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The review report of the PhD thesis by Paules Zakhary, titled "Measurement of Nuclear Recoils in Liquid Argon for Dark Matter Searches"

The thesis was prepared in the Particle Astrophysics and Technology Centre (AstroCeNT) at the Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences by Paules Zakhary under supervision of Dr. hab. Marcin Kuźniak and Dr. Masayuki Wada. The dissertation contains 128 pages with 112 pages of main body preceded by 16 pages comprising the title page, the abstract in English and Polish, the acknowledgements, and finally Table of Contents and List of Illustrations. The main text is written in English and is divided into 5 chapters, where the author presents: introduction to description of part of the Universe mass using Dark Matter (DM); the principle of operation of Liquid Argon Detectors and the design of the detector used in this study; the calibration procedure of the experimental setup; the data analysis and most important results; and finally, the conclusion and perspectives. The chapters are properly structured into subsections that introduce the reader to the topic presented in the dissertation and depict the work step-by-step, showing a well-defined plan of investigations. The bibliography is provided as usual at the end of the manuscript and contains numerous references supplementing the study with relevant information for investigators interested in specific details. Two appendixes are added with derivation of the formula used for calculation of scattered particle momentum and with description of production and use of ^{37}Ar source for the LAr TPC detector.

In chapter I the author describes cosmology models incorporating existence of DM as necessary component to explain the evolution of Universe. Example of different distribution of mass and plasma components is given as one of the indicators for DM existence. Next, DM candidates are considered and their potential properties are discussed, pointing to Weakly Interacting Massive Particles (WIMPs) as observables investigated in the scope of this research. The author presents the detection scenarios indicating registration of nuclear recoils from WIMPs elastic scattering as the source of signal that can be utilized to prove the existence of DM in the mentioned form.

Chapter II contains description of operation principle of noble gas detectors based on Ar. The author presents scenarios leading to luminescence that can be readout to produce detectable signals. Subsequently, particle discrimination capability of Ar-based detectors is presented as possible due to differences in singlet and triplet state decay times and population when induced by electrons or nuclear recoils. The author describes also accompanying processes causing scintillation quenching.

Next, the concept of a dual-phase time projection chamber (TPC) containing Ar in liquid (LAr) and gaseous forms is described. The author depicts signal generation in LAr through scintillation and electroluminescence. The chapter is finalized with examples of experiments utilizing dual-phase LAr TPCs.

Chapter III depicts the calibration procedure for measurement of neutron recoils energy by electroluminescence signal as the method for quantitative evaluation of LAr TPC performance. The chapter starts with a review of sensitivity limits achieved in a wide range of experiments devoted to WIMP detection. The thesis is defined on page 42, pointing to the measurement of the ionization of nuclear recoils in the energy range from 2 keV_{nr} to 10 keV_{nr}. The objective of the study is introduced in the framework of the ReD (Recoil Directionality) experiment. Subsequently, the author describes the experimental setup used for data collection. All crucial aspects including geometry of the measurement, detectors, shielding materials and radiation source are addressed providing good understanding of methodology implemented. The details given allow reproducing the experiment by other investigators. Thanks to this, the dissertation serves also as a valuable educational material, as this kind of setup is universal and could be used for characterization of other types of detectors. The construction of the dual-phase LAr TPC is presented extensively including numerous technical details of the cryogenic system and the light readout.

In chapter IV the author provides the description of data analysis performed within the scope of his PhD study. The following subsections reveal detailed information about:

- signal detection and processing,
- offset evaluation,
- coincidence resolving time measurement,
- neutron and gamma-ray events identification through Pulse Shape Discrimination (PSD) in Plastic Scintillators (PScis),
- neutron selection using Time of Flight (ToF) technique,
- gamma-ray background reduction,
- measurement of incoming neutron energy,
- reduction of accidental coincidence signals.

Subsequently, the author discusses thoroughly the factors influencing the neutron recoils energy resolution providing quantitative evaluation of uncertainty contributions, resulting in 16% relative uncertainty. Evaluation of g_2 gain is not presented in details and only preliminary value equal to 17.2 PE/e^- (photoelectrons per electron) is reported based on cross-calibration with DS-50 experiment data. Finally, ionization yield is calculated from recorded data. The Q^{NR} value is recoil energy dependent, the values are about 10% higher than DS-50 predictions. At higher recoil energy, the results are consistent with Joshi et al. and ARIS data. Worth mentioning is coverage of much wider recoil energy range, reaching down to 2 keV_{nr}.

