the COSINE collaboration to improve the detector performance and analysis that will increase the overall sensitivity of the apparatus to measure interactions with dark matter candidates.

The paper reports on the implementation of the encapsulation upgrade for the COSINE-100U detectors, background and contamination tests, and discusses the sensitivity calculations. The addition of the sensitivity results especially Figure 15 greatly improves the strength of the paper and the comparisons for 8NPE threshold calculations between COSINE-100 and COSINE-100U show the sensitivity gain resulting from the upgrade process.

The NaI[Tl] crystal upgrade process and outcomes are of interest to people engaged in detecting low-energy signals. The paper contributes to the understanding of the potential physics reach for the NaI detector technology as it is right now. There are not many studies on the background contributions in NaI based detector experiments measuring low-energy signals, so this information is beneficial to the community.

The paper now reads quite well with the details of the encapsulation method in a separate section at the end and with the inclusion of the sensitivity studies and plots.
We recommend the publishing of the paper with consideration to correcting or addressing some issues below.

Best of luck to the authors to achieve the sensitivity as predicted - we look forward to hearing the results of the COSINE-100U measurement.

Specific comments:

Abstract:
"An upgrade of the COSINE-100 experiment, COSINE-100U, has been prepared for installation at Yemilab, a new underground laboratory in Korea, following 6.4 years of operation at the Yangyang Underground Laboratory." This is a little confusing with the last clarifying phrase discussing COSINE-100.
Consider: Following 6.4 years of operation at the Yanyang Underground Laboratory, an upgrade of the COSINE-100 experiment, COSINE-100U, has been prepared for installation at Yemilab, a new underground laboratory in Korea.
Another option is to create two sentences.
Preferred grammar: ...reported by the DAMA/LIBRA. → reported by the DAMA/LIBRA collaboration.

Line 55: typo ...standard weakly interacting massive particle (WIMP) dark matter model → models

Line 76: Introduction to section 2.
This section starts with a detailed technical explanation without context.
It would be helpful to the reader to describe in general the COSINE-100 detector in a brief paragraph with an overall motivation to set the context of the details to follow.
Consider a description of the COSINE-100 detector, perhaps a figure like that of Figure 11, or a figure showing the previous

encapsulated detector and shielding. A statement explaining what the overall differences are between the COSINE-100 and COSINE-100U configurations would be helpful. This could be a couple of sentences starting with explaining the old setup and then what was changed.

Table 1: It would be helpful to the quick understanding of the mass difference for COSINE-100 to indicate which crystals were used or which excluded. Consider either putting the ones used in bold, or an asterisk on the ones excluded, or a mention in the caption. The paragraph discussing which crystals were excluded is later on page 8 whereas the table is on page 5.

Lines 100-111: There is some confusion about which improvements were done for NEON and which for COSINE. In Line 106, "...we have improved…" would imply for COSINE being the current paper but from the later part of the sentence, this was for NEON. The confusion arises from the considerable overlap of authors of reference 26 and those of the current paper. I suggest a mention that some of the current authors participated in the NEON upgrade - or even the current authors gained experience from their work on the NEON upgrade. Essentially, the COSINE upgrade is the same as that for NEON with the addition of the 45 degree beveling. Or is that not correct?
Even if the explanation is not made, "NEON" should be used and not 'we' unless the reference is to the current work on COSINE-100U.

Line 126: (minor) Please give the section number of the method section

Line 130: …not yet ready for the operation… remove 'the' to read "...not yet ready for operation of …"

Fig 5 caption: Comparison of energy resolution at 59.54 keV between the COSINE-100 (black dashed line) and COSINE-100U (black dashed line) setups. → the COSINE-100U line is red dashed

Line 154 waveform → waveforms (plural)

Line 155-157 The windows were chosen to avoid 'multiple photoelectrons' and then it is stated that up to 4 PE clusters were included in the fits. I would expect that multiple PEs would include 3 or 4 PE. Perhaps change the phrase to avoid "large" PE clusters.

Line 175 …although the COSINE experiment contained eight crystals….. (suggest change 'used' to 'contained' or 'included' because the three crystals were not used.

End of Section 3.2: Is there a reason why the PMT noise is now not a problem for C1? Did the PMTs get replaced? It would be appreciated to include a sentence explaining how C1 noise was reduced or eliminated and could now be used.

Figure 7 contains a large number of 'dots', requiring time for the spooling to complete and taking a large amount of black ink. It is likely that figure 7a is the reason why this page was difficult to print. Is there a way to reduce the ink or 'dots' on the page from figure 7a?

Line 249: Consider adding the depth in meters-water-equivalent, m w.e.

Line 273: Reference [37] states an increase in light yield by about 5% at -35 degree. Is that also the expectation here? If yes, can you explicitly state that to give the reader an idea on what improvement will be expected by cooling down the crystals? Also, is there a reason to go to -30 deg? Will the additional 5 degrees make a difference or is there an experimental reason to be at -30 and not -35 as the title of the reference indicates.

Line 294: COSINE-100 -> COSINE-100U as it is the new installation

Figure 12 caption: "... the C5 and C8 crystals were installed." add 'crystals'.

Lines 315-317: Perhaps as a proceedings having a time reference would make sense, but being a journal article, the information should not be time-bound. "Over the past two months of measurements, no performance issues have been observed." Change to "During two months of measurements, no performance issues were observed."
"The modification of the gaskets is now being applied to all COSINE-100U crystals." Change to "The modification of the gaskets was applied to all COSINE-100U crystals."

Line 320-321: Suggest removing the sentence "The entire process is expected to be completed within a few months." Consider "With the current schedule, the COSINE-100U experiment will begin physics operations at room temperature in early 2025." However, considering that it is now early 2025, can you state that room temperature operations have already begun or will begin generically in 2025?

