Review Article

Open Access CrossMark

Probing dark matter through particle interactions in next-generation detectors: a multi-modal approach

Abstract

Dark matter (DM) remains one of the most elusive components of the universe. In this study, we investigate the detection potential for both Weakly Interacting Massive Particles (WIMPs) and ultralight bosonic dark matter using a multi-modal approach (NY-diamond directional detectors, quantum sensors, and a multi-messenger strategy). Our simulations, which incorporate realistic detector parameters (energy threshold ~0.5 keV and resolution ~5%), yield an improved signal-to-noise ratio (SNR ~19) for recoil events. However, the classification accuracy for distinguishing between WIMP-induced and neutrino-induced recoils is currently limited to approximately 55%, highlighting the challenge of overcoming the neutrino floor. In our multi-messenger analysis, we report a cross-section sensitivity of ~1.0×10^{-45} cm^2, which must be carefully compared with the lower limits (on the order of 10^{-47} cm^2) achieved by state-of-the-art experiments such as XENONnT and LZ. These findings indicate promising directions yet also underscore the need for further refinement in both detection and signal processing techniques.

Keywords: Dark Matter, WIMPs, Ultralight Bosons, NY-Diamond Detector, Quantum Sensors, Multi-Messenger Detection, Simulation, Directional Detection

Volume 9 Issue 3 - 2025

Davies Tembo,[1] Manyika Kabuswa Davy[2]

[1]Mulungushi University, School of natural and applied Sciences, department of Physics, Zambia

[2]National Institute of Public Administration, Research, innovation and Consultancy Division, Zambia

Correspondence: Manyika Kabuswa Davy, Mulungushi University, School of natural and applied Sciences, Department of Physics, Zambia

Received: May 1, 2025 | **Published:** July 15, 2025

Introduction

The identity of dark matter, which accounts for over 80% of the universe's matter content, remains unknown (Planck Collaboration, 2020).[1,2] While astrophysical and cosmological evidence strongly supports its existence, the particle nature of DM has defied detection. Among the leading candidates are WIMPs, predicted by supersymmetry (Jungman et al., 1996) and expected to interact weakly with normal matter.[3] Another emerging paradigm involves ultralight bosonic particles (e.g., axions) (Hui et al., 2017) which behave as coherent fields on galactic scales.[4] This work presents a simulation-based approach to optimize next-generation detection systems, focusing on NY-diamond detectors, quantum technologies, and the integration of multi-messenger data.

NY-Diamond detectors for directional WIMP searches

Motivation and physics basis

Directional detection is a promising strategy to overcome the "neutrino floor," (Billard et al, 2014) a key sensitivity limit due to solar and atmospheric neutrinos. NY-diamond detectors offer high resolution and low-energy thresholds, making them ideal for sub-10 GeV WIMP searches.[5,]

Simulation framework

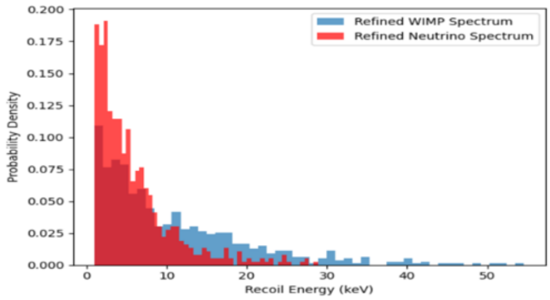
We modeled nuclear recoils using the Helm form factor and simulated WIMP and neutrino interactions. The simulation incorporated energy resolution, detection thresholds, and background rejection using a Random Forest classifier.[7,8] Our simulation framework builds upon custom Python scripts and leverages established libraries (e.g., NumPy, SciPy, and Matplotlib) for model implementation. In addition, the software infrastructure was cross-checked using modules similar in spirit to Geant4, although not directly using it, to ensure the reliability of the nuclear recoil simulations. The galactic halo is modeled using a Navarro-Frenk-White (NFW) profile (Bullock & Boylan-Kolchin, 2017) with a scale radius of ~20 kpc and a local dark matter density of 0.3 GeV/cm³, while solar and atmospheric neutrino fluxes are parameterized based on reported experimental values.

