Lowering the energy threshold in COSINE-100 dark matter searches

The COSINE-100 Collaboration

G. Adhikari, E. Barbosa de Souza, N. Carlin, J. J. Choi, S. Choi, M. Djama, A. C. Ezeribe, L. E. Franca, C. Ha*, I. S. Hahn, E. J. Jeon, J. H. Je, W. G. Kang, M. Kauer, H. Kim, H. J. Kim, K. W. Kim, S. K. Kim, Y. D. Kim, Y. H. Kim, Y. J. Ko**, E. K. Lee, H. S. Lee, J. Lee, J. Y. Lee, M. H. Lee, S. H. Lee, D. S. Leonard, B. B. Manzato, R. H. Maruyama, R. J. Neal, S. L. Olsen, B. J. Park, H. K. Park, K. S. Park, R. L. C. Pitta, H. Prihtiadi, S. J. Ra, C. Rott, K. A. Shin, A. Scarff, N. J. C. Spooner, W. G. Thompson, L. Yang, G. H. Yu

*Department of Physics, Sejong University, Seoul 05006, Republic of Korea
bDepartment of Physics and Wright Laboratory, Yale University, New Haven, CT 06520, USA
cPhysics Institute, University of São Paulo, 05508-090, São Paulo, Brazil
dDepartment of Physics and Astronomy, Seoul National University, Seoul 08826, Republic of Korea
eDepartment of Physics, Bandung Institute of Technology, Bandung 40132, Indonesia
fDepartment of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, United Kingdom

gDepartment of Physics, Chung-Ang University, Seoul 06973, Republic of Korea
hDepartment of Science Education, Ewha Womans University, Seoul 03760, Republic of Korea
iCenter for Underground Physics, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea
jDepartment of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA
kDepartment of Physics, Kyungpook National University, Daegu 41566, Republic of Korea
lIBS School, University of Science and Technology (UST), Daejeon 34113, Republic of Korea
mKorea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea
nDepartment of Accelerator Science, Korea University, Sejong 30019, Republic of Korea
oDepartment of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
pDepartment of Physics, University of California San Diego, La Jolla, CA 92093, USA

Abstract

COSINE-100 is a dark matter search experiment that uses NaI(Tl) crystal detectors operating at the Yangyang underground laboratory in Korea since September 2016. Its main goal is to test the annual modulation observed

*Corresponding author
**Corresponding author

Email addresses: chha@cau.ac.kr (C. Ha), yjko@ibs.re.kr (Y. J. Ko)
by the DAMA/LIBRA experiment with the same target medium. Recently
DAMA/LIBRA has released data with an energy threshold lowered to 1 keV,
and the persistent annual modulation behavior is still observed at 9.5σ. By low-
ering the energy threshold for electron recoils to 1 keV or lower, COSINE-100
results can be directly compared to those of DAMA/LIBRA. In this article, we
discuss the COSINE-100 event selection algorithm, its validation, and efficien-
cies near the threshold.

Keywords:  COSINE-100, dark matter, low threshold, NaI(Tl)

2010 MSC:  00-01, 99-00

1. Introduction

A quarter of the total mass-energy of universe is thought to be dark matter,
as has been evidenced by various observations over the last few decades [1, 2].
Theories suggest that dark matter is composed of particles that interact with
Standard Model particles through very weakly interacting processes. Weakly
interacting massive particles (WIMPs) that were thermally produced in the
early universe with an abundance roughly reproduce the relic abundance of
Ω_{CDM} = 0.25 assuming a weak, self-interaction cross section [3, 4, 5].

Direct detection experiments [6, 7, 8, 9] search for signals produced by
WIMPs that interact with nuclei in the material of the target. To date, no exper-
iments have been successful in finding a positive signal that can be interpreted
as resulting from WIMPs, with the notable exception of the DAMA/LIBRA ex-
periment that measures an annual modulation signal from their residual count
rate in the energy range of 2 to 6 keV recorded from NaI(Tl) crystal detec-
tors [10]. The implication of the DAMA’s result that this annual modulation is
driven by a changing flux of WIMPs through the Earth due to the Earth’s ro-
tation around the sun has caused a controversy [11, 12, 13] and an independent
verification is essential.

