JAGIELLONIAN UNIVERSITY IN KRAKOW

Faculty of Physics, Astronomy and Applied Computer Science

Kraków, 20.01.2025

dr hab. Aleksandra Wrońska, prof. UJ
Wydział Fizyki, Astronomii i Informatyki Stosowanej
Uniwersytet Jagielloński
ul. Łojasiewicza 11
30-348 Kraków

Review and assessment of the doctoral dissertation of Mr. Paules Zakhary
"Measurement of Nuclear Recoils in Liquid Argon for Dark Matter Searches"

This review has been prepared upon the request of prof. dr hab. Piotr Życki, chairman of the Scientific Council of the Nicolaus Copernicus Astronomical Center (CAMK) in Warsaw, expressed in the letter dated October 26, 2024, and the following correspondence. By accordance with the requirements of the Higher Education and Science Act, the aim of this assessment is to determine whether the submitted dissertation fulfills the prerequisites for the conferment of a doctoral degree, which are the following:

1. the doctoral dissertation constitutes an original solution to a scientific problem,
2. the dissertation demonstrates the candidate's general theoretical knowledge in a given scientific discipline,
3. the dissertation demonstrates the candidate's ability to independently conduct scientific work.

In my report, I will refer to those points.

The thesis presented by Mr. Zakhary is focused on detection techniques relevant in Dark Matter (DM) searches. Overall, it comprises 128 pages, and the content is organized in five chapters, 2 appendices and a bibliography. The main part is preceded by an abstract presented both in English and Polish, complying to the legal requirements in this respect. The content of the thesis is presented in very good and easy readable English language, and incorporates 47 figures and 2 tables. The figures are carefully thought through and prepared, and significantly facilitate assimilation of the dissertation content by the reader. Notably, the dissertation has been prepared as a part of the DarkSide (DarkSide-20k) project.

The purpose of Mr. Zakhary's doctoral project was to characterize the response of a liquid-argon (LAr) detector in the form of a dual-phase time projection chamber (TPC) to nuclear recoils (NRs) with kinetic energies of 1-10 keV. Such exploratory studies are prerequisites to extending the experimental quest for Weekly Interacting Massive Particles (WIMPs), one of the postulated constituents of DM, to lower masses thereof (~1 GeV/c^2). As quite stringent constraints on the WIMP-nucleon cross sections for WIMP masses above 10 GeV/c^2 have been provided by other experiments, it is important to explore the lower-mass region with sufficient experimental precision, accuracy and sensitivity, necessary to obtain meaningful results. Mr. Zakhary's work is a step in this important direction.

ul. prof. Stanisława Łojasiewicza 11
PL 30-348 Kraków
tel. +48(12) 664-48-90
fax +48(12) 664-49-05
e-mail: wydzial.fais@uj.edu.pl

In the first chapter, a reader finds a comprehensive introduction to DM – from observational indications of its existence, through the hypotheses about its composition, to the theoretical consideration about the detection of DM particles with a focus on WIMPs. The next chapter explains the operation principle of noble liquid detectors. While initially rather general, it soon focuses on argon, discussing various microscopic effects affecting the signals, such as quenching and recombination. Also, particle identification capabilities with LAr detectors as well as the physics program of the DarkSide collaboration and its successors are discussed in this chapter. On the substantive side, Author's main contributions are contained in the next two chapters. In chapter III, the Author presents experimental setup ReD incorporating an LAr TPC along with a neutron source and scintillating detectors for neutron tagging, and describes the measurements performed by him at the INFN LNS in Catania in the first months of 2023 (the total duration of his stay in Catania was 7 months). Chapter IV contains a presentation of the used methods and techniques of data analysis, the obtained results, and a thorough discussion of systematic uncertainties. The thesis is concluded with chapter V, where readers will also find the directions of future work envisaged by the Author. The content is supplemented with two appendices – one presenting the kinematical derivation of formulae required to calculate the kinetic energy of NRs in neutron scattering, and the other describing a spin-off project carried out by the Author on ^{37}Ar source on-demand production and deployment via CaO irradiation with neutrons.

