ANALYSIS OF PHOSPHORESCENCE EVENTS IN COSINE 100 EXPERIMENT FOR DARK MATTER SEARCH

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ABSTRACT

The existence of dark matter is supported by strong astrophysical and cosmological evidence, yet its particle nature remains unresolved. In over two decades of direct detection searches, DAMA/LIBRA remains the only experiment to report an annual modulation in NaI(Tl), a result in strong tension with the null findings of other detection technologies. Motivated by this discrepancy, the COSINE experiment is a direct dark matter search using the same NaI(Tl) target material as DAMA/LIBRA operated at the Yangyang Underground Laboratory (Y2L). The COSINE is designed to provide an independent test of the DAMA/LIBRA claim. Here, we analyze the COSINE-100's findings, which show no evidence for modulation consistent with dark matter interactions and place stringent limits on Weakly Interacting Massive Particles (WIMPs) parameter space. We further discuss the implications of these findings for the DAMA anomaly, the role of complementary NaI(Tl)-based efforts such as ANAIS and SABRE, and the impact on dark matter searches.

Keywords: COSINE-100; dark matter; direct searches; WIMPs; annual modulation signature

Introduction

Dark matter (χ) is a cornerstone of modern cosmology and astrophysics, invoked to explain a wide range of phenomena that cannot be accounted for by visible matter alone. Observational evidence spans multiple scales, such as the galactic rotation curves remaining flat at large radii where the luminous matter is insufficient, the gravitational lensing maps reveal the mass distributions far exceeding visible matter, and anisotropies in the cosmic microwave background (CMB) measured by WAMP and Planck tightly constrain the dark matter density. Collectively, these results indicate that nearly ~25% of the Universe's form density is in the form of unseen matter. The microscopic nature of the unseen matter remains unknown. Then, it is called the dark matter.[1-2]

A promising path to resolving this puzzle is the direct detection technique, which seeks to observe the rare interactions between the dark matter particles and atomic nuclei in the ultra-sensitive detectors. Among the most distinctive predicted signatures is annual modulation, which means a periodic variation in the interaction rate caused by the Earth's orbital motion around the Sun. It modulates the relative velocity of the detector with respect to the galactic dark matter halo. The DAMA/LIBRA experiment, operating with NaI(Tl) scintillation crystals at the Gran Sasso National Laboratory, has long reported the observation of such a modulation signal with more than 9.3σ. Their most recent result, based on 1330 kg year data with a 1 count^{-1} day^{-1}keV^{-1}kg^{-1} on average of the background level crystal array in the single-hit distribution of events in the region of interest (ROI) of the 2-6 keV with an amplitude of 0.0112 $\pm$ 0.0012 count^{-1}day^{-1}keV^{-1}kg^{-1}, a phase of 144 $\pm$ 7 days and a period of 0.998 $\pm$ 0.002 years. This result is often said to be consistent with the simplest theoretical expectations for dark matter detection.[3-5]

However, this result remains in sharp conflict with null findings from a broad range of experiments with other detector technologies and materials, resulting in one of

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the most debated anomalies in the field of dark matter search.[6-7] Numerous other direct search experiments employing diverse target materials such as xenon (XENON, LUX, PandaX), germanium (CDMS, EDELWEISS), and liquid argon (DEAP, DarkSide) have reported null results.[8-12]

These results had strongly constrained the parameter space where DAMA's signal could arise. The difficulty lies in the fact that those experiments use different target materials, making direct comparisons model-dependent. Since DAMA's findings rely exclusively on NaI(Tl) crystals, independent confirmation using the same target material is critical. This necessity has motivated the development of new NaI(Tl)-based experiments, including COSINE-100, ANAIS, and SABRE, aimed at directly testing the DAMA modulation under comparable experimental conditions.[13-17]

To clarify this discrepancy, an independent confirmation with the same target material is essential. The COSINE-100 experiment was established with an array of high-purity NaI(Tl) detectors. COSINE is specifically designed to test the DAMA/LIBRA claim under low-background environments. COSINE-100 offers a model-independent method to verify or refute the DAMA/LIBRA's modulation signal. Its results, which show no modulation consistent with dark matter interactions, not only place strong limits on WIMP parameter space but also reshape the direction of ongoing and future dark matter (DM) searches.[17]