Recently, the DAMA/LIBRA collaboration updated their results with more
statistics and an energy threshold that is lowered from 2 to 1 keV [14]. The
new results show that the annual modulation signal persists in the extended energy range (1 to 2 keV) as well. Experiments to test the DAMA/LIBRA experiment are actively being carried out by several groups\cite{15, 16, 17} using the same low-background NaI(Tl) target material and reaching the same energy threshold of 1 keV electron equivalent energy. In addition to facilitating the direct comparison with the claimed modulation signal, because the expected event rate of the WIMP-induced nuclear recoil scattering off a target nucleus follows an exponentially decreasing signature as a function of the measured energy, the lowering of the threshold significantly improves the WIMP detection sensitivity, and provides coverage of smaller cross sections and masses. Here, we present an event selection procedure that enabled COSINE-100 to achieve a 1 keV threshold.

2. The COSINE-100 experiment

The COSINE-100 experiment consists of eight low-background NaI(Tl) crystal detectors surrounded by layers of shielding. The crystals are cylindrical and individually encapsulated in copper and coupled to 3-inch Hamamatsu R12669SEL PMTs on each flat end surface of the cylinder. These crystals are submerged in 2200 liters of liquid scintillator (LS) that tags LS-crystal coincident interactions. Events that are tagged as coincident interactions can be excluded from the signal search region because of the negligible probability of a WIMP scattering twice within the detector volume due to their minuscule cross sections. Additionally, the tagged events provide a control sample of events that can be used to test or fit background models independently from the WIMP analysis, which only uses single-hit events. Outside of the LS, 3-cm thick copper and 20-cm thick lead shields provide attenuation of environmental radiation. The entire array is surrounded by 37 scintillating plastic panels providing a $4\pi$ coverage of the detector for identifying and vetoing cosmic-ray muons. Details about the experimental setup can be found elsewhere \cite{18, 19, 20, 21, 22}.

PMTs are known to generate noise pulses caused by dark current, occasional
flashes, and radioactivity in their adjacent dynode circuitry [23]. Since at low energies the rate of these noise pulses is overwhelmingly higher than that of the desired scintillation pulses, one must reject the PMT-induced noise before performing a WIMP search. Fortunately, these noise pulses have decay forms that are distinct from those for particle-generated scintillation pulses in the crystal. We describe an event selection method that achieves a noise contamination level of less than 1% of the signal rate in the 1 to 1.5 keV energy bin by rejecting almost all PMT-noise induced events.

3. Pulse Shape Discrimination for Lowering Threshold

3.1. Parameters based on pulse shape

Particle-induced pulses are produced from scintillation light with the ∼250 ns characteristic decay time of NaI(Tl) crystals [24]. This decay time is longer than that for PMT noise pulses, which are mostly 50 ns or less. Hence, the charge-weighted mean time of the PMT pulse can be used to separate most PMT-noise events from scintillation events. The mean times of the two PMT pulses recorded in a crystal are calculated and combined into one parameter defined as

\[ p_m \equiv \ln \left( \langle t \rangle_1 + \langle t \rangle_2 \right), \]

where \( \langle t \rangle_i \) is the charge-weighted mean time of the \( i \)th PMT [25].

The mean-time parameter provides an effective method for separating scintillation events from PMT-noise events above 2 keV (see Fig. 1). However, it is apparent in the figure that at energies below 2 keV, a distinct type of PMT noise pulse occurs with mean times that extend well into the mean-time region that is characteristic of signal events. Thus, at these low energies, selection criteria based only on mean-time-based parameters do not remove a significant fraction of the noise. An additional quantity is needed.