The content of the thesis shows that the Author has broad knowledge on DM both from the theoretical and experimental side. The ReD experiment described required from Mr. Zakhary to develop expert skills in hardware as well as in data analysis, although in the latter aspect he certainly took advantage of the existing data-analysis codes of the collaboration. This shows, that **the requirements 2 and 3 listed above have been met**. The main result of the ReD experiment, i.e. determination of the argon ionization yield Q_y^{NR} in the detector-independent units gives impressive results that extend the scarce data delivered by other experiments for the NR energies of 2-10 keV. This analysis is preceded by a careful calibration of all involved detectors. I enjoyed in particular a very clear, exemplary description of the noise characterization of silicon photomultipliers (SiPMs) in section 3.6.1. The other project described in Appendix B, although concluded with only indirect evidence of ^{37}Ar production from the presence of ^{42}K, paves a way to further experimental studies on the topic. Notably, the project and its outcome have been published as an article in the *Journal of Instrumentation*, signed solely by Mr. Zakhary, which shows that he was the driving force of this research. The outcome of this and the main doctoral project show that **the requirement 1 has been fulfilled as well**. Additionally, Mr. Paules Zakhary co-authored five other articles (including one preprint) of the DarkSide-20k collaboration (3), Global Argon Dark Matter Collaboration (1) and in a group of three authors (1). This shows that the Candidate, over the years of his work on the doctoral project, has integrated with the community and was able to contribute to the DM research conducted by it.

As for the Author’s contributions to the thesis content, it is clearly stated in pages 39/40, 67 and 89/90.

Having listed the merits of Mr. Zakhary’s dissertation, I would pose several questions that occurred to me when reading the thesis and indicate some shortcomings/mistakes/errors. I divided them into two categories based on their importance.

JAGIELLONIAN UNIVERSITY IN KRAKOW

Faculty of Physics, Astronomy and Applied Computer Science

Major issues and questions:

1. In Section 1.1, the reason for introducing the Λ factor is incorrect – it was introduced by Einstein long before the observation of the expansion of the Universe.
2. Eq. 1.6 is not supported with a reference and the symbols Ω with an additional subscript "0" are not explained.
3. In the first paragraph of Section 1.4.1, the Author brings up the argument of electric moment of the neutron, without giving a reference. Are other particle types relevant in the axion search as well?
4. In Section 1.4.3 the Author discusses sterile neutrinos. I am missing references for the last paragraph about the ongoing experimental/observational efforts.
5. Section 2.3.1, first paragraph describing formula 2.4: from the description, l.h.s of the upper equation if the energy loss (integral quantity), while the quantities on the r.h.s. are both differential (stopping powers).
6. For Eq. 2.6, the interpretation of parameters κ and ε is not stated (for κ it appears later in the text).
7. On page 31, in the last paragraph, the Author quotes different values of the α parameter in the literature and leaves the reader without any comment on the huge discrepancy visible.
8. In page 37 we find the statement "Conversely, for low-mass WIMPs, which generate nuclear recoils in the lower energy range of 1–30 keV_{nr}, background differentiation relies on the detailed analysis of the ionization signal spectrum rather than PSD which is less effective.". A reader that is not an insider is missing a supporting argument or an example.
9. How is it possible that the left and right axis scales in Fig. 3.1 that show the same quantity in different units, span different ranges in orders of magnitude? (left: 13, right:14), if the units are simply related by a factor of 10^{24}?
10. The neutron flux quoted on page 43 is inconsistent with the numbers from the preceding paragraph, which lead to the flux of 3.03e3 neutrons/s.
11. Spectra in Fig. 3.7 call for a more elaborated fit than a bare gaussian peak, including some background modelling, to avoid bias, in particular for Co-60 and Eu-152, where the photopeaks are located on a non-constant background. Moreover, the figure caption states the energy resolution of the BaF detectors, without specifying at which energy it was determined (the quantity is energy-dependent!). Are the quoted values arithmetic means of resolutions from the four peaks? How could one have presented it better?
12. In Table 3.1, the b parameter should bear the units of keV. I would also expect to see the uncertainties of the parameters resulting from the fit.
13. In page 51 one finds: "and reconstructed the waveforms by utilizing a prolonged charge integration window of 500 ns". The sentence is unclear, I thought the waveforms were recorded (no need for reconstruction!) and the charge was obtained from waveform integration. Or wasn't it?
14. Fig. 3.9 Rather than the gain, I would expect to see the formula allowing one to recalculate charge in ADC units to energy in keV. The form of results is confusing – if "(1.000)" is the gain uncertainty, then it is stated with excessive precision, different than the result itself, violating the rules.
15. For formulae 3.2: It would be good to indicate that these formulae are valid for a signal that peaks at t=0, not starts at t=0. In general, an offset is needed.
16. Figure 4.1: how can the time bin width be below 1 sample?
17. Figure 4.3: is the data plotted for a single PSci channel? Because given the scatter of the peak location for different PScis before the correction, I would

ul. prof. Stanisława Łojasiewicza 11
PL 30-348 Kraków
tel. +48(12) 664-48-90
fax +48(12) 664-49-05
e-mail: wydzial.fais@uj.edu.pl

expect the peaks in figure 4.3 to become narrower after the application of offsets, which is not really visible here.