To account for the persistent discrepancy between DAMA/LIBRA and other null-result experiments, alternative hypotheses have been proposed. One such explanation suggests that the DAMA modulation signal might not originate from dark matter interactions but rather from non-radioactive delayed photon emissions, similar to those from the muons, resulting from the gradual release of previously stored energy within the NaI(Tl) crystals. Although the precise mechanism responsible for such delayed relaxation has not been conclusively identified, prior studies have reported long-lasting photon emission phenomena in NaI(Tl) scintillators. Notably, Saint-Gobain—the manufacturer and supplier of the NaI(Tl) crystals used in the DAMA/LIBRA experiment—has observed phosphorescent light emission lasting from hours to several days following exposure to ultraviolet radiation. These observations raise the possibility that long-lived luminescence processes, such as phosphorescence or delayed fluorescence, could contribute to background variations in NaI(Tl)-based detectors, thereby influencing the interpretation of dark matter signals.

Therefore, the objective of this research is to systematically investigate the origin and characteristics of delayed photon emissions in NaI(Tl) crystals under controlled conditions. This research investigates whether these emissions contribute to the observed annual modulation signal. It will direct examination of long-lived luminescent behavior in the same detector material used by DAMA/LIBRA, particularly in the low-energy region relevant to dark matter searches, which has not been explored in previous studies.

Methods

The COSINE Experiment Design

The COSINE-100 experiment, located deep within the Yangyang Underground Laboratory (Y2L) in South Korea, is about 700 meters underground and has been operating since 2016 in the search for potential evidence of dark matter interactions. Operating such an experiment at the surface level would be nearly impossible due to the overwhelming background signals from the surrounding natural environmental radiation. Particularly, Cosmic-ray muons are constantly bombarding the Earth's surface and can mimic or completely mask the subtle signals at the detector. Even with extensive shielding, these high-energy particles would create far too much noise and impact ROI.[17-18]

COSINE-100 benefits from the natural shielding of rock, which reduces the flux of cosmic-ray muons by several orders of magnitude (~10^5 reduction). This drastically lowers the background event rate and allows for much weaker signals that would otherwise be lost. The underground environment provides a more stable temperature and reduced radiation interference, both of which are essential for operating highly sensitive detectors over long timescales. Thus, the underground setting is not simply a convenience but a fundamental requirement for experiments like COSINE-100. Without such protection, the search for dark matter already requires extraordinary sensitivity. It would be drowned out by the constant background noise. The muon flux in A5 tunnel is measured to be $3.8 \pm 0.01_{(stat)} \pm 0.12_{(syst)} \times 10^{-7}$ $cm^{-2}s^{-1}$.[17] while the flux in A6 tunnel is 2.7×10^{-7} $cm^{-2}s^{-1}$.[17] The A5 tunnel environment is characterized by a stable temperature maintained between ~22 and ~25 °C throughout the year, with the relative humidity in the vicinity of the inside rooms measured to be within the range of 60–70%.[17]

The detector hall**,** with an area of 44 m^2 and a height of 4 m, is maintained as an access-controlled, cleanroom environment. To mitigate exposure to the tunnel atmosphere, which contains 1.20 ± 0.49 pCi/L of ^{222}Rn, the radon reduction system has been installed. The internal atmosphere is continuously recirculated through high-efficiency particulate air (HEPA) filtration, ensuring that the concentration of dust particles exceeding 0.5 μm in diameter does not surpass 1,500 per cubic foot. During detector installation and other critical operations, the facility is supplied with radon-suppressed air, whose contamination level is reduced by a factor of ~100 relative to the ambient tunnel concentration. The environmental control system further stabilizes the laboratory conditions by maintaining the temperature at (23.5 ± 0.3) °C and the relative humidity at (40 ± 3)%.[17]

COSINE has been constructed with eight thallium-doped sodium iodide NaI(Tl) crystals, with a 4x2 configuration and totaling ~106 kg in mass. Eight crystals were carefully grown to achieve extremely low levels of radioactive impurities, a crucial factor in reducing background noise that could obscure potential dark matter signals. Each NaI(Tl) crystal is paired with two photomultiplier tubes (PMTs), which capture and amplify the faint flashes of light produced when a particle interacts with the crystal. To further enhance sensitivity, the entire crystal array is submerged in 2,200 liters of liquid scintillator. This liquid not only helps to detect and tag background radiation but also acts as an active shield, allowing researchers to identify and suppress unwanted signals.[19-20]