Another quantity that characterizes the PMT-pulse shape for each PMT is

\[ t_{d,i} = -\ln \left( \frac{Q_{\text{tail},i}}{Q_{\text{head},i}} \right) \frac{T_{\text{tail},i}}{T_{\text{tail},i} - T_{\text{head},i}}, \]

(1)

where \( Q_{\text{head},i} \) (\( Q_{\text{tail},i} \)) is a charge sum of the first (second) half in time of the \( i \)th PMT and \( T_{\text{head},i} \) (\( T_{\text{tail},i} \)) is a charge weighted mean time in the first (second)...
The parameter \( t_d \) denotes the decay time difference between the points \((T_{\text{head},j}, Q_{\text{head},j})\) and \((T_{\text{tail},j}, Q_{\text{tail},j})\).

We incorporate \( t_d \) into a new selection parameter \( p_d \), called the pulse-shape parameter, as \( p_d \equiv \ln (\sum_i t_{d,i}) \). The right plot of Fig. 2 shows that PMT-noise events can be separated from scintillation events only with the mean-time parameter. By comparing the two plots in Fig. 2, one can see that new type noise events only appear at energies below 2 keV. Whether new type or not, the waveforms of PMT-noise events have sharply peaked distributions in the short time range unlike that of scintillation events, as shown in Fig. 3. However, new type noise has a characteristic in that the shape of the pulse contains a higher tail than other PMT-noise events, and, thus, these events cannot be separated from scintillation events by requirements on the mean-time parameter only. On the other hand, the accumulated pulse shape of PMT-noise events that have large values of the pulse-shape parameter, has a more attenuated tail. The PMT-noise events that have a pulse shape with a high tail tend to have larger values of the mean-time parameter than those for the low-tail case. Consequently, PMT-noise events cannot be separated from scintillation events efficiently in the low-energy region below 2 keV by either the mean-time parameter or the pulse-shape parameter by themselves, a selection requirement that is based on both of them is required.

3.2. Likelihood parameter

The combination of mean-time and pulse-shape parameters gives good separation capability for event selection at energies below 2 keV, but it has limitations. The definition of \( t_d \) in Eq. [1] requires that the PMT pulse is divided into first (head) and second (tail) halves. Thus, each of the crystal’s two PMT pulses has to contain two or more single-photoelectron hits, and this becomes an efficiency issue for the low-energy region below 2 keV where the number of

\[ ^1 \text{The first and second half are divided with an event time span between the trigger time and the time of the last single photoelectron pulse within a 8 \( \mu \)s window.} \]
hit counts is low. In addition, the full information contained in the waveform is not fully characterized by just the mean-time and pulse-shape parameters, so we have developed a single 1-D metric that computes the likelihoods that the waveform matches either a signal or a noise event.

In order to obtain Compton-scattered low-energy events as a pure signal sample, data were taken for 27.9 days using a $^{60}$Co calibration source. Here, a noise-free sample of $e/\gamma$-induced scintillation signals can be extracted from multiple-hit events, defined as coincident-hit events with one or more crystals. We select events with a mean-time parameter cut only and make scintillation-event reference waveforms from 5000 of those events. In order to construct corresponding noise reference waveforms, all types of PMT-noise events are selected via criteria based on both parameters, from the events in the physics-run data. The two sets of reference waveforms are distinctly different, as shown in Fig. 3 and a logarithmic likelihood of a waveform summed over the two PMT pulses associated with each event is evaluated for the signal and noise reference waveforms using

$$\ln \mathcal{L} = \sum_i \left[ T_i - W_i + W_i \ln \frac{W_i}{T_i} \right],$$

(2)

where $T_i$ and $W_i$ are the summed heights of the $i^{th}$ time bin in the waveform for the template and event, respectively.

We then have two logarithmic likelihood values for a crystal that are related to each of the two reference waveforms: scintillation and the PMT-noise events. In order to construct a parameter from the logarithmic likelihoods, we define a score as

$$p_l = \frac{\ln \mathcal{L}_n - \ln \mathcal{L}_s}{\ln \mathcal{L}_n + \ln \mathcal{L}_s},$$

(3)

where $\ln \mathcal{L}_s$ and $\ln \mathcal{L}_n$ denote logarithmic likelihoods obtained with scintillation-event and PMT-noise-event references, respectively. If an event has a small value of $\ln \mathcal{L}_s$ ($\ln \mathcal{L}_n$), it is more likely to be a scintillation (noise) event. Therefore, a large $p_l$ for an event implies that the event is more closely matched to the scintillation rather than the noise template. The upper and lower bands
in Fig. 4 denote the scintillation and the PMT-noise events, respectively, and demonstrate that this likelihood-based score parameter has better separation capability in the 1 to 2 keV energy region than the mean-time parameter and pulse-shape parameter.