Results and optimization

a) Recoil spectra for WIMPs peaked around 5–10 keV, overlapping with neutrino events.

b) Optimized thresholds (~0.5 keV) and ~5% resolution yielded best signal-to-noise performance (SNR ~19). By lowering the energy threshold to ~0.5 keV and achieving an energy resolution of about 5%, the detector's capability is significantly enhanced. These parameters yield a strong signal-to-noise ratio (SNR ~19), meaning that low-energy signals are captured with high clarity, effectively separating genuine events from background noise.[9,10]

c) Classification metrics (~55% accuracy) indicate a need for improved feature space and machine learning strategies.



(a)

	precision	recall	f1-score	support
0.0	0.55	0.55	0.55	201
1.0	0.55	0.55	0.55	199
accuracy			0.55	400
macro avg	0.55	0.55	0.55	400
weighted avg	0.55	0.55	0.55	400

(b)

Figure 1 Figure 1(a) shows refined WIMP and neutrino recoil energy spectra while, Figure 1(b) show the classification report.

Our simulation results show that the optimized detector settings (energy threshold ~0.5 keV and ~5% resolution) yield a strong signal-to-noise ratio (SNR ~19), ensuring that low-energy events are captured with high clarity. To differentiate between WIMP-induced and neutrino-induced recoil events, we employed a Random Forest classifier trained on simulated recoil energy distributions (Liu et al., 2022). Using an 80/20 split for training/testing and applying standard cross-validation, we evaluated performance using metrics such as precision, recall, and the confusion matrix. The current classifier achieves approximately 55% accuracy when using recoil energy as the sole feature. This baseline performance indicates that additional observables from timing profiles and angular distributions to pulse shape characteristics are needed to enhance event discrimination and further push the sensitivity below the neutrino floor.

Implications

Further enhancements in machine learning strategies such as deep learning-based classifiers could improve classification performance beyond the current 55% threshold.[11] Additionally, detector parameters must be finely tuned, and multi-dimensional observables such as angular information could drastically improve event discrimination in future experiments.

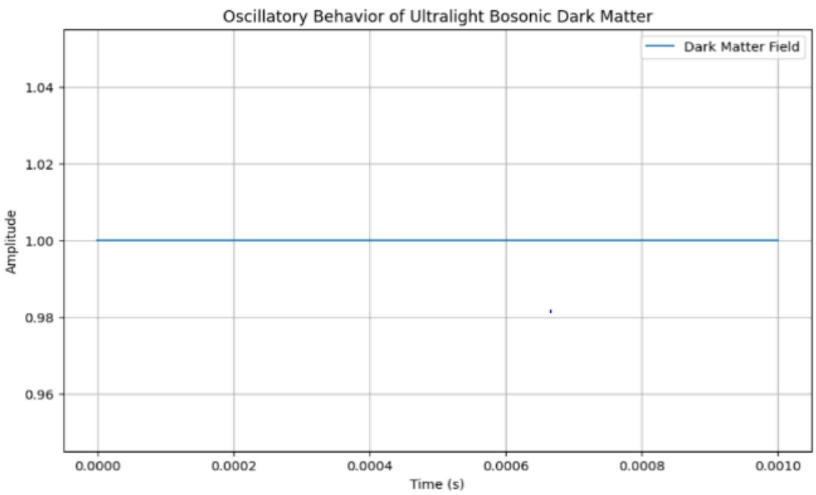
Quantum signatures of ultralight bosonic dark matter

Theoretical Background

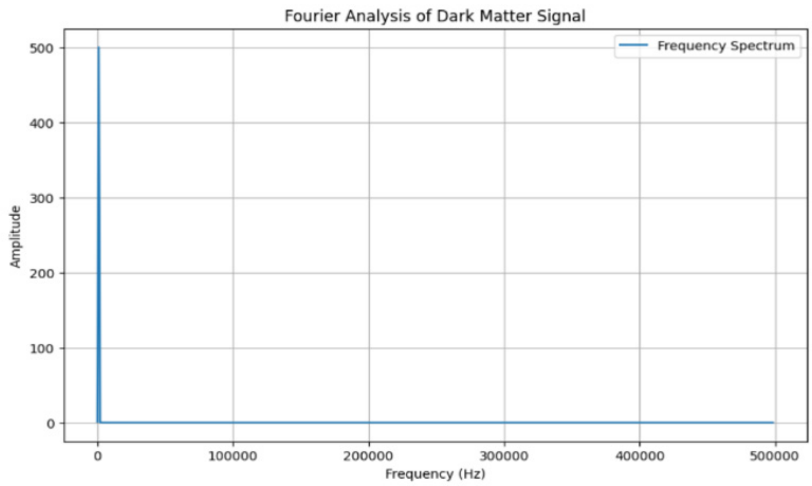
Ultralight bosons (mass ~10^{-22} eV) (Arvanitaki et al., 2010) are predicted in string theory and exhibit wave-like behavior.[12,13] They induce oscillating fields that affect fundamental constants, potentially detectable by atomic clocks or optomechanical systems.