Surrounding this core detection system are additional layers of protection, including high-purity copper, thick lead shielding, and panels of plastic scintillator**.** These barriers work together to minimize interference from external sources such as environmental radiation and cosmic-ray muons, ensuring that only the most promising and rare particle interactions are recorded. By combining these layers of precision engineering and shielding, COSINE-100 provides one of the world's most sensitive environments for investigating the elusive nature of dark matter.[19] Figure 2 shows the structure of the COSINE 100 detector. The main part of the structure is the plastic scintillators with black covers and the orange copper box housing the 5-inch PMT. The 800-kg copper box top cover is shown being moved with a hoist.[20]

Figure 1. The COSINE-100 detector

Figure 2 shows the outermost layer inward, the system consists of muon panels (3 cm thick, light blue), a lead-brick castle (20 cm thick on all sides, grey), a copper box (3 cm thick), an acrylic box (1 cm thick), and eight encapsulated crystal detectors immersed in liquid scintillator (with at least 40 cm separation between the crystal assembly and the surrounding walls).[17]

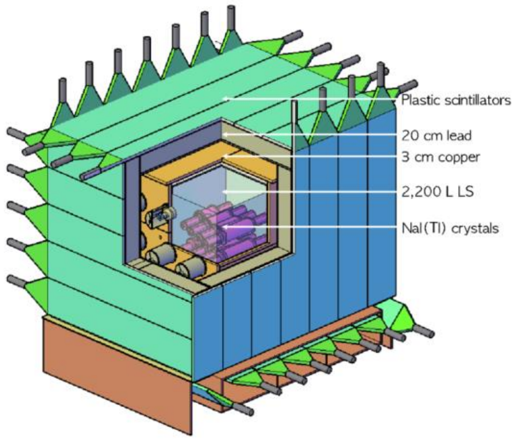

Figure 2. Overview of the COSINE shielding setup.

Direct detection experiments are designed to measure the tiny energy deposited when a dark matter particle, such as a WIMP, scatters elastically off a target nucleus. This process produces nuclear recoils, which can be detected through scintillation light, ionization, or phonons, depending on the detector medium. In NaI(Tl) crystals, nuclear recoils are observed as faint scintillation signals, with the challenge being to distinguish them from electron recoils caused by natural radioactivity. Pulse-shape discrimination and careful background modeling are therefore critical in identifying potential dark matter-induced nuclear recoils. An additional smoking-gun feature is annual modulation of the recoil rate, arising from the Earth's motion through the galactic dark matter halo, which DAMA/LIBRA has long claimed to observe.[20-21]

COSINE-100 has performed both a direct search for nuclear recoils from WIMP interactions and a search for annual modulation using 106 kg of NaI(Tl) crystals at the Yangyang Underground Laboratory. The experiment has reported null results for modulation consistent with dark matter, placing strong constraints on DAMA's parameter space under standard halo models. In addition, COSINE-100 has set competitive exclusion limits on the spin-independent WIMP-nucleon cross section, ruling out a large portion of the region where DAMA's signal would be interpreted as WIMP scattering. These results provide a crucial check on the DAMA claim, demonstrating that if dark matter is responsible for the observed modulation in DAMA/LIBRA, it likely cannot be explained by standard elastic WIMP-nucleus interactions.[20-25]

In dark matter direct detection experiments, the annual modulation arises because the Earth's velocity relative to the Galactic dark matter halo changes over the course of a year (due to Earth's orbit around the Sun). The general differential recoil rate (events per unit detector mass, recoil energy, and time) is

$$\frac{dR}{dE_R}(E_R,t) = \frac{\rho_\chi}{m_\chi m_T}\sigma_T(E_R)\eta(v_{min},t) \quad (1)$$

where:

ρ_χ = local dark matter density (~ 0.3 GeV/cm^3)

m_χ = dark matter particle mass

m_T = target nucleus mass

$\sigma_T(E_R)$ = scattering cross section (depends on recoil energy E_R)

v_{min} = minimum DM velocity needed to produce recoil E_R

$\eta(v_{min},t)$ = mean inverse velocity integral of the dark matter velocity distribution in Earth's frame

Time dependence for the Earth's velocity relative to the galactic frame is shown in Equation 2.[23]

$$\vec{v}_E(t) = \vec{v}_\odot + \vec{v}_\oplus(t) \quad (2)$$

where:

$\vec{v}_\odot$ = Sun's velocity relative to galactic rest frame (≈220 + 12 km/s)

$\vec{v}_\oplus(t)$ = Earth's orbital velocity around the Sun (≈30 km/s). Modulated with a 1-year period.

