Physikalisches Institut•Apl.Prof. Dr. H. Fischer•Hermann-Herder-Str. 3•D-79104 Freiburg

Faculty of Physics, Astronomy and Applied Computer
Science, Deans Office

Jagellonian University
Ul tojasiewicza 11
30-348 Kraków
Polen

Albert-Ludwigs-Universität
Freiburg

Physikalisches Institut

Apl. Prof. Dr. Horst Fischer

Hermann-Herder-Str. 3
79104 Freiburg

Tel. 0761/203-5813
Fax 0761/203-5705

Horst.Fischer@cern.ch
http://hadron.physik.uni-freiburg.de

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Review and assessment on the doctoral dissertation of

Mrs. Swathi Karanth,

“Novel method to search for axion-like particles in storage rings”

1. Formal grounds for the review

The formal and legal framework for reviewing Swathi Karanth's dissertation is established through a letter from Prof. Jacek Golak, the Chairman of the Physical Sciences Council at Jagiellonian University Krakow, dated June 22, 2023. In 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.

Given that the dissertation represents an original contribution to an academic issue, it should also exhibit a thorough understanding of the research domain, methodology, theoretical underpinnings, as well as a comprehensive discussion and interpretation of the findings. To evaluate the dissertation, I have taken into account the following criteria: the scientific significance of the topic, the purpose and scope of the work, the structure of the dissertation, the research methods employed, the theoretical and methodological foundations, as well as the selection of relevant literature and sources.

2. Basic information about the dissertation

The dissertation submitted for assessment comprises 125 pages, organized in ten chapters along with an accompanying appendix. The content is presented in very good and easy readable English language and incorporates 7 tables and 46 figures to enhance clarity. Notably, this dissertation is an integral component of the JEDI Project at the Cooler Synchrotron at the Research Center Jülich (Germany). Over the course of this initiative since 2013, a collection at least 24 dissertations addressing diverse subjects have emerged. What sets Ms. Karanth's work apart is her pioneering investigation into the quest for axion-like particles (ALPs) searches at a storage ring, harnessing the potential of a polarized deuteron beam and utilizing Feldman-Cousins for possible polarization jump inference. Her remarkable research findings have been showcased in the publication Physical Review X 13, 031004 (2023), where she serves as the primary author. A second publication with Mrs. Karanth as primary author appear in in Nucl. Inst. and Methods in Physics Research, A 987, 164797 (2020).

Another doctoral dissertation, utilizing some of the data utilized by Mrs. Karanth in her dissertation, but with a greater emphasis on the preparatory stage of EDM experiments, was submitted to the Korea Advanced Institute of Science and Technology by Seung Pyo Chang in December 2021. For the two doctoral theses, the data are analyzed completely independent of each other. Notably, Mrs. Karanth's data evaluation exhibits a level of thoroughness that clearly outperforms Chang's work, which turns out to be exceedingly basic and in quality not comparable to the analysis of the work under review. Such an approach with two parallel but independent analyses is widely used in larger research teams to ensure the quality of the results and does not devalue Ms. Karanth's work as original work in any way.

3. The meaning of the topic taken, purpose and scope of work

I consider it very important to take up the research topic of Swathi Karanth's dissertation because the approach fills a gap in the literature on axion and axion-like particle searches at very small mass scales. The Peccei-Quinn theory introduced the concept of an axion, which is a dynamically oscillating field aimed at solving the strong CP problem in the field of subatomic physics. For axion masses above ~1μeV, this axion field could be observed in strong magnetic fields by coupling it to photons, either directly with energy sensitive tracking devices or by using microwave cavity resonators for signal enhancement. However, this is not feasible for smaller masses due to suppressed axion-photon coupling and the need for impractically large resonance structures. This is where axion-gluon coupling comes into play, inducing a time-varying electric dipole moment (EDM) in nucleons. In their publication in 2019 Chang et al. (PRD 99, 083002) laid out the storage ring technique to detect the oscillating EDM signal. This involves adjusting the conditions of the storage ring to resonate with the oscillation frequency of the axion background field, rather than completely canceling the g-2 frequency. The method offers higher sensitivity and better handling of systematic errors compared to other approaches.

The focus of Swathi Karanth's thesis is the pursuit of axion or ALP detection through two ingenious methodologies. The first approach is to detect oscillating electric dipole moments using a magnetic storage ring. In a storage ring charged particles experience a significant electric field due to their relativistic motion within the magnetic field. This electric field constrains the particle's orbit, causing a resulting force to always point towards the center of the ring. The EDM of the charged particle, aligned with its spin, encounters a torque from this electric field, resulting in a rotation of the spin about the orientation of the electric field. If the EDM is static, this rotation causes the polarization of a particle ensemble to oscillate around its initial position due to polarization precession in the ring plane, which periodically reverses the effect of the torque. However, when the EDM oscillates in time at the same rate as the torque reversals, these rotations accumulate, resulting in a detectable polarization component perpendicular to the ring plane. In addition, a secondary coupling of the axion field involves a "pseudomagnetic" effect that induces spin rotation in a nucleon or nucleus around the gradient of the axion field, analogous to a magnetic field. Notably, this pseudomagnetic field is always tangential to the beam orbit, serving as a uniform high-frequency solenoid distributed evenly along the circumference of the ring. The dissertation submitted for review uses both these methods to search for axions and ALPs. Mrs. Karanth's meticulous attention to detail, coupled with the intricate dance of particle spins, resonances, and frequencies, speaks volumes about the dedication of the scientists embarking on the journey to unravel the secrets of the axion. Through these two methods, the dissertation under review invites us to peer into the frontier of particle physics, where ingenious experimentation opens doors to understanding the enigmatic axions and their potential role as a cornerstone of the universe's dark matter puzzle.