4. Machine learning technique for 1 keV threshold

For more efficient noise separation, we adopt a machine learning algorithm based on the parameters developed above. A Boosted Decision Tree (BDT) method that accounts for the correlations between individual parameters is efficient in combining several weak discriminating parameters into a single powerful discriminator. We trained a BDT to further reject the low energy PMT-noise events. The decision tree undergoes multiple iterations of trial selections based on the input variables associated with features of the scintillation event and PMT-noise event signals. As the iteration proceeds, the weights, based on the efficiency and purity of scintillation events in the previous event sample, are updated and the BDT is trained on subsequent events with the updated weights applied. Eventually, a single discriminating parameter is created by combining the various selections according to their corresponding weights as a BDT score \[26, 27\]. It should be noted that the BDT in this paper is updated relative to the BDT described in a previous COSINE-100 publication \[9\] by the inclusion of additional discrimination parameters. The input BDT parameters used in the previous analysis are summarized in Ref. \[28\] where we have updated two parameters by changing the \( MT \) (Eq. (3.6) in the reference) to mean-time parameter and by adding the above-described likelihood-based score parameter.

4.1. Event selection for BDT training

A challenging aspect of BDT training is the need for pure event samples that are used to model the scintillation and PMT-noise events. The Compton scattering events of \( \gamma \)-rays from a \(^{60}\)Co source (the events above the red line in Fig. 4) are used as pure scintillation events. We modeled the events between
1.0 and 1.5 keV to estimate the scintillation event purity in this band at these energies to be more than 99%. This was done by extrapolating the noise distribution into the signal region as shown in Fig. 5. The first 59.5 days of the physics-run data, which is dominantly PMT noise-like events, is used as the noise sample for training the BDT. The BDT score as a function of energy of the physics-run data shown in Fig. 6 exhibits clear separation between scintillation and PMT-noise events for energies that are above 1 keV. The events to the right of the red line are selected as scintillation-like events.

4.2. Re-weighting the calibration variables for validation of the BDT

Even with the good event separation, it is mandatory to validate the BDT and to quantify the selection efficiency. This would ensure that the events in the training calibration data behave the same way as those in the physics-run data. In order to validate the BDT training process, we compare input variables using the calibration scintillation events used to train the BDT with those events selected from the independent physics-run data. The energy spectrum of the $^{60}$Co-calibration data is not the same as that for the physics-run data because the calibration data is dominated by Compton scattering events. Therefore, we apply weights to the $^{60}$Co spectrum to match the background spectrum before making the comparison.

Figure 8 shows the validation of the six input variables used to construct the BDT. The black line is the raw data while the red line is scintillation data from the calibration run. For each variable, we overlay the scintillation-like events selected by BDT selection with a blue line that shows good agreement with the energy-weighted calibration data. In addition to the meantime and likelihood parameters, the other variables are defined as the charge fraction of an integrated charge between 500 ns and 600 ns to an integrated charge for the first 600 ns (Slow Charge), the charge fraction of an integrated charge between 0 ns and 50 ns to an integrated charge for the first 600 ns (Fast Charge), the balance of the deposited charge from two PMTs (Charge Asymmetry), and, the average of clustered pulses (Average Cluster Charge).
The energy spectrum for the full simulation of the background radioisotopes is used to determine the spectrum weights. Figure 7 shows the weighted spectrum from the $^{60}$Co-calibration data. The weights are applied to all selection variable distributions for the $^{60}$Co data to make them suitable for modeling the WIMP-search physics-run data. After weighting, there is good agreement for the variables between two independent samples as shown in Fig. 8. The consistency between the two samples validates the BDT selection procedure. The selection efficiency for the energy bin between 1 and 1.5 keV is determined from samples of scintillation events in the $^{60}$Co data sample and found to be greater than 70% for each of the COSINE-100 crystals.