Thus, the event rate can be expanded as in Equation 3.

$$\frac{dR}{dE_R}(E_R,t) \approx S_0(E_R) + S_m(E_R)\cos\left(\frac{2\pi}{T}(t-t_0)\right) \quad (3)$$

where:

$S_0(E_R)$ = unmodulated (constant) event rate

$S_m(E_R)$ = modulation amplitude (a few % of S_0)
T = 1 year
t_0 ≈ June 2 (when Earth's velocity relative to the halo is maximal)

The COSINE-100 experiment has performed the annual modulation analysis for 1.7 years of data exposure, corresponding to an exposure of 97.7 kg·yr, in order to probe the presence of a dark matter–induced modulating signal in the NaI(Tl) crystal array. In the COSINE-100 analyses, the event selection procedure is usually referred to as the data selection cuts, with more specific terms such as the event selection cut with Boosted Decision Tree (BDT) criteria to reject noise significantly.[23-25]

COSINE-100 performed a simultaneous fit of all crystals, using common modulation parameters while allowing different background components per crystal, as shown in Table 1. The 2–6 keV region of interest showed an average rate of 2.7 cpd/kg/keV (≈670 events/day). A χ^2 minimization was carried out with the modulation period fixed at 365.25 days, testing both free and fixed phase values (halo-model and DAMA/LIBRA). After initial blinded analysis, anomalous noise events were found during unblinding, leading to the development of the BDT algorithm for improved noise rejection. The best-fit modulation amplitude was 0.0092 ± 0.0067 cpd/kg/keV with a phase of 127.2 ± 45.9 days. Likelihood and Feldman–Cousins analyses showed the results are consistent with both the DAMA/LIBRA modulation signal and the null hypothesis at 68% C.L.[25-26]

COSINE-100 is expected to achieve 3σ sensitivity to the DAMA region within five years, with improvements in dataset size, energy threshold, and event selection efficiency further reducing the required exposure.

The modulation amplitude was measured in 1 keV bins for 1.7 years of COSINE-100 data, and is shown in Figure 3. Comparing multiple-hit and single-hit events with DAMA/LIBRA phase 1 and phase 2 results. The fit used a fixed period of 365.25 days and phase of 152.5 days, with horizontal error bars showing bin widths and vertical error bars indicating 1σ uncertainties.[27-29]