Signal modeling and fourier analysis

The dark matter field was modeled as a high-frequency cosine function.[14,15] Simulated quantum sensor output was analyzed using Fourier transforms to extract frequency components indicative of DM presence.



(a)



(b)

Figure 2 Figure 2(a) represents the simulation of the ultralight bosonic dark matter field, figure 2(b) below shows the results of Fourier analysis.

Citation: Tembo D, Davy MK. Probing dark matter through particle interactions in next-generation detectors: a multi-modal approach. *Phys Astron Int J.* 2025;9(3):168–172. DOI: 10.15406/paij.2025.09.00382

The dark matter field was modeled as a high-frequency cosine function corresponding to an ultralight bosonic candidate (~10^{-22} eV). However, the Fourier analysis of the simulated quantum sensor output (Figure 2(b)) exhibits a predominantly flat response. This is attributable to the current integration window and sampling rate failing to resolve the anticipated MHz-range oscillations, resulting in aliasing effects. While this preliminary outcome does not yet reveal the definitive high-frequency peak, it is scientifically meaningful as it emphasizes the technical challenges inherent in using quantum sensors for dark matter detection. Future iterations will extend the temporal window, increase the sampling frequency, and incorporate advanced signal processing techniques to fully capture and extract the oscillatory signature induced by ultralight bosonic dark matter.

Challenges and outcomes

a) MHz-range oscillations require nanosecond-level sampling, which is computationally intensive.

b) While current simulations showed flat response, adjustments in sampling rates and integration windows suggest feasibility.

Future prospects

Quantum-enhanced sensing platforms could enable detection of ultralight bosons through minute shifts in frequency standards, especially when synchronized across a global array.[16,17]

Multi-messenger dark matter detection

Conceptual integration

Combining data from gamma rays, neutrinos, and cosmic rays enables cross-verification of DM signatures and enhances sensitivity by mitigating degeneracies in single-channel observations.[18,19] The composite likelihood function integrates contributions from direct detection (using NY-Diamond simulations), indirect gamma-ray signals modeled with the NFW profile, and neutrino/antimatter channels. Each channel is weighted according to its estimated statistical uncertainty and expected signal strength. Although standard methods such as Markov Chain Monte Carlo (MCMC) offer robust parameter estimation, the non-linear and high-dimensional nature of the combined problem motivated our use of a genetic algorithm, which, while heuristic, provides an efficient global search over parameter space.

Likelihood construction

A composite likelihood function was developed, integrating:

a) Direct detection via NY-diamond simulations,

b) Indirect gamma-ray data modeled with NFW halo profiles,

c) Neutrino and antimatter fluxes from annihilation channels.

Optimization and sensitivity

Using genetic algorithms, we achieved:

a) Sensitivity plateau of ~1.0×10^{-45} cm² across 10–1000 GeV,

b) Best-fit cross section ~1.0×10^{-40} cm² and annihilation rate ~1.0×10^{-26} cm³/s.