4.3. Sensitivity improvement with 1 keV threshold

In order to study the sensitivity of the annual modulation search with the 1 keV threshold, Monte Carlo experiments are used to calculate projected limits from the COSINE-100 detector in the case of no observed annual modulation signal. We assume a two years running time with a 3-counts/kg/day/keV flat background (which excludes the two low-light-yield high-background crystals). The simulated data are fitted to a sinusoidal function with a fixed period and phase of one year. The fit is used to determine the simulated modulation amplitude observed by COSINE-100 at nuclear recoil energies ranging from 1-20 keV. We find that the DAMA/LIBRA modulation signal region with the lowered 1 keV threshold can be directly challenged by COSINE-100 data. Further details can be found in Ref. [29].

Separately, in order to study WIMP cross-section sensitivity as a function of WIMP mass, we assume a 3-counts/kg/day/keV flat background with 5% overall systematic uncertainty and a systematic uncertainty from the efficiency estimation. A thousand pseudo-data sets based on the null hypothesis are used for the sensitivity estimation, where the assumed exposure is 10000 day-kg. Figure 9 shows COSINE-100 comparisons for different thresholds. The 1 keV threshold analysis shows a factor of ten improvement in sensitivity compared to the 2 keV threshold. Additionally, we show a projected sensitivity for the
low mass WIMPs with an assumed 0.5 keV threshold. Another factor of ten improvement for a 10 GeV/c² mass WIMP is expected compared with the 1 keV threshold analysis. To achieve this threshold, the development of additional improvements for the rejection of the remaining PMT-noise events is on-going.

5. Summary & Outlook

A new PMT-related noise rejection algorithm based on a likelihood estimator and BDT training procedure is developed for the COSINE-100 dark matter experiment, which has been collecting data for more than three years at the Yangyang underground laboratory. The likelihood parameters calculated using categorized noise templates and the particle scintillation template helped to reject noise events down to energies of 1 keV and possibly lower. The current challenge for accessing events below 1 keV is largely due to the low number of produced photoelectrons and existence of sources of PMT-noise events. Further developments in software and hardware are necessary.

With the improved energy thresholds, and more than 3.5 years of running, COSINE-100 data can be directly compared to the DAMA/LIBRA annual modulation signal. Additionally, a spin-independent interaction sensitivity study of COSINE-100 shows that a significant improvement for the low mass WIMP search can be achieved. Furthermore, the method to reject noise events in the NaI(Tl) crystal detector can be utilized in low-threshold NaI(Tl) experiments for coherent neutrino-nucleus scattering \[30\]. The crystals become interesting in terms of neutrino-nucleon coherent elastic scattering if the threshold can be lowered to 0.5 keV with sufficient noise rejection. The same crystals can be used in the neutrino property measurement with high flux neutrinos, e.g. from a nuclear reactor or supernova.

Acknowledgments

We thank the Korea Hydro and Nuclear Power (KHNP) Company for providing underground laboratory space at Yangyang. This work is supported
References

[1] D. Clowe, et al., A direct empirical proof of the existence of dark matter, Astrophys. J. 648 (2006) L109. doi:10.1086/508162

[2] N. Aghanim, et al., Planck 2018 results. VI. Cosmological parameters (2018). arXiv:1807.06209

[3] B. W. Lee, S. Weinberg, Cosmological lower bound on heavy-neutrino masses Phys. Rev. Lett. 39 (1977) 165–168. doi:10.1103/PhysRevLett.39.165
URL https://link.aps.org/doi/10.1103/PhysRevLett.39.165

[4] G. Jungman, M. Kamionkowski, K. Griest, Supersymmetric dark matter, Physics Reports 267 (5) (1996) 195 – 373. doi:https://doi.org/10.1016/0370-1573(95)00058-5
URL http://www.sciencedirect.com/science/article/pii/0370157395000585