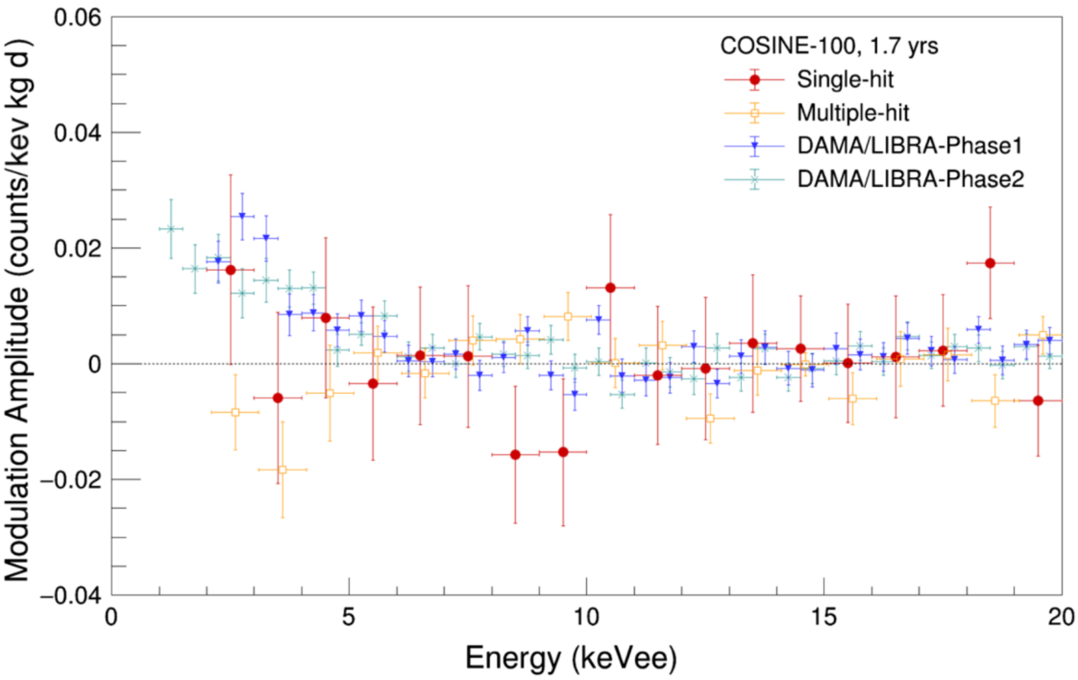

Figure 3. The modulation amplitude of COSINE-100

These findings prompted further investigation into possible non-dark-matter origins of low-energy event modulations, including delayed luminescence phenomena within NaI(Tl) crystals. Phosphorescence in NaI(Tl) scintillators refers to the emission of light persisting beyond the ~250 ns primary fluorescence decay time.[17]. Multiple studies have reported phosphorescence over a wide range of durations, from about 1.5 µs up to as long as 45 days,[17,22] suggesting the presence of multiple underlying decay mechanisms. No consistent dependence on crystal size or temperature has been observed. Phosphorescence can be induced by several types of excitation, including cosmic rays, radioactive sources, and ultraviolet (UV) or visible light exposure. For short-lived components (below one second), the initial intensity scales with the incident radiation intensity, while for longer-lived emissions (lasting minutes to hours), it correlates with the absorbed dose.[17]

Notably, both the ANAIS and KIMS dark matter experiments have observed increased trigger rates following large energy depositions. ANAIS reported decay times ranging from 70–100 ms and extending up to several minutes, whereas KIMS observed decays lasting several seconds. The manufacturer of the DAMA/LIBRA crystals identified a phosphorescent component persisting from hours to days after UV exposure. In contrast, the DAMA collaboration has not reported any evidence of phosphorescence within their data sample. Although no detailed phosphorescence analysis has been publicly disclosed, DAMA asserts that no events within the dark matter signal region are attributed to this effect. Generally, phosphorescence corresponds to low-energy emissions, with Saint-Gobain reporting energies up to approximately 10 keV.

Table 1. The COSINE-100 crystals. The unit for light yield is photoelectrons per keV (PEs/keV)

Crystal	Mass (kg)	Size (inches diameter *x* length)	Powder	Light yield (PEs/keV)
Crystal 1	8.3	5.0 *x* 7.0	AS-B	14.9 ± 1.5
Crystal 2	9.2	4.2 *x* 11.0	AS-C	14.6 ± 1.5
Crystal 3	9.2	4.2 *x* 11.0	AS-WSII	15.5 ± 1.6
Crystal 4	18.0	5.0 *x* 15.3	AS-WSII	14.9 ± 1.5
Crystal 5	18.3	5.0 *x* 15.5	AS-C	7.3 ± 0.7
Crystal 6	12.5	4.8 *x* 11.8	AS-WSIII	14.6 ± 1.5
Crystal 7	12.5	4.8 *x* 11.8	AS-WSIII	14.0 ± 1.4
Crystal 8	18.3	5.0 *x* 15.5	AS-C	3.5 ± 0.3
DAMA	250	-	-	5.5 – 7.5

The Analysis of the Phosphorescence Event

The analysis method follows a systematic workflow designed to investigate potential delayed light emissions and their contribution to low-energy background signals in NaI(Tl) detectors in Figure 4. The process begins with energy calibration using a 241Am source to establish the energy scale, after which both good and bad sub-runs are incorporated to maintain statistical reliability. The calibrated data are then processed through the Data Production (V00.04.15) framework, where standard reconstruction algorithms are applied.

