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Review of the PhD thesis of mgr. Paules Zakhary: "Measurement of Nuclear Recoils in Liquid Argon for Dark Matter Searches"

The PhD thesis of mgr. Paules Zakhary has 112 pages, including a bibliography and appendices. The main contents of the thesis are a series of analyses conducted at the ReD (Recoil Directionality) experiment to understand the liquid argon's (LAr) response to low-energy nuclear recoils within the $2 - 10$ keV$_{nr}$ range. In this kinematic region, an isolated ionisation signal called the S2 (or S2-only) signal is important. The analyses performed by the author aim to estimate the ionization yield ($Q_y^{\rm NR}$), which is an important detector-independent parameter for the S2 signal as a function of the nuclear recoil energy. These analyses have great scientific value since a good understanding of LAr's response to low-energy nuclear recoils is crucial for LAr-based direct dark matter (DM) detection experiments with a dark matter mass range around $1 - 5$ GeV. In fact, the current world-best limit on the spin-independent DM-nucleon cross section in this mass range is obtained by the DarkSide-50 experiment exploiting the S2-only signal. A better understanding of this signature, as well as the background and uncertainties, has the potential to improve the DM detection sensitivity of the DarkSide experiment further.

The thesis consists of five chapters, a bibliography and two appendices. Chapter 1 provides an overview of dark matter, beginning with its scientific history. Section 1.1 briefly describes the ΛCDM model, introducing the dark matter energy density Ω_χ. The cosmic microwave background (CMB) and its relevance for the determination of Ω_χ is briefly described in section 1.2. The bullet cluster is mentioned in section 1.3 as evidence of dark matter. In section 1.4, the properties of dark matter, such as coldness and stability, are laid down. Also three promising dark matter candidates, i.e. axions, WIMPs and sterile neutrinos, are briefly mentioned and discussed. Section 1.5 is devoted to the WIMP's direct detection. It starts with the standard halo model and discusses the estimation of dark matter's velocity and density profiles. Using this profile, the next subsection tries to estimate the DM-nucleus event rate (per unit mass) in terms of the DM-nucleus elastic cross section. In the next subsection, the event rate is rewritten in terms of the sum of the spin-independent and spin-dependent DM-nucleon cross sections weighted by the respective form factors.

In Chapter 2, the author provides an overview of the WIMP detection strategy with liquefied noble gases, in particular, the scintillation and ionization mechanisms in the liquid argon (LAr) detector. The signature (or background) of the liquid argon detector is the scintillation light emitted when excited molecules (excimers) decay radiatively into a lower energy state. Those excimers are formed when some particle (possibly dark matter) scatters off the argon atom and deposits some energy. Section 2.1 describes two primary processes, i.e. excitation and ionization followed by recombination. The electronic quenching processes are also briefly mentioned. These processes effectively reduce the scintillation light yield when the exciton density is high. Section 2.2 briefly mentions the singlet and triplet excimer states. In section 2.3, the author discusses the energy loss that occurs before the recoiled nucleus produces the scintillation signal. Two independent sources of energy loss are described. One is caused by the recoiled nucleus exciting and ionising the surrounding atoms. The other is due to several reactions between two excited states, resulting in de-excitation without emitting scintillation light. The nuclear quenching factor characterises the former effect, while the electronic quenching factor quantifies the latter. Section 2.4 describes the scintillation signal (S1 signal) and the electroluminescence signal (S2 signal) and relates them with the numbers of exitons and ions. In section 2.5, the author discusses the operational principles of a dual-phase liquefied noble gas time projection chamber (TPC) and how the S1 and S2 signals are detected. Finally, section 2.6 details a series of experiments within the DarkSide program.

Chapters 3 and 4 contain the main result of the thesis. Chapter 3 describes the motivation and setup of the ReD experiment and discusses the calibration of detector components. In section 3.1, the author emphasises the importance of the low energy nuclear recoil signature for low mass dark matter searches. It shows that the current understanding of the ionization yield caused by the nuclear recoil in the energy range below 5 keV_{nr} is limited. This motivates the ReD experiments, which can directly measure the ionization yield in this energy range. Section 3.2 mentions the primary motivation of the ReD experiment. This is the investigation of the columnar effect, leading to the dependence of the TPC's scintillation and ionization responses on the scattering angle. The experimental data, however, confirms this effect has a negligible effect for the dark matter searches. Section 3.3 explains the setup of the ReD experiment. Section 3.4 describes the calibration of two detector components: One is the Barium fluoride (BaF_2) Crystal connected to photomultiplier tubes (PMTs). The other is the Plastic Scintillators (PScis). Section 3.5 details the time projection chamber (TPC) of ReD, including its Cryogenic System and the Silicon Photomultipliers (SiPMs). Section 3.6 describes the calibration of SiPMs with lasers. Also, various sources of the noise in SiPMs are mentioned and discussed. The data acquisition (DAQ) system and triggering are briefly mentioned in section 3.7.