Line 327 - "...the COSINE-100U experiment will transit to low-temperature operation." → transition so that "...the experiment will transition to …"

Line 342: The radioactivity of the PMTs was measured and values for natural radioactivity are given in the table. Are there also results on whether there is indeed Cs or Ba in the PMT glass as suspected for the origin of the 33keV peak? It seems like that is not taken into account in Fig 14, just the increase due to the other contaminants in the PMT. Consider a note in the figure caption that potential Ba and Cs contamination are not considered

Line 350: Include a reference to the earlier discussion on surface alphas (see Section …)

Line 377: …experiment with a CsI[Tl] crystal..” include article ‘a’

Line 380: … to account for …. Perhaps you wish to say “...to emphasize the substantial improvements…” or maybe "...to illustrate the substantial improvements..."

Line 414: remove the word ‘even’

Line 435: Consider “ …and a 5 NPE analysis energy threshold.” adding the qualifying word analysis.

The start of Section 8 Method is confusing. This may be due to the use of “we” for NEON work.
“To maximize light collection efficiency, we used 3-inch diameter crystals to match the PMT diameters in the NEON experiment [35]. However, COSINE-100 crystals have larger diameters than the PMTs, as summarized in Table 1.”
Do you mean to say that in the NEON experiment, the light collection efficiency was maximized with the encapsulation method alone because the crystals and the PMTs were matched in diameter. Whereas for the COSINE experiment, the crystals are larger and have a diameter greater than that of the PMTs used. This necessitated the extra step of needing to bevel the crystals. This is the conclusion drawn from the discussion. An introductory sentence or two would be helpful to explain the motivation for the encapsulation process that is described here.

Line 530: The authors declare that…. Change ‘declares’ to ‘declare’ and a period is needed at the end of the statement.

Reviewer #4

(Remarks to the Author)
comments to the editors only - no additional comments for authors.

General changes

→ We would like to thank the reviewers for their valuable feedback. Based on your insightful comments, we have made significant changes to our manuscript as outlined below:

We have revised Section 2.2 to provide a concise introduction to the upgraded encapsulation, focusing on the key differences between the COSINE-100U and NEON encapsulation designs. To avoid redundancy, all detailed descriptions have been relocated to the Methods section, which now includes updated information while maintaining some overlap with Ref. [24] for completeness.

Additionally, we have expanded Section 6 to provide a more comprehensive discussion of the scientific investigations enabled by the upgraded COSINE-100U experiment. This includes detailed explanations of the anticipated improvements in sensitivity to low-mass dark matter detection and the broader implications of these advancements for the field. We hope these revisions address the concerns and emphasize the significance of our work. During this process, we identified an error in our sensitivity evaluation and have updated the values accordingly, following multiple cross-checks. Despite this correction, our overall conclusion remains unchanged.

We have provided detailed, line-by-line responses to the reviewers' comments, incorporating necessary modifications into the text wherever applicable.

We hope these modifications address the reviewers' concerns and meet the standards *Communication Physics*

Reviewer #1 (Remarks to the Author):

This paper provides a detailed description of how the COSINE-100 experiment was decommissioned and the parts reused for an upgraded experiment, COSINE-100U, in the new Yemilab underground lab. The procedure for preparing the COSINE-100 crystals for re-use, and the new improved encapsulation design, are carefully explained, followed by the qualification tests done to characterise the new crystal assemblies.
The improvement to the crystal lightyield is substantial, and no significant radioactive impurities seem to have been introduced during the refurbishing. Together with the placement of the experiment in a lab with better muon shielding, and improved operating conditions, this will allow the new experiment to perform a competitive search for light

WIMPs, in addition to the continued test of the DAMA/LIBRA claim.

The upgrade procedure and the performance of the crystal assemblies is of interest to the community, so are the projections for the WIMP sensitivity.

→ Thank you for your thorough review and valuable feedback. We greatly appreciate the time and effort you put into assessing our work. We've done our best to address all your comments and concerns to the best of our ability.

A number of comments/suggestions regarding specific parts of the text follow:

L82: I was confused about what 'crystal-6' meant until reading the next section. Maybe you can explain here already that there are 8 crystals of slightly different dimensions, as shown in Tab 1, and that you will be using the crystal labelled C6 as an example.

→ Thank you for pointing that out. We've added a clarification just before this line:

"These cylindrical crystals of slightly different dimensions, as shown in Table 1, were hermetically…"

L96: grammar - eliminating, minimizing

Thanks. Corrected.

Fig1: The teflon wrapper is not shown?

→ It is challenging to visually separate the Teflon wrapper from the crystal in the figure. Instead, the colored crystal can be interpreted as the crystal wrapped in Teflon. To clarify this, we have added a note to the figure caption. "The crystal is wrapped with a Teflon sheet."

Tab 1: The light yield is abbreviated as PEs/keV in the table and NPE/keV in the text (L98). I think it is common to just use "PE/keV". Any way, please chose a consistent label (also for later in the text)

→ Thanks for your point. We have standardized the unit to "NPE/keV" throughout the text and Table 1.

L206: the part of the comma doesn't really fit into the sentence unless the LY with the old encapsulation is also given. However, since the table has all the numbers, it would suffice in the text to just leave out the part "from the mean … C6", so it reads " … provides an average light yield increase of approximately 35%. Results for each crystal are summarised in Table 1".

→ We have revised the sentence as follows to improve clarity:
"We observed an average light yield increase of approximately 35%. Results for each crystal are summarized in Table 1."

Fig 9: It is hard to tell from this figure how much of the sea-level spectrum comes from muon-induced background and how much might be from new internal background (due to the closer placement of the PMTs, and any possible contamination introduced during assembly). The figure is therefore difficult to interpret. It is also not clear to me what the origin of the peaks at 33 keV and 47 keV is. Since those peaks are used for stability measurement, I feel it is important to explain them a bit more.

→ Measurements for COSINE-100U at sea level were conducted with a simplified shield (10 cm lead and 20 cm liquid scintillator), compared to COSINE-100, which used 20 cm lead, 3 cm copper and 40 cm liquid scintillator. This likely results in additional background contributions not only from cosmic muons but also from external gammas. While it's challenging to separately identify these sources at this stage, underground measurements will soon provide more precise insights.