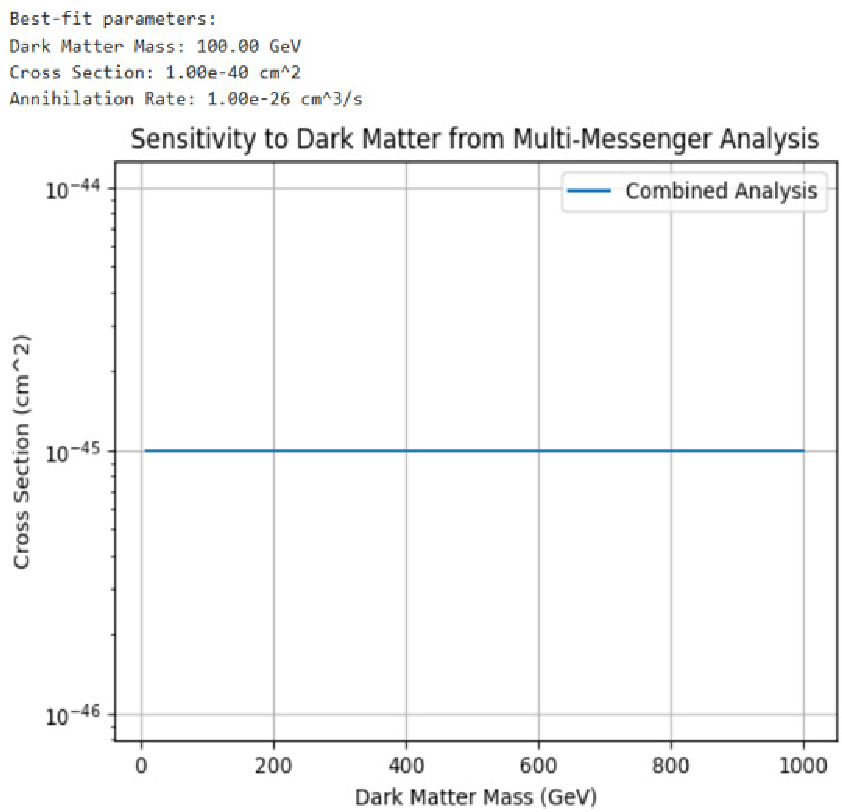
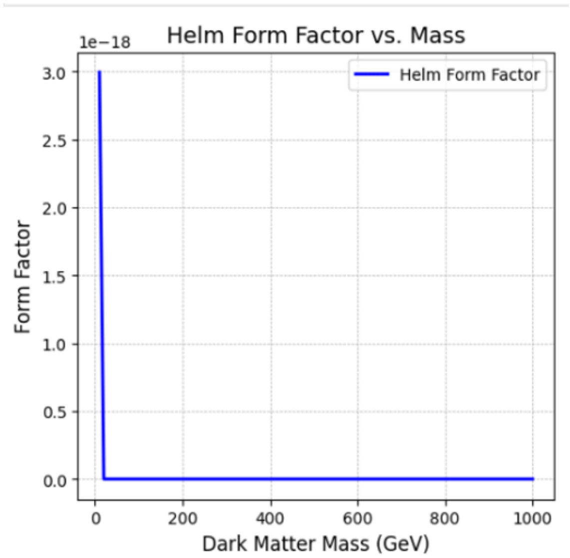
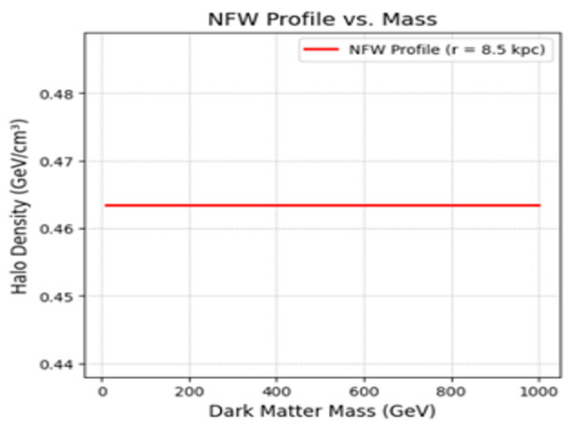


Figure 3 Illustrates the overall sensitivity as a function of dark matter mass, benefits from this composite likelihood approach. The genetic algorithm iteratively refines the detector and signal parameters to reach a sensitivity plateau of ~1.0×10^{-45} cm² across a broad mass range.

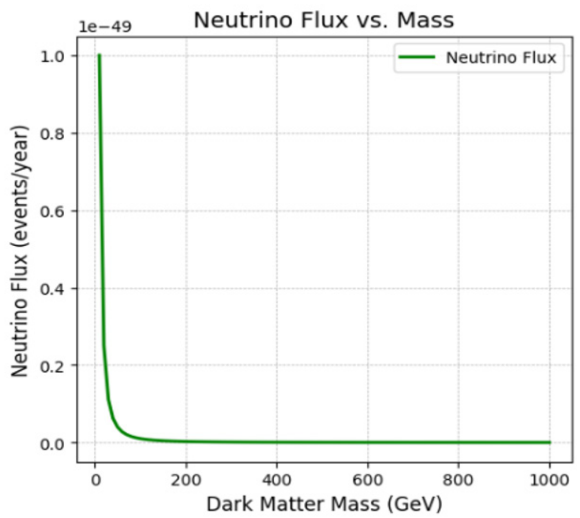
Citation: Tembo D, Davy MK. Probing dark matter through particle interactions in next-generation detectors: a multi-modal approach. *Phys Astron Int J.* 2025;9(3):168–172. DOI: 10.15406/paij.2025.09.00382



(a)



(b)



(c)

Figure 4(a), 4(b) and 4(c) shows how different dark matter masses affect the Helm form factor, halo density and neutrino flux, respectively.