[5] M. Schumann, Direct Detection of WIMP Dark Matter: Concepts and Status, J. Phys. G46 (10) (2019) 103003. arXiv:1903.03026 doi:10.1088/1361-6471/ab2ea5

[6] E. Aprile, et al., Dark Matter Search Results from a One Tonne×Year Exposure of XENON1T, Phys. Rev. Lett. 121 (11) (2018) 111302. arXiv:1805.12562 doi:10.1103/PhysRevLett.121.111302
[7] B. J. Mount, et al., Lux-zeplin (lz) technical design report (2017). arXiv:1703.09144

[8] R. Agnese, et al., Results from the Super Cryogenic Dark Matter Search Experiment at Soudan, Phys. Rev. Lett. 120 (6) (2018) 061802. arXiv:1708.08869, doi:10.1103/PhysRevLett.120.061802

[9] G. Adhikari, et al., An experiment to search for dark-matter interactions using sodium iodide detectors, Nature 564 (7734) (2018) 83–86. arXiv:1906.01791, doi:10.1038/s41586-018-0739-1

[10] R. Bernabei, et al., Final model independent result of DAMA/LIBRA-phase1, Eur. Phys. J. C 73 (2013) 2648. arXiv:1308.5109 doi:10.1140/epjc/s10052-013-2648-7

[11] D. Nygren, A testable conventional hypothesis for the DAMA-LIBRA annual modulation, unpublished (2011). arXiv:1102.0815

[12] J. H. Davis, Fitting the annual modulation in DAMA with neutrons from muons and neutrinos, Phys. Rev. Lett. 113 (2014) 081302. doi:10.1103/PhysRevLett.113.081302

[13] J. P. Ralston, One Model Explains DAMA/LIBRA, CoGENT, CDMS, and XENON, unpublished (2010). arXiv:1006.5255

[14] R. Bernabei, et al., First Model Independent Results from DAMA/LIBRA-Phase2, Nucl. Phys. At. Energy 19 (2018) 307–325. arXiv:1805.10486 doi:10.15407/jnpae2018.04.307

[15] G. Adhikari, et al., Search for a dark matter-induced annual modulation signal in NaI(Tl) with the COSINE-100 experiment, Phys. Rev. Lett. 123 (2019) 031302. arXiv:1903.10098 doi:10.1103/PhysRevLett.123.031302

[16] J. Amare, et al., First results on dark matter annual modulation from ANAIS-112 experiment, Phys. Rev. Lett. 123 (2019) 031301. arXiv:1903.03973 doi:10.1103/PhysRevLett.123.031301
[17] M. Antonello, et al., The SABRE project and the SABRE Proof-of-Principle, Eur. Phys. J. C 79 (4) (2019) 363. arXiv:1806.09340 doi:10.1140/epjc/s10052-019-6860-y

[18] G. Adhikari, et al., Initial Performance of the COSINE-100 Experiment, Eur. Phys. J. C 78 (2) (2018) 107. arXiv:1710.05299 doi:10.1140/epjc/s10052-018-5590-x

[19] H. Prihtiadi, et al., Muon detector for the COSINE-100 experiment, JINST 13 (02) (2018) T02007. doi:10.1088/1748-0221/13/02/T02007

[20] G. Adhikari, et al., The COSINE-100 Data Acquisition System, JINST 13 (09) (2018) P09006. arXiv:1806.09788 doi:10.1088/1748-0221/13/09/P09006

[21] G. Adhikari, et al., Study of fast neutron detector for COSINE-100 experiment, Journal of Instrumentation 13 (06) (2018) T06005–T06005. doi:10.1088/1748-0221/13/06/T06005
URL https://doi.org/10.1088%2F1748-0221%2F13%2Ft06005

[22] J. S. Park, et al., Performance of a prototype active veto system using liquid scintillator for a dark matter search experiment, Nucl. Instrum. Meth. A 851 (2017) 103. doi:10.1016/j.nima.2017.01.041

[23] H. P. K. K., Photomultiplier Tubes - Basic and Applications, 3rd Edition, Hamamatsu Photonics K. K., 1994.
URL https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