Chapter 4 describes the result of the data analysis conducted by the author. Section 4.1 outlines the analysis to select a clean sample of neutron events demanding coincidental signals in the three detectors, Barium fluoride (BaF_2) Crystal, time projection chamber (TPC) and Plastic Scintillators (PScis). Selecting a narrow range of the time of flight (ToF) and cutting on f_{prompt}, the author managed to reduce the gamma contamination to a level less than 0.01%. Section 4.2 then describes the reconstruction of the recoil energy of the argon atom from the ToF and the distance measurements. The kinematical analysis outlined in Appendix A plays an important role for this reconstruction. A strong correlation between the recoil energy and the S2 signal strength is established after various cuts in Figure 4.11. The systematic uncertainty of the recoil energy estimation is discussed in section 4.3. In order to translate the S2 signal strength into the detector-independent ionization yield (Q_y^{NR}), the gain factor g_2 has to be identified. In section 4.4, two methods for estimating g_2 are briefly discussed. In particular, an ongoing analysis using echo events is mentioned. The analysis relies on a well-characterized calibration source, such as ^{37}Ar. The production and deployment of ^{37}Ar source is discussed in Appendix B. Section 4.5 describes the determination of the ionization yield as a function of the recoil energy, assuming a particular value of the g_2 factor. This main result is presented in Figure 4.17. The result appears to be consistent with the estimation used in the analysis of the DarkSide-50 experiment.

Finally, Chapter 5 is devoted to conclusion and future work.

Overall, the thesis of mgr. Paules Zakhary is well-written and mostly clear. The thesis presents the motivation for the dark matter search, liquid argon's (LAr) response to low-energy nuclear recoils, the scintillation and ionization signatures in the time projection chamber (TPC) and details of the ReD experiment and author's analysis to determine the ionization yield with the ReD data. Although the final result presented in Figure 4.17 is not yet complete, as the g_2 factor used remains preliminary, it represents a significant step forward in improving the sensitivity of the DarkSide experiment to dark matter candidates with masses in the range of 1–5 GeV. The presented results are original and hold significant scientific value and impact.

While the quality of the thesis meets the standard, there are a number of places where the thesis can be improved. First, the thesis lacks the proper introduction. The first chapter of the thesis should be devoted to the overall introduction describing the scientific background and motivation for the main experiment and analysis. The presented mathematical equations are occasionally imprecise. For example, σ^{SD} in the bottom equations in (1.38) cannot be the same σ^{SD} defined in (1.37). Eqs. (4.6)−(4.8) are not properly written. For example, (4.7) should be written as $\frac{1}{E_{\mathrm{rec}}}\frac{\partial E_{\mathrm{rec}}}{\partial t} = -\frac{2}{t}$ instead of $\frac{\partial E_{\mathrm{rec}}}{E_{\mathrm{rec}}} = -\frac{2}{t}\partial t$. On page 9, it should be $\tau_{DM} \gtrsim 10^{17}$ s rather than $\tau_{DM} \sim 10^{17}$ s. Additionally, the logical steps are sometimes difficult to follow, and some technical terms are used without being defined. For example, on page 3, Ω and ΛCDM model are not defined. It is unclear what the author wants to say with Eq. (1.10), $G_F^2 m_\chi^2 \propto \frac{g^4 m_\chi^2}{M^4}$, where the left-hand-side and right-hand-side represent the DM annihilation cross sections in different theories. Why does the author connect them with the proportionality symbol? The author claims that Eq. (1.15) is obtained by solving Eq. (1.14), but this cannot be done without specifying $\Phi(r)$ or postulating some relation between $\Phi(r)$ and $\rho(r)$. In fact, Eq. (1.15) contains the σ_v factor, which does not appear at all in Eq. (1.14). In Eq. (1.19) the average should be taken together with σ, i.e. $\langle \sigma v \rangle$ rather than $\sigma \langle v \rangle$ unless σ is independent of v. However, there is no such statement in the text. In section 1.5.3, the spin-independent and -dependent cross sections are not clearly defined. In section 3.4.2, BaF0 and BaF1 are not defined. In section 3.7, “CAEN V1730 Flash ADC boards” are not defined. In section 4.2, why is KE_n^{in} relativistic, while KE_n^{out} in Eq. (4.3) is non-relativistic? On page 75, “Fig. 4.11” is probably a typo.

Apart from those points, the contents of the thesis are understandable, and the results have significant scientific value. In addition to the analysis, the author contributed to the ReD experiment by assembling and adjusting hardware devices and performing calibrations. Together, it shows the author’s firm understanding of the experiment and capability to perform scientific works independently.

Summing up, I consider the doctoral thesis of mgr. Paules Zakhary to be a valuable contribution 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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