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Review of Iftikhar Ahmad's PhD Thesis

PhD Thesis of Iftikhar Ahmad is entitled **Investigating backgrounds in dark matter searches: Argon-37 activation and cosmogenic neutron suppression in the DarkSide experiments.**

The thesis consists of six **Chapters**, a **List of Abbreviations**, an **Appendix A** with information on the ReD experiment, plots illustrating calibration procedures of plastic scintillators, and conclusions. The **Abstract**, **Acknowledgements**, **Contents**, **List of Figures** and **Tables** are also included. It is greatly appreciated that the **Bibliography** includes hot links to all referred publications. Overall, the manuscript is well-structured and organised.

General comments:

As evident in all CERN-based publications, European scientists adhere to UK spelling norms. The thesis, however, follows US norms, preferring, for instance, "minimize" over "minimise." While it is a minor issue, I recommend following the European tradition in the future.

Similarly, many spelling mistakes could have been avoided by using a spelling- and grammar checker. It is a pity that such a tool was not used.

Cutting-edge experiments, like the DarkSide program, involve decades of work by large teams of experts. Therefore, unless explicitly stated, it's impossible to judge what part of the work was done by the author. I wish clear statements had been given to clarify his contribution.

The thesis contains many excellent figures and photographs. Some illustrations are credited to other publications, but the photos have no credits. Are all non-credited figures and photos made by the author?

Title

The accepted writing convention in English is to capitalise words in the title. Hence, the title should be **Investigating Backgrounds in Dark Matter Searches: Argon-37 Activation and Cosmogenic Neutron Suppression in the DarkSide Experiments.**

Abstract

An abstract is expected to be a summary of the thesis. For instance, the text on page 3 of the manuscript contains the information one would expect to find in the abstract. Instead, we have

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a mini-introduction on DM and general information about DarkSide. Additionally, some sentences in the abstract are confusing and ambiguous. For instance:

"The existence of dark matter in the universe is one of the most intriguing components."
Existence is not a component. Did you mean, "Dark matter, if it exists, is one of the most intriguing components of the universe"?

"The evidence for dark matter ranges from galactic to cosmological scales, from its indirect effects."
I find this sentence confusing as it mixes the scale of the observations (galactic to cosmological) with the detection method (indirect effects). After all, indirect DM detection in a laboratory would also satisfy us.

Apparently, "(Add pulse shape discrimination, cost/scaling up, easy to purify)" was a note used during drafting the text and not removed afterwards.

"Cosmogenic muons can still originate backgrounds in underground detectors. It can produce high-energy neutrons or neutron sources by interacting with the experimental setup or the laboratory materials."

The previous sentence refers to cosmogenic muons (plural), so the following sentence should start with "They" rather than "It."

There should be a comma after "Due to their nature".

List of Abbreviations

1. There is inconsistency in the List of Abbreviations. Some of the entries start with a capital letter; some don't. For instance: "**LXe** liquid xenon" and "**LAr** Liquid argon".
2. The abbreviations should but are not listed in alphabetic order.

"**MB** Mother board"
Motherboard is usually spelt as one word.

Chapter 1 provides a comprehensive introduction to dark matter. It reviews the evidence collected from the galactic rotation curves, gravitational lensing, the analysis of the cosmic microwave background gathered by the Planck mission, and Big Bang nucleosynthesis. Formulas, graphs, and references to the relevant papers support the presented evidence.

1.1.1 Galactic rotation curves

"One of the most important evidence…" sounds clumsy. I would suggest "The primary evidence…" or "One of the most important pieces of evidence…".

The cluster mass estimated from equation 1.3 is about two orders of magnitude higher than the average nebula mass for the Virgo cluster. Please add "of magnitude".

One thing that could have been added is information on the proposed alternative explanations for the observed gravitational anomalies, such as MOND.

More information on spin-dependent and spin-independent interaction cross-sections would also be welcome.

Next, DM properties deduced from the available evidence are listed. The list overlaps with the consensus held by most DM researchers. Nevertheless, given the hypothesis promoted by Krzysztof Meissner's group, I would expand the darkness property definition to include charged but very massive and rare gravitinos. Likewise, I would add them to the proposed DM candidates in **Chapter 1.3**. Currently, only axion, neutrino and WIMP-hypotheses are given. These are/were indeed the leading contenders. Naturally, the primary attention is paid to WIMPs, as they are the target of searches by the DarkSide programme.