The purpose of this figure is to highlight the appearance of the 33 keV peak, which arises due to the absence of a quartz window, as detailed in Section 3.3. This peak may originate from the K-shell dip of iodine nuclei caused by nonproportional behavior, x-rays from Ba in the PMT glass, and potentially Cs and In in the PMT photocathode. Further studies will be conducted underground to better understand these contributions.

The 47 keV peak is attributed to internal 210Pb contamination, but PMT contamination might also contribute. At this stage, we don't observe any indications of an increased level of this peak, likely due to the large continuum background. Internal ^{210}₩text{Pb} contamination has been investigated using alpha measurements, and no significant increases have been found in either surface or bulk contamination.

Additionally, while there may be x-ray or gamma-ray contributions from the PMTs, simulations discussed in Section 5 indicate their effect in the low-energy region is negligible.

We have also updated the figure caption to include explanations for the 33 keV and 47 keV peaks for greater clarity and context.

Fig 10 : I assume that the two peaks in the spectrum are the 5.5 and 6 MeV Rn222 chain alphas, and that they appear at 2.5-3 MeV because of some quenching effect. I suggest adding an explanation in the text about why the Rn222 alphas show up at the 'wrong' energy.

→The two peaks in the spectrum are characteristics of the COSINE-100 crystals, as identified in a dedicated study using COSINE-100 data (Astropart. Phys. 158, 102945 (2024), Ref 35). Interestingly, alphas of the same energy exhibit a two-peak structure, though the precise origin of this behavior remains unknown. The dominant peaks have been attributed to 210Po decays (5.3 MeV) with two distinct quenching effects.

To clarify this point, we have added the following explanation to the figure caption:
"The two peaks are caused by ^{210}Po decays, showing two different α quenching effects observed in the COSINE-100 experiment [35]."

L269: The two week stability monitoring period was already explained at the beginning of the section.

→ We have revised the sentence for clarity and removed redundancy. The updated text now reads:

"The stability of the assembled crystals is monitored by tracking the radiation peaks: 33 keV, as explained above, and 46.5 keV from internal \$^{210}\$Pb.".

L318 'room temperature' is confusing here, because this term usually refers to ~20C, while here I believe it refers to -30C. Maybe the information can be added to the sentence in L313 "... warehouse-type refrigerator with a 10kW cryocooler to serve as the ... "

→ We have modified the sentence on L313 to clarify the temperature context as your comment.

L321/322 I was confused because the wording implies that the recycling of the shielding is what prevents radiation from external sources, and I was thinking along the lines of the shielding material itself having decreased radioactivity due to being underground for a long time or something like that. However I now think that the part about recycling the material is just an aside, and the rest is just an explanation of why the shielding is needed in the first place. Please re-organize the first two sentences to make this clear.

→ We have reorganized the paragraph to improve clarity and avoid confusion:

Also ‘prevent’ -> ‘block’.

→ Modified.

L350 ‘remained’ -> ‘remaining’

→ Modified.

L367 The table gives just 238U and 232Th, but no individual isotopes further down the chain. Do you assume secular equilibrium in the simulations then? If so, it is worth mentioning in the text.

→ We have clarified the assumptions in the table caption by adding the phrase “assuming secular equilibrium”.

To address potential confusion about the simulation, we also revised L367 to read: “based on our understanding of the COSINE-100 backgrounds [41] and the measured contamination levels of the encapsulation materials, we simulated the expected background contributions of radiation components.”.

Reviewer #2 (Remarks to the Author):

We applaud the work by the COSINE collaboration to improve the detector performance and analysis that will increase the overall sensitivity of the apparatus to measure interactions with dark matter candidates.

The overall improvement of the crystal design seems to be the point of the paper and not just the encapsulation, though the encapsulation process is highly emphasized and discussed in detail.

While about 60% of the paper focuses on the encapsulation upgrade and the subsequent tests, the remaining 40% presents the decommissioning and installation of the upgrade, the expected backgrounds, simulations and sensitivity studies.

The paper reports on the implementation of the encapsulation upgrade for the COSINE-100U detectors, background and contamination tests, and discusses the sensitivity calculations. The NaI[Tl] crystal upgrade process and outcomes are of interest to people engaged in detecting low-energy signals. The paper contributes to the understanding of the potential physics reach for the NaI detector technology as it is right now. There are not many studies on the background contributions in NaI based detector experiments measuring low-energy signals, so this information is beneficial to the community.

In reading the paper, questions arose that were not addressed or there was confusion that needed some calculations to clarify. Explanations of these items would be helpful for the reader.

The following are suggested clarifications or overall considerations. Specific questions or suggestions at a line in the text are given below.
→ Thank you for your thorough review and valuable feedback. We greatly appreciate the time and effort you put into assessing our work. We have done our best to address all your comments and concerns to the best of our ability.

In the introduction, the encapsulation improvement paper is referenced [24] which describes "the development of an encapsulation technique that simplifies the overall design by attaching the photo sensors directly to the crystal so that light losses are minimized. The light yield of a NaI(Tl) crystal encapsulated with this technique was improved by more than 30%, and as many as 22 photoelectrons per keV have been measured." as written in the abstract.
It is mentioned in the paragraph above section 2.1 that changes were made for an inner and outer structure.
There were many details described in that paper [24] including the cutting down and beveling, and it would be helpful to understand if there were major differences in the process for the COSINE crystals. For example, is section 2.2 redundant or can it be reduced as several of the details and pictures seem similar to the referenced NIM paper.
→ Thank you for your valuable suggestion. We have revised Section 2.2 to provide a

concise introduction to the upgraded encapsulation, focusing on the differences between the COSINE-100U and NEON encapsulation designs. All detailed descriptions have been moved to the Methods section, which now includes a few redundant but updated details from Ref. [24]. This adjustment ensures that the main text flows smoothly while maintaining the necessary technical information for readers who may wish to reference the encapsulation process in more depth.