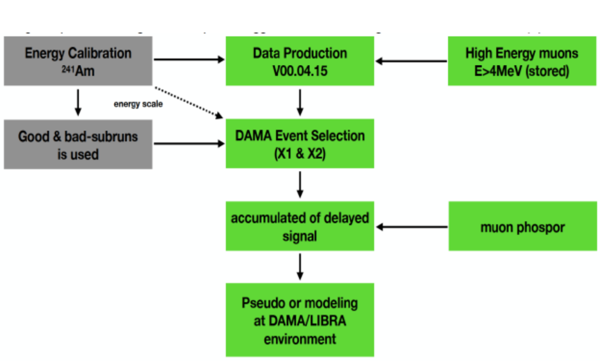

Figure 4. Design of the phosphorescence events triggered by muon interactions

Following this, the DAMA event selection criteria**,** based on the pulse-shape discrimination parameters X_1 and X_2, are implemented to identify scintillation-like events while suppressing prompt PMT noise. High-energy muon events with energies exceeding 4 MeV are also stored and analyzed, as they can induce long-lived muon phosphorescence within the crystal. These muon-induced delayed emissions are subsequently accumulated and examined to assess their persistence beyond DAMA's standard event cuts. The goal is to determine whether radiation- or muon-induced delayed signals that survive the DAMA filtering process could mimic genuine low-energy events in the 2–6 keV region of interest. Finally, the accumulated delayed signals are used to construct pseudo and environmental models that simulate the DAMA/LIBRA experimental conditions. This modeling helps evaluate how such delayed processes might contribute to apparent modulation patterns or keV-scale backgrounds, offering critical insight into the feasibility of non-dark-matter explanations for the DAMA signal.

High-energy muons are identified through a tagging process that begins when a muon is detected by the plastic scintillator panels. After being tagged, the muon deposits a significant amount of energy into the liquid scintillator (LS), typically exceeding 3 MeV, while the corresponding crystal dynode signal surpasses 4 MeV. Once the muon traverses the liquid scintillator, the system records the muon multiplicity ($n\mu \geq 2$) for events involving multiple crystal interactions, or $n\mu=1$ for single-muon hits. The directionality of the muon can then be determined using information from the surrounding panel detectors. This tagging and energy-deposition procedure ensures accurate identification of high-energy muon events, which are essential for studying muon-induced backgrounds and their correlation with delayed phosphorescence signals in NaI(Tl) crystals.

To evaluate delayed signals following direct muon interactions in the crystal, the BMuon variable was used with a 30-ms time window, while BMuonDiff was employed to record the time differences between muon events and subsequent signals in each crystal. To study the time dependence of event rates following direct muon interactions, full SET3 data (including both good and bad runs) were analyzed. Events were selected using pre-cut conditions from PMT and crystal data, considering both single and multiple-hit events, and further filtered using DAMA event selection parameters (X_1 and X_2). Timing cuts were applied to examine phosphorescence effects, where enhanced event rates were observed within approximately 1 second after muon passage, while normal background levels were restored after about 4 seconds. The selection excluded events with muon–delta T_0 greater than 30 ms, t_1 cuts, and DAMA-specific cuts.

Results and Discussion

This analysis aims to enhance our understanding of phosphorescence events by exploring how molecular structures, environmental factors, and energy transfer mechanisms influence their distinct luminescent properties. These phosphorescence events typically occur at low energy levels and involve the emission of thousands of photons. Such phenomena may produce low-energy modulations that align with the phase of muon-induced variations. In crystal-based observations, muon interactions are generally observed at a rate of approximately 1–3 events per crystal per hour, depending on the crystal size.

On this analysis, delayed signals in NaI(Tl) crystals could potentially contribute to the DAMA/LIBRA signal region. Considering the possibility that radiation-induced delayed signals in NaI(Tl) persist even after DAMA's event selection cuts, these signals might serve as a background source that passes the trigger conditions and appears as keV-scale events. This potential background component may not have been fully accounted for in the DAMA analysis.