The introduction to **Chapter 1.4** is very brief but includes **Fig. 1.9**. Such schematic representations are prevalent in publications and presentations. However, I couldn't find it in [**43**: JodiCooley. Dark Matter direct detection of classical WIMPs. *SciPostPhys.Lect.Notes*, page 55, 2022. doi: 10.21468/SciPostPhysLectNotes.55. URL https://scipost. org/10.21468/SciPostPhysLectNotes.55. 18, 19, 20, 21].

Also, I would prefer to tone down the statement that "there is overwhelming evidence of DM at astronomical and cosmological scales." The evidence is convincing and consistent with the DM hypothesis but perhaps not overwhelming. The author confirms this in the following chapter (**Chapter 1.4.1**), where he admits that Cherenkov telescopes [45, 46], the Fermi Large Area Telescope [47, 48], and others have failed to detect DM annihilation products. The only evidence we have comes from gravitational anomalies.

Chapter 1.4.3, "Direct detection of dark matter", explains the topic well and provides a good selection of figures. In particular, the combination of **Fig. 1.11** and **Tab. 1.1** is very helpful.

Chapter 1.5, "Current status of direct detection of WIMPs," is brief but well-referenced and illustrated.

Chapter 2.1. The sentence "used 5 times more LAr targets than its predecessor" is somewhat clumsy. The author probably meant "with the target containing 5 times more LAr".

It would be helpful to the reader to have the operation periods for each phase of the DarkSide project clearly stated in Chapter 2.1. For instance, Dark-Side-10 operated in Gran Sasso from 2011 to 2012.

Chapter 2.2, "Target medium UAr". Although all abbreviations are listed and explained on page ix, it's a good practice to provide their meaning where they appear in the text for the first time. That concerns UAr as well.

Chapter 2.6.1, Photomultiplier tubes (PMT).
It should be (PMTs).
"As more photoelectrons hit each succeeding dynode in this cascade process, it results in a high amplification of the initial photon, as shown in figure 2.3."
Photoelectrons are emitted only from the photocathode. Electrons knocked out from dynodes are secondary electrons, as correctly marked in Fig. 2.3 but incorrectly named in the quoted sentence.

Chapter 2.6.2, Silicon photomultipliers (SiPMs)

"Impact ionization starts at a characteristic voltage, called a breakdown voltage, above which the avalanche process becomes self-sustained i.e. Geiger-mode Avalanche Photo Diodes (G-APDs)."
The sentence is confusing. You probably meant, "…, therefore SiPMs are also called Geiger-mode Avalanche Photo Diodes (G-APDs)."

"A Silicon photomultiplier (SiPM) comprises hundreds to tens of thousands of SPADs arranged in a two-dimensional array called pixels [112, 113, 114, 115]." Arrays are not called pixels. Pixels are elements of an array of pixels.

Chapter 2.6.2.2, Pixel recovery time

Providing the numerical recovery time range for the SiPMs used in your devices would be beneficial. The reader should know if it is in the nano- or micro-second range. Since the equation $t \sim C_d \cdot R_q$ is given, the meaning of these parameters should also be explained.

Chapter 2.6.2.4, Afterpulses

"To calculate the probability of afterpulse, the time constant for recharge can be tuned so that most trapped charge carriers are released during the recovery phase [113]."

The statement is not correct. What [113] says is that "…in order to reduce the afterpulse probabilty (or at least its visible effect), the recharge time constant can be tuned in order that most of the trapped charge carrier release happens when the cell is not yet (fully) recharged. Consequently a long SPAD recharge time generally reduces the afterpulse probability."

Chapter 2.6.2.5, Optical cross talk

Crosstalk is one word, not two.

Chapter 2.7, Dual-phase TPC

While "liquid noble detectors" is an often-used colloquial phrase, they should be called "liquid noble gas detectors".

"This volume represents a much cleaner region in the innermost part of the TPC,". The adjective cleaner may indicate higher purity of the liquid, while the purpose of selecting the fiducial volume is to reduce the background by benefiting from self-shielding.

Chapter 2.8.1.1, The DarkSide-50 TPC

"The TPC consists of a 36 cm by 36 cm cylinder…" It would be good to clarify that 36 refers to the diameter, not the radius.

The drift length and drift field strength are not listed.

Chapter 2.8.1.2, Neutron veto

The paragraph following the two bullets is unrelated to the neutron veto. It describes the **triggering and operation** of the DarkSide-50 experiment. Therefore, this paragraph should be in a sub-chapter.

Relevant information is also missing. For instance, what was the width of the coincidence gate for rejecting the neutron and muon-induced background?