The paper provides much detail on the encapsulation, and not as much detail on the analysis for example for the light yield and energy resolution. In section 3.2 lines 208 through 211, the paper states that Figure 8b 'clearly demonstrates improved energy resolution' as a result of the increased light yield and similar improvements were seen in other crystals. This analysis is not described, and the quantitative improvement that was achieved is not provided.

→ Thank you for your observation. We have updated Section 3.2 to include example fits for the 59.54 keV peak used to obtain the energy resolution (Fig. 5(b)). Additionally, we have added a comprehensive comparison of the measured energy resolutions for all crystals between the COSINE-100 and COSINE-100U setups in Table 2. This update provides a clear presentation of the quantitative improvements in energy resolution, alongside the corresponding increases in light yield, for a more balanced and detailed analysis.

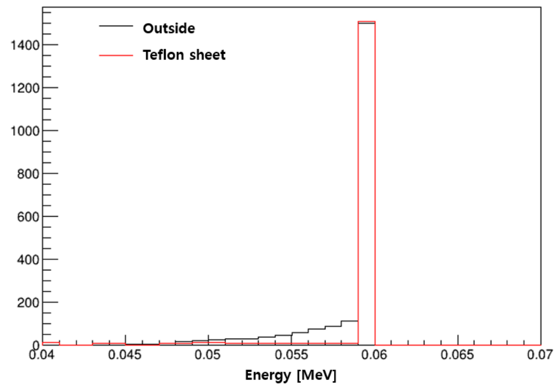
In Figure 8b, there is an asymmetry to the peak shape for the COSINE-100 peak response to the 241Am source. Was that asymmetry characteristic of the detector crystals? Could that be accounted for in the analysis? The improved peak is more symmetric which leads to a better energy resolution. Is this correction understood considering the new configuration?

→ Thank you for raising this important point. The asymmetry observed in the COSINE-100 peak response to the 241Am source is primarily caused by Compton scattering in the encapsulation materials, such as copper.

To investigate this phenomenon, we performed a GEANT4 simulation, generating 241Am gamma-rays both outside the encapsulation and near the Teflon sheet. The results are shown in the figure below. The energy distribution for the Teflon sheet generation exhibits a single, well-defined peak, while the distribution for the external source generation shows a peak with a low-energy tail.

According to the simulation results, the main contribution to the energy loss and resulting asymmetry is Compton scattering within the encapsulation material. To account for this effect, we modeled the data using a Crystal Ball function, which effectively represents the energy loss component due to scattering. This approach was applied to evaluate the energy resolution of the COSINE-100U detector crystals.

The improved symmetry in the COSINE-100U peak is attributed to the upgraded encapsulation design and reduced materials between calibration source and the crystal, which reduces the scattering effect, leading to better energy resolution. This correction and understanding have been incorporated into our analysis and are reflected in the results.



The paper emphasizes the encapsulation upgrade and provides background testing and then sensitivity calculations in a few pages. If the paper is to be balanced, then perhaps the details of the encapsulation process might be moved to an appendix. For the overall sensitivity presentation of the new set-up, the encapsulation details and figures interrupt the flow. These details have their importance for someone wanting to repeat the process, so removal is not recommended, but an appendix may be the right place.
→ Following your suggestion, we have streamlined this section by providing only a brief description of the encapsulation changes. All detailed information about the encapsulation process has been moved to the Methods section, where it is readily accessible for readers who may wish to replicate the process. This adjustment ensures better balance in the paper, allowing the sensitivity presentation of the new setup to flow more seamlessly without interruption, while still preserving the importance of the encapsulation details for technical reference.

The 30 keV peak discussed in lines 240-246, is referenced to paper [34]. This paper also discusses the 210Pb (210Bi*) decay to produce the '46.5 keV' line that is seen at 49 keV. The reference and explanation for the peak around 48-49 keV in Figure 9 (but around 46 keV in Figure 11a) referred to as the 46.5 keV peak is not explained.

→ Figure 9 and Figure 11 (a) present peaks in same location. However, due to small size, C1) have larger background from external radiation, which has strong energy dependence as making decrease slope as lower energy. Due to such background, we see shift of peak to left side from C1. However, proper modeling of background slope resulted consistent peak position.

The peaks presented in Figure 9 and Figure 11(a) correspond to the same energy location. However, the detector C1 exhibits a larger background contribution from external radiation due to its smaller size. This background has a strong energy dependence, creating a decreasing slope toward lower energies. As a result, the peak appears slightly shifted to the left in Fig 11(a) for C1.

Nevertheless, proper modeling of the background slope was performed, accounting for this energy-dependent background. This modeling resulted in consistent peak positions across the detectors, ensuring that the observed discrepancy is not due to a physical difference but rather an artifact of the uncorrected background.

The paragraph lines 349 through 354 discusses the installation and testing of the crystals with the process to be completed in about a month after the writing of the paper. The conclusion of the hardware part of the upgrade process would be stronger with a definitive statement. This information should be updated.

→ We have updated the section to include the latest test results and revised plans. During recent tests, we observed air leakage when the detector was cooled to low temperatures. This issue was identified as being caused by the contraction of the PTFE gasket under temperature changes. To address this, we plan to replace the PTFE gaskets with Viton O-rings, which offer better sealing performance under such conditions.

Additionally, we plan to begin physics operations at room temperature while continuing to ensure low-temperature stability through tests with a dedicated test crystal. All this updated information, including the modified plans and recent findings, has been incorporated into the section to provide a more definitive and robust conclusion to the hardware upgrade process.

The paragraph on the sensitivity calculation mentions including the increased light yield values. The threshold is taken as the project analysis value with added tools of 5 NPE. With an increased light yield, wouldn't the threshold be able to be reduced below the COSINE-100, 8 NPE threshold? This would involve a calculation and assumptions about quenching factors as given in the reference that produced the 8 NPE threshold.
The authors could consider showing the impact of the increased light yield without the projected lowering of the threshold through analysis techniques.