Evidence of phosphorescence triggered by muon interactions has been identified in the sixth crystal of the COSINE-100 detector, as illustrated in Figure 5. The photon rate exhibits a sharp increase immediately following a muon event and then decays exponentially. This muon-induced phosphorescence has been proposed as a possible source of modulating background within the energy region of interest for NaI(Tl)-based dark matter experiments.[30]

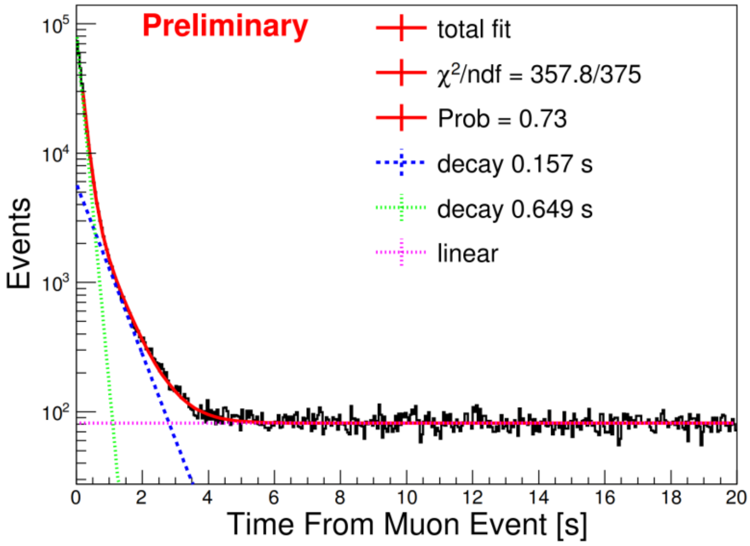

Figure 5. The phosphorescence events triggered by muons.

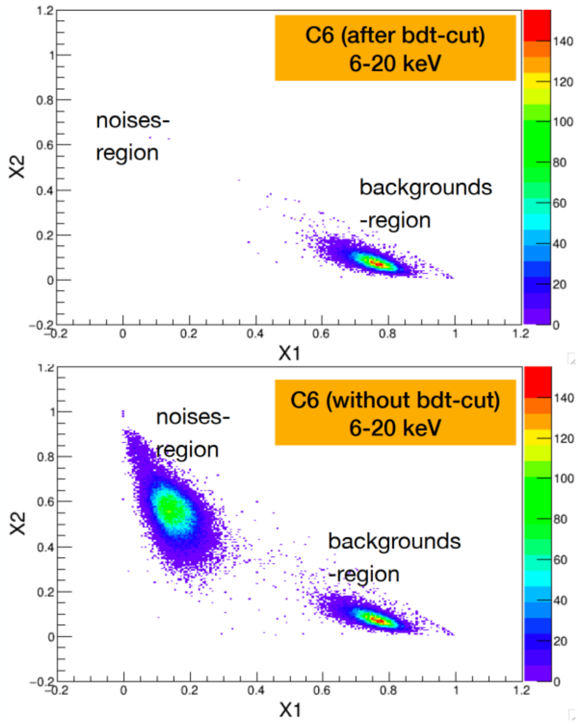

Figure 6. The data indicates at the X1–X2 parameter space (a). After the BDT-cut (b). without BDT.

Since most phosphorescence events are not fully removed by the noise filtering process, a comparison of data recorded before and after two seconds reveals excess events in the 2–6 keV range. This observation emphasizes the importance of evaluating whether muons and muon-induced phosphorescence can mimic genuine low-energy scintillation signals. To distinguish true NaI(Tl) scintillation events from noise-like signals, the DAMA/LIBRA experiment defines pulse-shape discrimination parameters—X_1 and X_2—which represent, in Equation 4, the fractions of delayed and prompt pulse integrals, respectively:

$$X_1 = \frac{A[100,600]ns}{A[0,600]ns}, X_2 = \frac{A[0,50]ns}{A[0,600]ns} \quad (4)$$

Figure 6 shows that the muon and the intensity of delayed light emission in NaI(Tl) by promote the release of stored energy within the material. Additionally, external factors like controlled variations in temperature, pressure, or mechanical vibrations might also influence the buildup and release of stored energy in NaI(Tl) detectors and similar systems. Because NaI(Tl) scintillation pulses have relatively long decay times, while photomultiplier tube (PMT) noise events that satisfy the coincidence requirement tend to have shorter durations, a genuine NaI(Tl) scintillation signal is expected to exhibit a higher X_1 value and a lower X_2 value. Precise analysis of these pulse characteristics, combined with a better understanding of delayed photon emissions, will enhance the discrimination between true low-energy events and background signals, ultimately improving the reliability of future dark matter detection efforts.