Finally, to describe the outcome of DarkSide-50, I would include a figure analogous to Figure 2.11.

Chapter 2.8.2, DarkSide-20k

"DS-20k is currently assembled in Hall C of LNGS and is aimed to start operation by 2027. DS-20k is designed to detect the high-mass WIMPs (in the range of 30 keV to 200 keV) [124]. DS-20k will have a negligible instrumental background in the region of interest."

One could have used bullet points instead of having three sentences in raw with identical beginning. Also, "is assembled" indicates that the construction has ended. You probably meant that the detector is being assembled.

"…reaching the neutrino fog."
Fig. 2.11 clarifies that while DarkSide-20k will be approaching the neutrino floor, it won't reach it.

It may not be obvious to everybody what a "ProtoDUNE-like cryostat membrane" is. You could have referred to Figure 2.15.

"Figure 2.14: Outer cosmic veto of the DS-20k experiment under construction at LNGS."
What dominates the photo is the massive support constructed for the membrane tank to hold LAr. Where is the outer cosmic veto?

Chapter 2.8.4, DarkSide-LowMass

"Figure 2.17: Conceptual detector design:"
Is there a name of this project?

Again, comparing the project's reach on a figure similar to Figure 2.11 would be good.

Chapter 3.1, Introduction

"…radioactive isotopes are activated by cosmic rays."
You probably meant "produced by cosmic rays".

"In this chapter details are provided on, the UAr transport and the main backgrounds in DS-50 along with my contribution to measuring the activation of 37Ar."

There are misplaced commas in this sentence. It should be:
"In this chapter, details are provided on the UAr transport and the main backgrounds in DS-50 along with my contribution to measuring the activation of 37Ar."

Chapter 3.2, Transportation history of UAr

"3.1 shows the transport path…"
It should be: **Fig.** 3.1 shows the transport path…

Chapter 3.3, Production of radioactive isotopes in argon

"The production channels are given in the below equations."
These are not equations. An arrow is not the same as an equal sign.

"I will describe the main backgrounds DS-50."
It should be: I will describe the main DS-50 backgrounds.

Chapter 3.4.4, Muons

"The direct DM search experiments are placed and run at underground laboratories providing the Earth overburden and thus shielding against cosmic rays muons and their secondaries [143, 144, 42]. "

Earth, spelt with capital "E", is our planet; spelt with a lowercase "e" means soil. In the context of the quoted sentence, the second meaning is appropriate.

Chapter 3.4.5, Cherenkov radiation
"The Cherenkov signals can be produced when high-energy electrons interact with high refractive index detector materials [146]."

Cherenkov light is always emitted when high-energy electrons traverse materials with n>1.

Chapter 3.5.1, Data extraction
The chapter contains five figures with hardly any explanations. Consequently, the reader is left with more questions than answers. For instance, most of the events in Figs. 3.4 and 3.6 saturate at some Y-values, but a few do not. Why?

The meaning of the blue diagonal dotted line in Figure 3.2 has not been explained.

Chapter 3.5.2, Background consistency

One of the elements of Figure 3.7 (70-day Background) is invisible.

The standard abbreviation for Background is BG, not Bkg.
The legend of Fig. 3.7 is inconsistent. It contains abbreviated and unabbreviated Background.

It is not indicated which data set represents the last 400-day data.

"The fiducial volume ~~is~~ of 19.9±0.3 kg is used for this study."

Chapter 3.5.3, Analysis strategy

One of the elements of **Figure 3.11** (70-day Background) is invisible.

Chapter 3.5.4, Results and Discussion

I do not understand why decay time is preferred over the half-life. Most publications, e.g. https://arxiv.org/abs/1008.0691 , and Wikipedia, give half-life rather than decay time. Therefore, both values should be given for easy comparison (without a calculator).

Chapter 3.6, Conclusion

The chapter's name (singular) contradicts multiple statements in the content. I think "Summary" would be a better title for this chapter.

Chapter 4, DarkSide-20k: Cosmogenic muons study

It is the first chapter with clearly stated contribution by the author:

"I contributed to translating the geometry from the technical design report of DS-20k [102] in FLUKA, creating the singularity container to run the simulation on the cluster, and in data analysis of the simulation results."
By the way, it should be [translating the geometry] **into** FLUKA.

The chapter is very technical, and the text does little to help readers comprehend the steps described and the figures presented. Many statements and facts are given without comments or explanations. We learn what was done but not why it was done. For instance, "The DS-20k FLUKA simulation was performed for a livetime equivalent to 229.2 years." There is no explanation for why such a value was chosen and no comments on whether it is too much, too little, or just right.