→ Thank you for your valuable suggestion. In response, we have included sensitivity comparisons for three different energy threshold scenarios: the COSINE-100 setup with an 8 NPE threshold, the COSINE-100U setup with an 8 NPE threshold, and the COSINE-100U setup with a 5 NPE threshold. These comparisons demonstrate the impact of both the improved detector design and the enhanced analysis techniques. By showing results for the COSINE-100U setup with the same 8 NPE threshold as COSINE-100, we isolate the improvement due solely to the increased light yield. Additionally, the 5 NPE threshold highlights the potential gains from advanced analysis techniques.

The following are specific editorial suggestions:

Line 59: a clarification of what "detector performance" refers to would be helpful to the reader. For example, what improvement is the most important?
→ We have revised the text to clarify what "detector performance" refers to. The updated sentence now reads:

"While further studies may still be required to fully understand DAMA/LIBRA's results, improving detector performance, such as lowering the analysis threshold and reducing internal background contamination, is critical to enhancing dark matter detection sensitivities for the next phase of experiments."

Line 66, 105: coherent neutrino-nucleus scattering → coherent elastic neutrino-nucleus scattering
→ Modified

Figure 1 - are the Teflon sheets included in the drawing and if so, could they be indicated. If possible, thicker arrows would be helpful for seeing the place being referenced.

→ It is challenging to visually separate the Teflon wrapper from the crystal in the figure. Instead, the colored crystal can be interpreted as the crystal wrapped in Teflon. To clarify this, we have added a note to the figure caption. "The crystal is wrapped with a Teflon sheet."

Line 98: Here it is mentioned that there is an approximate 50% light yield improvement over COSINE-100 crystals. Later in line 204 it is stated there is an approximate 35% increase in light yield. The indication of the approximate increase is different in each case. One needs to go to Table 1 to calculate the 33% increase for C6 crystal and separately to see that the 22 PE/keV is overall about 50% higher than the originals around 15 PEs/keV compared to 22 PEs/keV. Clarification here would be very helpful to not confuse the reader and necessitate extra study of Table 1.

→ In case of small crystals used for the NEON experiment, we have approximately 23 NPE/keV that are approximately 50% increased light yield compared to COSINE-100. However, with larger size crystals of COSINE-100U, we observed approximately 35% increase approximately 20 NPE/keV.

We clarified the numbers and added specific values:

- L98: "The light yield of COSINE-100 crystals was approximately 15 NPE/keV."
- L204: "We observed an average increase in light yield of approximately 35%."

Line 106: Not clear from the text at this place; how is the liquid scintillator involved? Only for NEON or also COSINE? Overall it seems like a few more details about the experiment would be good before discussing the upgrade. A drawing of the overall design would be useful to not have to refer to a previous reference.

→ Both the NEON and COSINE detectors are immersed in liquid scintillator, which serves as an active veto to suppress background signals. To address the comment, we have included a drawing of the COSINE-100U detector, as well as a schematic view of the shielding structure, to provide a clearer understanding of the experimental setup.

Line 109: typo We→ we

→ Fixed

Line 121: Why was 45 degrees for the beveling chosen? Would a larger angle than 45 degrees be even better? What was the trade-off for the decision?

→ We did not conduct a detailed study on the machining edge for the 45-degree beveling. Initially, we chose 45 degrees for the beveling in crystal 1 as a test, and the results demonstrated an approximate 50% improvement in light yield (table 1). Optimizing the slope of the edge is certainly worth further investigation. However, the fragile nature of NaI crystals introduces a significant risk of breakage during machining processes. Since we successfully implemented the 45-degree without any issues, we decided to continue using this angle to minimize the risk of crystal damage.

After reading that the crystal was machined, the question arises, how large is the loss of active mass due to this? Table 1 shows about a 1 kg loss in each case, or less than 1 kg for most crystals. A brief phrase with reference to Table 1 would quickly answer that question for the reader.

→ The mass loss depends on the diameter of the crystals, as the edges are beveled at a 45-degree angle.

We have clarified the impact of the machining process by adding the following phrase after L121:

"As shown in Table 1, the machining process results in a mass loss of approximately 1.1 kg, 0.8 kg, and 0.5 kg for 5-inch, 4.8-inch, and 4.2-inch crystals, respectively, primarily due to beveling the edges at a 45-degree angle."

Fig 2: In figure c the optical pad is mentioned. Where is the optical pad in the drawing? Is it the same optical pad as before?

→ We have updated corresponding figure indicating the optical pad.

To clarify further, the optical pads in the previous and new encapsulation are different. Previously, Alpha Spectra (crystal company) used their own silicon elastomer as the optical pad for encapsulation. For the new encapsulation, we used an optical pad manufactured by Eljen Technology. The background contamination of this optical pad has been measured and is summarized in Table 3.

Line 204: The use of NPE/keV (number of photoelectrons per keV) is not consistent with Table 1 which has PEs/keV.

→ We have updated Table 1 to use NPE/keV (number of photoelectrons per keV) instead of PEs/keV to ensure consistency throughout the manuscript. The light yield units across the article have also been standardized to NPE/keV.

Line 155: It is mentioned that Figure 5a shows the crystal with mineral oil on it. Looking at 5a, it looks like the crystal is inside of a bag of some sort. The caption says that the crystal is moved to a glovebox but it is not clear in the picture that the crystal is in a glovebox. The caption does not mention the mineral oil coating.

→ The mineral oil was applied during the machining process to prevent cracks from developing on the crystal edges, which resulted in mineral oil contamination on the crystal surface. To better illustrate the process of moving the crystal to the glovebox, we have updated Figure 5a to include a wider view that clearly shows the glovebox.

Fig. 6a: It would be helpful to have some information on which color represents which material, in particular the Pb and liquid scintillator

→ We have updated Figure 6a to include annotations identifying the shielding materials, particularly the lead (Pb) and liquid scintillator. Additionally, the figure caption has been revised for the clarification.

Line 191: "Inside the container, an acrylic table was used to install one NaI(Tl) crystal for the first characterization, as shown in Figure 6." What is the 'first characterization'?