18. Page 71: Why two different metrics for ToF resolution have been introduced? Would it not be better to consistently use FWHM, which is shape-independent and thus applicable to both shapes: a Gaussian and an asymmetric peak? (and which is, notably, NOT a standard deviation, as described in the text! How was BAF1-PScis FWHM recalculated?)
19. Formula 4.5 neglects the possible correlations between the parameters. Is it justified?
20. Page 80: $\delta\theta_{scatt}$ expressed in % is puzzling and seems incorrect; Fraction of what?
21. Why has the work on elaborating the g_2 factor solely on ReD data finalized withing the scope of this thesis, if the steps seemed clear?
22. Figure 4.17 and the surrounding text: the argument that a different value of the g_2 factor may call for the need to expand the error bars is not quite correct. Change in g_2 would result in a systematic scaling of all the data points. Thus, it cannot restore consistency with the DS-50 model in the full investigated energy range.
23. Page 87, first bullet: does the Author mean by that a correction for the walk effect? Is it needed, if a constant-fraction-like timing was applied to waveforms?
24. Figure B.4: How was the binning adjusted? I would expect better fit quality for coarser binning (i.e. a rebinned spectrum).
25. Page 111: “HPGe measurement is susceptible to some uncertainties”. This type of detector is routinely used for high-precision spectroscopic measurements, also those aiming at activity determination. What kind of uncertainties are meant here?

Minor issues:

1. Although the level of English is very good, punctuation and capitalization are a somewhat weaker side.
2. Also, the use of italic/regular sub- and superscripts seem random and not always consistent. The same applies to common functions.
3. In the Polish version of the Abstract, the abbreviation NR remains undefined.
4. Friedman invoked in Section 1.1 is spelled with a single n.
5. The symbol z used presumably for redshift in page 4 is not defined/explained.
6. When using active voice, the Author switches between singular and plural.
7. Non-baryonic DM discussed on page 9 lacks a reference.
8. In Eq. 1.19, A must be a molar mass (not atomic mass, as stated), from the analysis of units.
9. Caption of Figure 2.1: incorrect description of colour coding.
10. Page 38: the abbreviation ROI is unresolved.
11. Last paragraph of 3.4.1: at this point it is totally unclear for the reader, if two PMTs are attached to a single crystal, or each of the two crystals was equipped with a different PMT. This becomes clear only later.
12. The length of the PScis active parts is not stated in 3.4.3.
13. In the second paragraph on page 56, I would expect an original reference to a handbook rather than a PhD thesis.
14. In page 58: “The raw waveforms...” - here details are missing: sampling frequency, typical signal shape – at calibration and from NR, integration window, etc. A reader only obtains them much later.

15. In page 61, there are two almost identical blocks of text starting with "Although/while the relationship between charge...". Probably leftover from editing.
16. Figure 3.18 and the text around: DCR should have the units of cps, not Hz, since the dark counts are not a periodic phenomenon.
17. Figure 4.11: These are not 1D distributions, so the caption should state "S2 signal versus the..."
18. Bibliography: lack of standarization for journal article entries: redundant URLs for those having dois, presence/absence of ISSN, fully capitalized authors names etc.
19. Obvious typo in the last entry of Eq. Set A.2: θ_1 should be θ_2.

While I would be happy to discuss the major points listed above during the public defense, they do not change my positive assessment of the dissertation and the overall outcome of Mr. Zakhary's doctoral project.

Summing up, I consider the doctoral thesis of Mr. Paules Zakhary to be a valuable contribution to the field of Dark Matter search and to meet both the substantive and the formal criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Aleksandra Wrońska

Podpisany elektronicznie przez
Aleksandra Wrońska
20.01.2025
0:15:34 +01'00'

JAGIELLONIAN UNIVERSITY IN KRAKOW

Faculty of Physics, Astronomy and Applied Computer Science

ul. prof. Stanisława Łojasiewicza 11
PL 30-348 Kraków
tel. +48(12) 664-48-90
fax +48(12) 664-49-05
e-mail: wydzial.fais@uj.edu.pl