Conclusion and prospects of continuation aimed at improvement of results are presented in chapter V. The author recalls the achievement of the dissertation goal, namely the determination of ionization yield for low-energy nuclear recoils in the range between 2 keV_{nr} and 10 keV_{nr}. Subsequently, he depicts a list of modifications, extensions and improvements to the experimental procedure that should result in achieving more precise and reliable result. I find the evaluation of the ionization signal gain (g_2) as the most crucial with tuning the timing performance and position reconstruction following. The author notices the non-proportional response of PScis and seems to be aware of this fact for BaF_2 detectors; however, I suppose taking into account these effects will not have a significant impact on the precision since the energy information about the incoming and scattered particle is derived from

the time differences recorded and the angles defined by setup geometry. Finally, the author highlights the significance of the major findings of this study, pointing the importance of bringing down the measurement threshold to 2 keV_{nr} only, much lower to measurements performed by other investigators. The provided result gives a valuable opportunity to compare the data with theoretical predictions, previously the only source of ionization yield estimation at such low recoil energy.

General remarks:

The author often uses plural forms to describe the efforts taken to present the results of the research. It is well understood and accepted that PhD dissertations in experimental particle physics or astronomy are carried out in large teams rather than by a single scientist. However, once it comes to editing the thesis, the author is meant to be the sole person responsible for text writing. The good thing is the author clearly stated his involvement in data collection and analysis in the chapter V (Conclusion and Further Work) leaving no doubt about his contribution.

There is no abbreviation list included in the thesis, it would be helpful to collect the abbreviations used in one place as they are used throughout all document. Most of the abbreviations are explained in the text, however the term "ΛCDM" is not (used on p. 2 for the first time). It is also not explained that z~1100 is corresponding to the redshift at which recombination occurred, however this fact is well recognized in the field.

It is a bit surprising that the goal of the dissertation is not clearly stated in neither abstract nor the introduction chapter; however, it finally appears to the readers in the middle part (p. 42).

Minor comments (no need to be addressed by the author):

p. 39: PSci not explained when used for the first time, defined on p. 44.

p. 48: "... at the recommended *supply voltage* ..." would be more accurate than "*power*"

p. 48: the effect of non-proportional response to absorbed radiation is not addressed in the calibration of BaF_2 detectors, however it should have a negligible effect for the analysis of data in this study.

p. 65: *Hz* is a unit used for description of quantities in periodical processes, while dark counts emission is stochastic. It is not proper to use *Hz* for dark count rate that should be reported in *1/s*, eventually counts-per-second (*cps*).

p. 68: instead of "$t = (d_{BaF\text{-}PSci}) / c$", more accurate would be to write "$t = (d_{PSci} - d_{BaF}) / c$", where d_k is the distance between the source and respective detectors, I believe the author meant the same.

p. 77: "*accedintals*" should be replaced with "*accidentals*" in text and Fig. 4.11.

Major comments (requested to be discussed by the author):

p.43: ^{252}Cf source of 26 kBq activity yields about 3000 n/s. The reported yield of 4500 n/s comes from a more active source, slightly above 1 μCi.

p. 45: The equation 3.1 defines recoil energy as a function of scattering angle in center-of-mass (CM) framework. In the *Appendix A* the author provides a derivation employing laboratory angle (LAB) of scattering, and it is still not reaching the formula for recoil energy, though it is not far

away from it. The readers should be informed about approximation used here and the author should be aware of the scale of difference that it introduces to the analysis.

p. 58: Description of procedure for evaluation of photoelectron yield is not 100% clear to me, was the meaning "Prominence *of the residual*, defined as the difference between the filtered waveform and the moving average, ..."?

p. 60: It would be valuable to have a comment why integrating window width was chosen 4 μs.

p. 76: Obtaining the incoming neutrons kinetic energy is a very good result. It would be valuable to compare it with ^{252}Cf energy spectrum presented in Fig. 3.3, some information about threshold and efficiency of the method could be possibly withdrawn.

In summary, the PhD thesis is presented with high quality and clearness. The introduction to the topic may serve as a good review of currently studied models of DM. I emphasize the value of detailed description of experimental setup and calibration procedure. It can be used for benchmarking similar detectors in other experiments in this field as beyond. Moreover, it has significant educational value, as can be used as source of laboratory tests based on performance characterization of experimental setup components separated or used jointly. Except for lack of discussion of using interchangeably laboratory and center-of-mass frame for recoil energy calculation as a function of scattering angle, the inconsistences pointed out in the review do not lower substantially the rating of this dissertation. The result obtained by the author is of great significance for preparation of the detection setup to the main goal of the experimental campaign, i.e. registration of WIMP signals through nuclear recoils from elastic scattering. The author revealed that he has profound knowledge of the topic by presenting rich theoretical description, details of experimental setup and calibration procedure, as well as data analysis and discussion. It proves that he is already experienced scientist that can contribute with substantial input to future experiments in either this field, or any other related that may incorporate ideas and technics used in the framework of this study.

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

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