The COSINE-100 experiment plays a central role in testing the long-standing DAMA/LIBRA annual modulation claim. By employing the same NaI(Tl) target material under low-background conditions, COSINE-100 provides a model-independent check that directly addresses DAMA's observation. Its null results have placed strong tension on the interpretation of DAMA's signal as being due to dark matter, thereby clarifying a major controversy within the community.

Importantly, COSINE-100 operates alongside other NaI(Tl)-based efforts such as ANAIS-112 in Spain and SABRE in Italy and Australia. Together, these independent experiments ensure that the DAMA anomaly is scrutinized from multiple angles, across different laboratories and detector conditions. The agreement or divergence among these results will be decisive in settling whether the DAMA modulation is an instrumental or environmental artifact rather than a genuine dark matter interaction.

Within the wider dark matter landscape, COSINE-100 complements alternative approaches that use liquid xenon (XENONnT, LZ), cryogenic germanium (SuperCDMS), and superheated fluid detectors (PICO). While xenon-based detectors set the strongest exclusion limits on spin-independent WIMP scattering, NaI(Tl) remains uniquely positioned to directly test DAMA's claim. COSINE-100, therefore, represents a bridge between the sodium-iodide tradition and the broader direct detection community, helping to consolidate results across technologies.

Building on COSINE-100, the collaboration is pursuing upgrades aimed at greater sensitivity. The planned COSINE-200 experiment will feature a larger detector mass and improved background suppression, enabling higher statistical power in testing annual modulation. Such advancements will be crucial in definitively confirming or excluding DAMA's long-reported signal.

Parallel NaI(Tl) efforts are also progressing. ANAIS-112 continues to accumulate exposure at the Canfranc Underground Laboratory, while SABRE is preparing dual-hemisphere deployments in Italy and Australia to disentangle potential seasonal systematics. In parallel, the next generation of xenon-based detectors (XENONnT, LZ, and eventually DARWIN) and argon-based projects (ARGO) will push sensitivity to the neutrino floor, probing WIMP–nucleon cross sections at unprecedented levels. Other innovative searches, such as directional detectors and bubble chambers like PICO, further expand the range of parameter space explored.

Looking further ahead, the dark matter field is also broadening beyond the WIMP paradigm. Candidates such as axions, sterile neutrinos, and ultralight "fuzzy" dark matter are gaining increasing attention, supported by dedicated experiments and astrophysical probes. Complementary approaches, including indirect detection with gamma-ray and neutrino telescopes as well as collider searches at the LHC, will continue to play a vital role. Together, these multi-pronged efforts underscore how COSINE-100 and its successors fit into a global, diversified strategy to solve the dark matter puzzle.

Taken together, COSINE-100 and related NaI(Tl) based experiments represent a pivotal effort to resolve one of the most persistent anomalies in direct detection. While larger liquid xenon and argon detectors are pushing sensitivity to ever-lower cross sections, only sodium iodide crystals can directly verify or refute DAMA's modulation claim. The outcome of these tests will not only clarify a decades-old puzzle but also shape the credibility and direction of the broader dark matter search program. In this sense, COSINE-100 serves as both a test case for experimental reproducibility in astroparticle physics and a foundation for the next generation of searches that extend across diverse detector technologies and dark matter models.

Conclusion

The search for dark matter remains a central challenge in modern physics, highlighted by the enduring controversy surrounding the DAMA/LIBRA experiment's claim of annual modulation, which contrasts sharply with null results from other direct detection efforts. The COSINE-100 experiment, employing the same NaI(Tl) crystal technology as DAMA/LIBRA, has observed no evidence of dark matter–induced modulation, instead revealing that delayed photon emissions—linked to muon-induced phosphorescence within the 2–6 keV energy range—may mimic low-energy scintillation events. These findings suggest that long-lived phosphorescence, environmental muons, and crystal-specific impurities could generate time-dependent background signals resembling dark matter interactions. Ongoing modeling and simulation studies aim to reproduce DAMA-like conditions to assess the impact of such processes, while upcoming upgrades, including COSINE-100U, COSINE-200, and the proposed COSINE-1T, will enhance sensitivity and radiopurity, enabling a decisive test of the DAMA claim. Through its null results, refined background characterization, and collaborative efforts with ANAIS and SABRE, COSINE strengthens the experimental and theoretical foundations of the global dark matter search program.

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