[24] M. Tanabashi, et al., Review of Particle Physics, Phys. Rev. D98 (3) (2018) 030001. doi:10.1103/PhysRevD.98.030001

[25] K. W. Kim, et al., Limits on interactions between weakly interacting massive particles and nucleons obtained with nai(tl) crystal detectors, Journal of High Energy Physics 2019 (3) (2019) 194. doi:10.1007/JHEP03(2019)
[26] J. H. Friedman, Greedy function approximation: A gradient boosting ma-
chine, Ann. Stat. 29 (2001) 1189.

[27] A. Hoecker, et al., Tmva - toolkit for multivariate data analysis (2007).
arXiv:physics/0703039.

[28] G. Adhikari, et al., COSINE-100 and DAMA/LIBRA-phase2 in WIMP
effective models. Journal of Cosmology and Astroparticle Physics 2019 (06)
(2019) 048–048. doi:10.1088/1475-7516/2019/06/048
URL https://doi.org/10.1088%2F1475-7516%2F2019%2F06%2F048

[29] W. G. Thompson, Current status and projected sensitivity of COSINE-
100, J. Phys. Conf. Ser. 1342 (1) (2020) 012134. arXiv:1711.01488, doi:
10.1088/1742-6596/1342/1/012134

[30] D. Akimov, et al., Observation of coherent elastic neutrino-nucleus
scattering Science 357 (6356) (2017) 1123–1126. arXiv:https://
science.sciencemag.org/content/357/6356/1123.full.pdf doi:10.
1126/science.aao0990
URL https://science.sciencemag.org/content/357/6356/1123
Figure 1: Mean-time parameter distribution as a function of energy. The upper horizontal band denotes scintillation-like (scintillation) events and the lower band shows the noise-like (PMT noise) events. Below 2 keV and high mean-time region, there are lots of noise events that cannot be separated from scintillation-like events using the mean-time parameter only.

Figure 2: Mean-time and pulse-shape parameter distributions for two different energy regions. The left (right) panel shows the distribution with the range of 1-2 (2-10) keV. The new type of noise events do not appear above 2 keV region as shown in the right plot and are the main source of noise events that are not separated from scintillation events at energies below 2 keV by only the mean-time parameter.
Figure 3: Scintillation (blue) and noise event (black) shape templates. The templates are normalized probability density functions. The red waveform is the accumulated waveform of new type noise events extracted from PMT-noise events.

Figure 4: Likelihood parameter as a function of the energy for multiple-hit events in the $^{60}$Co-calibration data. The events above the red line are used to train the BDT.
Figure 5: The BDT distribution for events in the energy range of [1, 1.5] keV (left) and the efficiency of scintillation events (right). In the left plot, the blue and red lines are fitted for scintillation events and PMT-noise events, respectively. The magenta region shows minimum/maximum lower limits of the red curve shown in Fig. 6. In this case, the purity of scintillation events in the upper region of the criterion is more than 99.8%. In the right plot, the black dots are scintillation event efficiencies for the BDT criterion and the blue line is a fitted line with a cumulative beta function.

Figure 6: BDT as a function of the energy in first 59.5 days of dark matter search data. The red line is the energy-dependent event selection where events on the right side of the red line are scintillation-like events that have less than 1% noise contamination in the energy range from 1 to 1.5 keV and negligible noise contamination at higher energies.
Figure 7: Energy spectra for $^{60}$Co multiple-hit events before and after weighting.

Figure 8: Six example variables used to validate the BDT output response. The black, red and blue distributions are the total background, $^{60}$Co coincident events and scintillation-like events from the physics-run data, respectively. All variables are energy-weighted.
Figure 9: The sensitivity of COSINE-100 with several thresholds. The black, red, and blue curves show the detector sensitivity for WIMP search with 0.5-, 1-, and 2-keV threshold, respectively. The cyan, green, and magenta contours show 1, 3, and 5$\sigma$ regions, respectively, allowed by the DAMA/LIBRA-phase1 annual modulation signal.