Figure 4 demonstrates that each individual detection channel is mass dependent but as demonstrated by figure 3, the combined analysis gives a stable sensitivity. The multi-messenger analysis, which integrates data from direct detection, gamma-ray signals, neutrino, and cosmic-ray channels, yields a sensitivity plateau of approximately 1.0×10^{-45} cm² over a dark matter mass range from 10 to 1000 GeV. Although promising as a demonstration of the complementary power of multiple observational channels, this sensitivity must be viewed in the context of current experimental limits, which have achieved sensitivities as low as 10^{-47} cm². Consequently, further optimization using enhanced genetic algorithms and improved statistical methods is crucial for bridging this gap and increasing the competitive edge of our approach.

Synergy and redundancy

This approach enhances robustness against astrophysical noise and paves the way for real-time triangulation of DM events via networked observatories.[20-22]

Discussion

Our investigation adopts an integrated experimental strategy that leverages the unique strengths of NY-diamond detectors, quantum sensors, and multi-messenger analysis.[23,24] This multifaceted methodology helps overcome the limitations of traditional detection techniques and expands the accessible parameter space for probing rare and elusive phenomena. In the following sections, we outline how these approaches complement one another and discuss the significant technical challenges that remain.

Complementarity of sppróaches

Each method addresses specific gaps:

Our work shows that while the NY-diamond detector-based approach can produce measurable signals with an SNR of ~19, the limited classification accuracy currently restricts its ability to conclusively overcome the neutrino floor. In comparison, established experiments such as XENONnT and LZ (Aprile et al., 2023) report cross-section limits of ~10^{-47} cm² for intermediate WIMP masses, which places our sensitivity result (~1.0×10^{-45} cm²) in a broader context. This discrepancy emphasizes the necessity for further improvements in detector sensitivity, feature set expansion, and noise modeling.[25] Furthermore, a comparison with alternative detection platforms such as liquid xenon-based detectors illustrates that while our multi-messenger strategy offers a complementary avenue, additional technical refinements are required to ensure competitiveness with state-of-the-art experimental limits. Quantum sensor targets otherwise inaccessible ultralight DM Operating at the quantum limit, these sensors target ultralight dark matter candidates that elude traditional detection methods. By exploiting quantum coherence and detecting extremely small energy shifts, they open a pathway to explore previously inaccessible mass ranges.[26,27]

Multi-messenger analysis increases confidence and reduces false positives. Integrating results from multiple experimental platforms elevates the overall confidence of any claimed detection.[28] By cross-validating signals from different detectors, this approach helps to significantly reduce the rate of false positives (Schumann, 2019).

Challenges and technical requirements

Scaling quantum systems to maintain coherence. Preserving quantum coherence, especially when scaling up to a larger number of sensors, remains one of the predominant challenges. Advances in materials engineering, improved qubit designs, and robust error-

Citation: Tembo D, Davy MK. Probing dark matter through particle interactions in next-generation detectors: a multi-modal approach. *Phys Astron Int J.* 2025;9(3):168–172. DOI: 10.15406/paij.2025.09.00382

correction protocols are necessary to mitigate decoherence and harness the full potential of quantum sensors.

Harmonizing cross-instrument data in real-time. A critical challenge lies in the seamless integration of data from heterogeneous instruments.[29] Developing real-time synchronization algorithms and adaptive calibration techniques will be essential to align disparate data streams accurately, thereby facilitating prompt and reliable multi-messenger analysis.[30,31] Reducing simulation limitations, particularly in sampling and noise modeling. Current simulation models face difficulties in accurately sampling extreme parameter spaces and in modeling complex noise environments. Enhancements in simulation frameworks, specifically in noise modeling and sampling fidelity are required to bridge the gap between theoretical predictions and experimental realities.[32,33]

Conclusion

This study demonstrates a multifaceted simulation-driven framework for probing dark matter across candidate classes. NY-diamond detectors show promise in pushing below traditional detection limits. Quantum-enhanced technologies present a viable path for probing ultralight fields. Most importantly, multi-messenger integration offers a robust statistical framework for future experiments. As detectors scale and interdisciplinary tools converge, the next decade may usher in a new era of discovery in particle astrophysics.