"**Figure 4.5**: Spectrum of the energy deposited by ~~a~~ 10 keV neutrons…"

Table 4.5

There is a mismatch between the error bars (with four digits after the decimal point) and the given event rate listed only with two digits after the decimal point.

Chapter 4.7, Conclusion

Again, the chapter's name (singular) contradicts multiple statements in the content. I think "Summary" would be a better title for this chapter.

Chapter 5, DarkSide-20k: Veto readout system

This chapter is also very technical and focused on details. It would help to have some guidance on the presented intricacies and to clarify the procedures' relevance to the final measurement's success.

5.1 Introduction

Two important points are missing from the list of SiPM advantages: a lower cost and a compact size.

"*Why use a neutron veto detector, and how does it work?* " I believe it should be a sub-chapter title for the text that follows it.

Figure 5.2: View from above of the PDU displaying 16 vTiles installed on the Mother board (MB) and shielded by an acrylic sheet. Figure taken from [102].

Please note that motherboard is usually spelt as one word.

Figure 5.3: Various stages of PDUs development for DS-20k.
This figure depicts not a development but a structure of the TPC optical plane.

Table 5.1: DarkSide SiPM Requirements

The required breakdown voltage for vTile is unlikely to be exactly 55 V. Usually, only a lower limit or a range of voltages is given. The breakdown voltage is also dependent on temperature.

Chapter 5.3, vPDU assembly procedure

I assume the author carried out part of this work, as the assembly procedures are described in detail and photographically documented. It would have been good to state it explicitly.

Figure 5.30: (a): Dust particles from the plastic holders on top of the vPDU. (b): vPDU holder with the capability of testing 10 vPDUs.

It should be "Dust particles visible on the…"

Chapter 5.8, Conclusion

Once more, the chapter's name (singular) contradicts multiple statements in the content. I think "Summary" would be a better title for this chapter.

Chapter 6, Conclusions and Future perspectives

Perspectives should be spelt with a capital P.

This is the final and most important chapter of the thesis. Care should be taken when phrasing each sentence of this short section. Repetitions ("The DS-20k uses UAr", "The DS-50 experiment employs UAr") should be avoided.

Question: DS-20k will use 50/20 tons of LAr. The biggest LAr-based TPC, currently under construction as part of the DUNE experiment, will be one thousand times larger. Is it possible/justified to propose a successor of DS-20k with a significantly larger fiducial mass?

Appendix A, ReD experiment

In my opinion, the ReD Experiment could have been one of the regular chapters of the thesis.

A.2 Conclusion
Again, I think "Summary" would be a better title for this chapter.

In summary, Iftikhar Ahmad's doctoral dissertation constitutes an original and significant contribution to the preparatory and construction phase of the DarkSide-20k experiment. He demonstrated in-depth knowledge of this cutting-edge project, especially the aspects related to the FLUKA simulations of neutron background, activation analysis for Argon-37, and hands-on work with the Veto Photon-Detector Unit (vPDU).

The most significant contribution of the thesis is presented in Chapter 4, where DarkSide-20k simulations are described in detail. After the necessary introduction to cosmogenic neutron production, neutron background estimation, the DS-20k-specific FLUKA environment and the detector geometry, the focus shifts to the simulation procedures and results. The procedures were validated "by simulating neutrons, α particles, and electrons of energy 10 keV in the OV detector (0,0,300 cm) and checking if outcomes agree with our expectation from input particles". Additional tests were performed "using neutrons in the DS-20k geometry FLUKA input file [153]". The results of these thorough validation tests were successful, adding credibility to the simulation approach and techniques. The simulations were performed for a "livetime equivalent to 229.2 years". This is ~23 times the planned running time for the experiment. The main conclusion of the thesis is that, based on the simulations, all cosmogenic background events will be unambiguously rejected in the data analysis using stringent selection cuts. **This conclusion is of fundamental importance to the DarkSide project and Dark Matter searches in general.** It shows that DS-20k is well designed and may indeed produce the long-awaited breakthrough in terrestrial searches of WIMP interactions with standard matter. If such interactions were detected and verified, it would certainly merit a Nobel Prize in Physics.

The submitted dissertation demonstrates the candidate's ability to conduct scientific work independently. I think **Iftikhar Ahmad's doctoral thesis** is a valuable contribution to the experimental physics program at AstroCeNT and meets the legal criteria for a doctoral dissertation. **Therefore, I request that it be admitted to public defence**.

Yours truly,

Wladyslaw Henryk Trzaska

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