→ To provide a clearer explanation, we have revised the sentence as follows:

"Inside the container, an acrylic table was used to install one NaI(Tl) crystal for the initial evaluation of its performance."

The first one described is the Am source runs. Later in line 290, the background measurements were in the shield setup as shown in Fig.6. Would that be Fig.6 a? So either the crystals were in the 6b set up for the Am run or in 6a in the shielded configuration for the background run? Please specify either a or b for the Figure 6 reference.

→ Figures 6a and 6b represent the same setup, with Figure 6b showing an actual photo of the inner liquid scintillator container depicted schematically in Figure 6a. Both the Am source run and the background measurement were performed using this setup.

To clarify, we've added text specifying the placement and removal of the Am source depending on the purpose of the measurement. This should help avoid any confusion regarding the configuration used for each run.

Line 197 What is the total length of a waveform? Where do the 2.6-4.6 and 3.6-5.6 us numbers come from?

→ We have added a brief description of our DAQ system, including the waveform recording length and trigger position, to clarify in the previous subsection.

Line 263: Using the data in Table 2, the bulk alpha decreases range from 3.5% to 6.6%. Considering The increases are larger than the stated error, but considering the long 22 year half-life of 210Pb, are these decreases significant? Is there a 'clear decrease' as stated?

→ We monitored the bulk alpha rate using six years of COSINE-100 data and additional measurements from COSINE-100U after encapsulation. A plot of the bulk alpha rate of C1 is provided below for reference.

As shown in the plot, the observed decrease in the alpha rate aligns well with the expected decay of 210Pb, consistent with its 22-year half-life. We found all crystals have similar consistency.

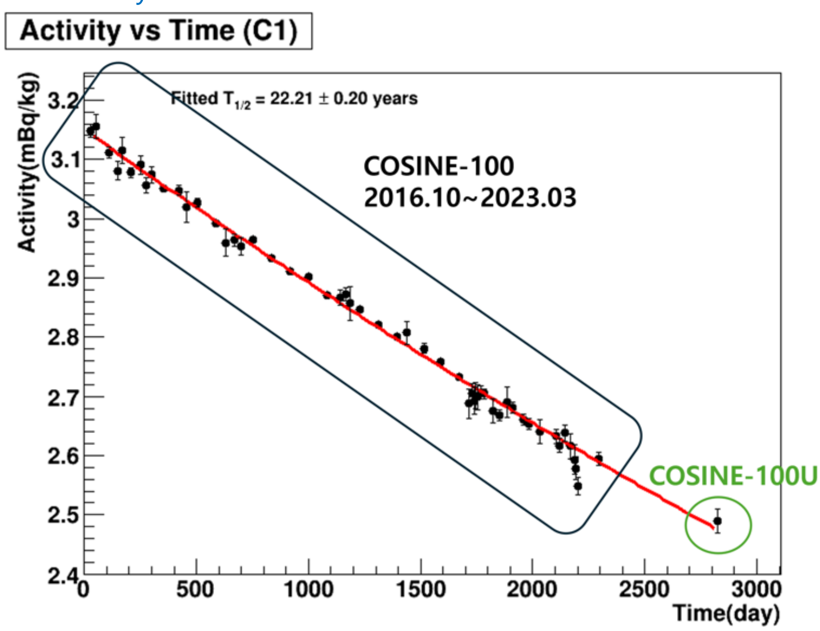


Figure 1 Activity of alpha event from ^{210}Pb over time.

Figure 11: The wording in the figure caption needs to be revisited as it is not well constructed and not clear.

→ We revised the caption of figure 11.

Figure 13: It would help the reader if the location of the COSINE hall is indicated more clearly on the figure. The writing in the figure is very small.

→ We have updated Figure 13(a) by adding red circles to clearly indicate the location of the COSINE hall. Additionally, we added the text in caption of this figure.

Line 291: Is there also a number in meters of water equivalent for the depth of the Yemilab? Should be around 2400 m.w.e. from the muon flux, which is pretty good.
How does that depth (in m.w.e.) compare to the previous location?

→ The water equivalent for the depth of the Yemilab is 2500 m.w.e (preliminary) while the Y2L is 1800 m.w.e.

Line 315: Were there tests already with cooled down crystals to determine the light yield? Is that part of the detector characterization? Was the liquid scintillator also tested at this temperature? (line 344 says that the individual components were all tested)

→ We have not tested the low-temperature operation of the COSINE-100U crystals yet. However, similar measurements were performed on a small test crystal, as referenced in [37]. This crystal was grown by the same company that produced the COSINE-100 crystals, and an improvement in light yield was observed.

Additionally, the liquid scintillator was tested in a small cell at low temperature and showed a slight increase in light yield. This result aligns with findings reported in the literature (Chin. Phys. C 38 (2014) 11, 116001). We have added text to deliver these details.

Line 350: grammar remained → remaining

→ Fixed.

Line 353: grammar with a month → within a month

→ Fixed.

Figure 15 caption typo shieling → shielding

→ Fixed.

Table 3: Were the optical pad and the quartz also studied and the radiopurity determined?

→ We performed gamma spectroscopy using a high-purity Ge detector to study the radiopurity of the optical pad and quartz. The results have been added to Table 3. For both materials, we were able to establish upper limits on their contamination levels, which are significantly lower than the contamination observed in the PMTs.

line 389: What about 40K from PTFE? Would this contamination impact at low energies? What about (alpha,n) reactions, are they simulated (is this discussed in a previous publication)?

→ We have consider 40K contamination from PTFE in our simulations and observed no significant impact at low energies.

Regarding (alpha, n) reactions, we have not conducted a detail study of their effects inside the crystals or encapsulation materials. However, the environmental neutron background was measured and incorporated into simulations to assess its impact. Within the current background level of COSINE-100 crystals (approximately 2-3 counts/kg/keV/day), the direct contribution from environmental neutrons was found to be negligible.