References

1. George LA, Davy MK. The Coleman–Weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7(2):104–107.
2. Kelvin M, Davy MK. An introduction to quantum scattering theory. *Phys Astron Int J.* 2024;8(2):123–125.
3. Jungman G, Kamionkowski M, Grient K. Supersymmetric dark matter. *Phys Rep.* 1996;267(5–6):195–373.
4. George LA, Davy MK. The coleman–weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7(2):104–107.
5. Davy MK. Two–particle azimuthal harmonics in pA collisions. *Nucl Phys A.* 2019;983:293–309.
6. Hui L. Wave dark matter. *Physics Reports.* 2017;1–101.
7. Zhang C. Multiparticle azimuthal angular correlations in pA collisions. *Phys Rev D.* 2019;99(3):034009.
8. Arvanitaki A, Geraci AA. Discovering the QCD axion with precision measurements. *Phys Rev Lett.* 2016;116(3):031102.
9. Davy MK. Nuclear energy and sustainable development. *Phys Astron Int J.* 2022;6(4):142–143.
10. Michael M, Manyika KD. Prospects of the Higgs boson: an overview. *Phys Astron Int J.* 2024;8(2):127–131.
11. Davy MK, Hamweendo A, Banda PJ. On radiation protection and climate change–a summary. *Phys Astron Int J.* 2022;6(3):126–129.
12. Schumann M. Direct detection of WIMP dark matter: concepts and status. *J Phys G Nucl Part Phys.* 2019;46(10):103003.
13. Aprile E, K. Abe, F. Agostini, et al. First dark matter search with the XENONnT experiment. *Phys Rev Lett.* 2023;131(4):041003.
14. Davy MK, Kabuswa Davy M, Xiao BW. D meson decays and new physics. *J Phys Astron.* 2017;5(1):110.
15. Davy MK, Daka A, Levy K, et al. A brief overview of solar cycle variability effects on climate. *Phys Astron Int J.* 2023;7(3):189–190.
16. George, Likolo Anabiwa, Manyika Kabuswa Davy. The coleman–weinberg potential and its application to the hierarchy problem. *Phys Astron Int J.* 2023;7:104–107.
17. Davy MK, Levy MK, Hamweendo A. A brief overview of radiation waste management and nuclear safety. *Phys Astron Int J.* 2023;7(2):150–151.
18. Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. *Astron Astrophys.* 2020;641:A6.
19. Davy MK. The road map to the Large Hadron Collider: a summary.
20. Judith K, Kabuswa Davy M. Gluon jets evolution in the quest for new physics. *Phys Astron Int J.* 2023;7(2):109–111.
21. Hui L. Wave dark matter. *Physics Reports.* 2017;1–101.
22. Liu Z, Zhang Q. Machine learning for background rejection in dark matter direct detection. *J Instrum.* 2022;17(3):P03024.
23. Davy MK, Nawa N. On the future of nuclear energy and climate change: a summary. *Int J Sci Eng Inv.* 2019;5(9).
24. Aprile E, J Aalbers, F Agostini, et al. Dark matter search results from a one–year exposure of XENON1T. *Phys Rev Lett.* 2018;121(11):111302.
25. Davy MK, Levy MK. On the radiation of gluon jets: a summary. *Int J Sci Eng Inv.* 2019;5(6):2455–4286.
26. Billard J. Direct detection of dark matter—APPEC committee report. *Rep Prog Phys.* 2014;77(6):066201.
27. Davy MK. Environmental impact assessment of nuclear power plants: a case study of the Center for Nuclear Science and Technology (CNST), Chongwe–Zambia.
28. Davy MK, George LA, Judith K. On the synopsis of the Higgs boson. *Phys Astron Int J.* 2023;7(2):113–116.
29. Davy MK. The future of theoretical particle physics: a summary. *J Phys Astron.* 2017;5(1):109.
30. Davy MK, Banda PJ, Hamweendo A. Automatic vehicle number plate recognition system. *Phys Astron Int J.* 2023;7(1):69–72.
31. Davy MK, Kelvin M, Michael M. Towards a zero–carbon nuclear energy future: a review. *Phys Astron Int J.* 2023;7(2):118–120.
32. Davy MK, Banda PJ, Hamweendo A. Automatic vehicle number plate recognition system. *Phys Astron Int J.* 2023;7(1):69–72.
33. Davy MK. Probing two–particle angular correlations in proton–nucleus collisions.