We also expect the (alpha, n) reaction rate inside the crystals and surrounding materials to be small, estimated at approximately one neutron per 10^5 alpha decays. This is supported by our background modeling of COSINE-100 data, which fit well without including contributions from (alpha,n) reactions.

Line 399: What is the impact of improved light yield on the improved sensitivity? Can that be clarified more, maybe a plot with a signal expectation for the old and new light yield?

→ Thank you for your suggestion. To address this, we have added a figure (Fig. 15) illustrating the expected signal rates for 2 GeV and 5 GeV WIMP interactions, indicating the impact of different energy thresholds: COSINE-100 with 8 NPE, COSINE-100U with 8

NPE, and COSINE-100U with 5 NPE. Additionally, we evaluated the sensitivities for these three scenarios to demonstrate the substantial improvements provided by the increased light yield, enhanced encapsulation design, and advanced analysis techniques. This comparison clarifies the contribution of each step toward improved sensitivity.

Fig 17: Inclusion of sensitivity in comparison to COSINE-100 results would be helpful to see the improvement in sensitivity for the upgrade.

→ Because previous result only showed the spin independent WIMP proton cross sections, we add the preliminary COSINE-100 3 years sensitives in figure 17. The 3 years result will soon be uploaded in arXiv and submitted to journal.

REVIEWERS' COMMENTS:

Reviewer #3 (Remarks to the Author):

Overall, the authors have greatly improved the manuscript from the first version. As mentioned previously, we applaud the work by the COSINE collaboration to improve the detector performance and analysis that will increase the overall sensitivity of the apparatus to measure interactions with dark matter candidates.

The paper reports on the implementation of the encapsulation upgrade for the COSINE-100U detectors, background and contamination tests, and discusses the sensitivity calculations. The addition of the sensitivity results especially Figure 15 greatly improves the strength of the paper and the comparisons for 8NPE threshold calculations between COSINE-100 and COSINE-100U show the sensitivity gain resulting from the upgrade process.

The NaI[Tl] crystal upgrade process and outcomes are of interest to people engaged in detecting low-energy signals. The paper contributes to the understanding of the potential physics reach for the NaI detector technology as it is right now. There are not many studies on the background contributions in NaI based detector experiments measuring low-energy signals, so this information is beneficial to the community.

The paper now reads quite well with the details of the encapsulation method in a separate section at the end and with the inclusion of the sensitivity studies and plots.
We recommend the publishing of the paper with consideration to correcting or addressing some issues below.

Best of luck to the authors to achieve the sensitivity as predicted - we look forward to hearing the results of the COSINE-100U measurement.
→ Thank you for your thorough review and valuable feedback again. We greatly appreciate the time and effort you put into assessing our work. We have done our best to address all your comments and concerns to the best of our ability.

Specific comments:

Abstract:
"An upgrade of the COSINE-100 experiment, COSINE-100U, has been prepared for installation at Yemilab, a new underground laboratory in Korea, following 6.4 years of operation at the Yangyang Underground Laboratory." This is a little confusing with the last clarifying phrase discussing COSINE-100.
Consider: Following 6.4 years of operation at the Yanyang Underground Laboratory, an upgrade of the COSINE-100 experiment, COSINE-100U, has been prepared for installation at Yemilab, a new underground laboratory in Korea.
Another option is to create two sentences.
Preferred grammar: ...reported by the DAMA/LIBRA. → reported by the DAMA/LIBRA collaboration.
→ Updated.

Line 55: typo ...standard weakly interacting massive particle (WIMP) dark matter model → models
→ Updated.

Line 76: Introduction to section 2.
This section starts with a detailed technical explanation without context.
It would be helpful to the reader to describe in general the COSINE-100 detector in a brief paragraph with an overall motivation to set the context of the details to follow.
Consider a description of the COSINE-100 detector, perhaps a figure like that of Figure 11, or a figure showing the previous encapsulated detector and shielding. A statement explaining what the overall differences are between the COSINE-100 and COSINE-100U configurations would be helpful. This

could be a couple of sentences starting with explaining the old setup and then what was changed.

→ We agreed to provide better context and motivations at the beginning of Section 2 before diving into the technical details of the crystal encapsulation process. To address this, we have added a brief introductory paragraph summarizing the COSINE-100 detector setup, its overall motivation, and the key differences between COSINE-100 and COSINE-100U. This revision ensures that the reader understands the purpose of the upgrades before encountering the technical description.

Table 1: It would be helpful to the quick understanding of the mass difference for COSINE-100 to indicate which crystals were used or which excluded. Consider either putting the ones used in bold, or an asterisk on the ones excluded, or a mention in the caption. The paragraph discussing which crystals were excluded is later on page 8 whereas the table is on page 5.

→ We marked the unused crystals and provided explanation in the caption.

Lines 100-111: There is some confusion about which improvements were done for NEON and which for COSINE. In Line 106, "...we have improved…" would imply for COSINE being the current paper but from the later part of the sentence, this was for NEON. The confusion arises from the considerable overlap of authors of reference 26 and those of the current paper. I suggest a mention that some of the current authors participated in the NEON upgrade - or even the current authors gained experience from their work on the NEON upgrade. Essentially, the COSINE upgrade is the same as that for NEON with the addition of the 45 degree beveling. Or is that not correct?
Even if the explanation is not made, "NEON" should be used and not 'we' unless the reference is to the current work on COSINE-100U.

→ Thank you for your detailed and constructive feedback. We have explicitly clarified that the initial encapsulation was developed for the NEON experiment and were later adapted for COSINE-100U. We also specify that some of the authors were involved in both the NEON and COSINE-100U projects, ensuring a clearer connection between the two. We explicitly state that the COSINE-100U encapsulation design is based on NEON's improvements, with the additional feature of 45-degree beveling to accommodate the larger-diameter crystals.

Line 126: (minor) Please give the section number of the method section

→ Done

Line 130: …not yet ready for the operation… remove 'the' to read "...not yet ready for operation of …"

→ Done

Fig 5 caption: Comparison of energy resolution at 59.54 keV between the COSINE-100 (black dashed line) and COSINE-100U (black dashed line) setups. → the COSINE-100U line is red dashed

→ Done

Line 154 waveform → waveforms (plural)

→ Done

Line 155-157 The windows were chosen to avoid 'multiple photoelectrons' and then it is stated that up to 4 PE clusters were included in the fits. I would expect that multiple PEs would include 3 or 4 PE. Perhaps change the phrase to avoid "large" PE clusters.

→ Thanks for your suggestion. We rephrase this sentence saying minimize large multiple PEs instead of avoiding all multiple PE contributions.

Line 175 …although the COSINE experiment contained eight crystals….. (suggest change ‘used’ to ‘contained’ or ‘included’ because the three crystals were not used.

→ Changed to “included”

End of Section 3.2: Is there a reason why the PMT noise is now not a problem for C1? Did the PMTs get replaced? It would be appreciated to include a sentence explaining how C1 noise was reduced or eliminated and could now be used.

→ We have now clarified the PMT replacement of C1 to reduce the PMT noise issues and increase of effective mass of COSINE-100U.

Figure 7 contains a large number of 'dots', requiring time for the spooling to complete and taking a large amount of black ink. It is likely that figure 7a is the reason why this page was difficult to print. Is there a way to reduce the ink or ‘dots’ on the page from figure 7a?

→ We have revised Fig. 7a by replacing the dot-based representation with a contour plot, which significantly reduces loading time, ink consumption, and overall visual clutter while maintaining the clarity of the presented data.

Line 249: Consider adding the depth in meters-water-equivalent, m w.e.
→ We put 2700 m.w.e. assuming a rock density of 2.7 g/cm^3.

Line 273: Reference [37] states an increase in light yield by about 5% at -35 degree. Is that also the expectation here? If yes, can you explicitly state that to give the reader an idea on what improvement will be expected by cooling down the crystals?
Also, is there a reason to go to -30 deg? Will the additional 5 degrees make a difference or is there an experimental reason to be at -30 and not -35 as the title of the reference indicates.
→ We have clarify the expected light yield improvement and explicitly stated the reasoning behind choosing -30 degree instead of -35 degree in the revised text.

Line 294: COSINE-100 -> COSINE-100U as it is the new installation

→ Done

Figure 12 caption: “... the C5 and C8 crystals were installed.” add ‘crystals’.

→ Done

Lines 315-317: Perhaps as a proceedings having a time reference would make sense, but being a journal article, the information should not be time-bound. “Over the past two months of measurements, no performance issues have been observed.” Change to “During two months of measurements, no performance issues were observed.”
“The modification of the gaskets is now being applied to all COSINE-100U crystals.” Change to “The modification of the gaskets was applied to all COSINE-100U crystals.”

→ Done

Line 320-321: Suggest removing the sentence “The entire process is expected to be completed within a few months.” Consider “With the current schedule, the COSINE-100U experiment will begin physics operations at room temperature in early 2025.” However, considering that it is now early 2025, can you state that room temperature operations have already begun or will begin generically in 2025?

→ We have revised the sentence to reflect a more conservative timeline, avoiding unnecessary specificity while maintain accuracy.

Line 327 - “...the COSINE-100U experiment will transit to low-temperature operation.” → transition so that “...the experiment will transition to …”

→ Done

Line 342: The radioactivity of the PMTs was measured and values for natural radioactivity are given in the table. Are there also results on whether there is indeed Cs or Ba in the PMT glass as suspected for the origin of the 33keV peak? It seems like that is not taken into account in Fig 14, just the increase due to the other contaminants in the PMT. Consider a note in the figure caption that potential Ba and Cs contamination are not considered

→ The 33 keV peak could originate from a combination of cosmogenic isotope of Te-121m and K-shell x-rays from stable isotopes of Cs and Ba. The radioactive decay inside the PMT or external radiation interacting with the PMT glass could eject K-shell electrons, leading to the emission of K-shell x-rays from these element. While we have observed x-ray background around 33 keV from PMT radioactivity (U,Th, and K) in Fig. 14, it is not sufficient to fully explain the peak observed in Fig. 6. A more detailed understanding requires further underground measurements, allowing for the decay of cosmogenic activations. We have updated the Fig. 6 caption and Section 3.3 to include the possibility of a contribution from Te-121m.

Line 350: Include a reference to the earlier discussion on surface alphas (see Section …)

→ Done

Line 377: …experiment with a CsI[Tl] crystal..” include article ‘a’

→ Done

Line 380: … to account for …. Perhaps you wish to say “...to emphasize the substantial improvements…” or maybe "...to illustrate the substantial improvements..."

→ Done

Line 414: remove the word ‘even’

→ Done

Line 435: Consider “ …and a 5 NPE analysis energy threshold.” adding the qualifying word analysis.

→ Done

The start of Section 8 Method is confusing. This may be due to the use of “we” for NEON work.
“To maximize light collection efficiency, we used 3-inch diameter crystals to match the PMT diameters in the NEON experiment [35]. However, COSINE-100 crystals have larger diameters than the PMTs, as summarized in Table 1.”
Do you mean to say that in the NEON experiment, the light collection efficiency was maximized with the encapsulation method alone because the crystals and the PMTs were matched in diameter. Whereas for the COSINE experiment, the crystals are larger and have a diameter greater than that of the PMTs used. This necessitated the extra step of needing to bevel the crystals. This is the conclusion drawn from the discussion. An introductory sentence or two would be helpful to explain the motivation for the encapsulation process that is described here.

→ We provide introductory sentences clarifying the motivation for the encapsulation process. Additionally, we remove the use of “we” when referring to the NEON work to clearly differentiate between NEON and COSINE-100U.

Line 530: The authors declare that…. Change ‘declares’ to ‘declare’ and a period is needed at the end of the statement.

→ Done

Reviewer #4 (Remarks to the Author):

comments to the editors only - no additional comments for authors.
→ Thank you very much for your time and effort in reviewing our manuscript.