The work represents an interdisciplinary approach to the subject of study between particle physics and accelerator studies. The author has taken up this challenge and implemented it with great care. Despite emphasizing this interdisciplinary nature, the dissertation remains strictly a part of the study of particle physics, having the search for axions and ALPs as its focal point. I consider the choice of the topic of the dissertation to be correct, justified and also very interesting for the reviewer.

4. Layout of the work

The overall structure of the paper is sound and effectively aligned with the research framework. The organization is carefully designed to serve the overarching research objective, resulting in a coherent and logically flowing composition.

The introduction (Chapter 1) of the thesis skillfully outlines the issues under consideration and provides a brief overview of the dissertation. A thorough Chapter 2 offers an illuminating overview of the topic and specifies the research aims and inquiries. It deftly contextualizes the author's experimental endeavors within the landscape of alternative methods for detecting axions and ALPs, while providing an overview of concurrent experiments within the research field, however, exploring different axion mass scales.

Next Chapter 3 takes a theoretical path, delving into the intricate notions of spin and polarization, and providing valuable insights into the dynamics of spin in storage rings. The value of the thesis lies primarily in Chapter 4 and the following five chapters, which delve into the empirical facet of the study. Ms. Karanth meticulously explains the methodology and prerequisites used in the search for axions and ALPs in the storage ring. She then briefly discusses the preparation of the deuteron beam, the WASA polarization measurement experiment, and the meticulously systematic execution of the measurements to build the basic data set.

Chapters 7 and 8 deal with the strategic use of the measured data. In a first phase, a comprehensive review of Mrs. Karanth's simulations and calculations using a simplified spin-tracking model is performed to validate the experimental parameters and to calibrate the data. In particular, these simulation results are used later to establish a correlation between the magnitude of the polarization jumps and the electric dipole moment. The author then details the analysis of the count rates captured by the WASA detector, effectively correlating them with the rotational frequency of the particle bunches. This analytical process is supported further by a rigorous statistical treatment using the Feldman-Cousins method, which strengthens the reliability of the measurement conclusions.

Given the absence of significant rotation frequency dependent polarization jumps, Mrs. Karanth astutely presents in Chapter 9 two illustrative calculations of the exclusion limits governing the axion-nucleon-photon interaction as a function of the axion mass.The dissertation culminates succinctly with a comprehensive summary, coupled with a glimpse of possible future directions.

5. Research methodology

Mrs. Karanth's dissertation is a remarkable blend of innovative, technologically sophisticated methods and cleverly applied analytical and statistical approaches. At its core is the meticulous data acquisition process at the Jülich COSY facility. Here, Mrs. Karanth and the team working at the accelerator facility, skillfully prepared individual deuteron bunches with different orientations and precisely measured the resulting vector polarization. A notable challenge is it to maintain spin coherence throughout each measurement phase, a feat achieved through the strategic use of sextupole magnets.

Ms. Karanth's skill extended to the determination of measurement parameters. In particular, she used simulations and calculations to set parameters such as step sizes in frequency scans. These simulations proved instrumental not only in calibration, but also in translating measurement results into exclusion bounds for the axion phase space. Her ingenuity is evident in treating the active accelerator components not individually piece by piece but utilizing rotation matrices for the overall description, simplifying the complex problem into manageable matrix multiplications.

The data analysis facet of her work reveals a diverse toolkit. The reliability of the measurement conclusions is reinforced by a rigorous statistical treatment using the Feldman-Cousins method. This algorithm, based on principles of likelihood, was utilized to examine possible changes in polarization. Its versatility is notable, as it is not restricted to particular statistical distributions, thus surpassing the limitations commonly linked to Poisson or Gaussian processes. Obviously, the author is aware of the research difficulties, especially with respect to the underlying systematic uncertainties. Although a discussion of these is brief in the dissertation, they are discussed in detail in the publication cited above.

6. Assessment of the content of the work

In my opinion, the dissertation under review is an exemplary piece of reliable research that encompasses both theoretical and empirical aspects. The high level of complexity is mainly due to the chosen research approach, which combines sophisticated experimental methods with complex data analysis. The first chapters of the dissertation provide a solid presentation of the research purpose, questions, problems, and research methods employed. The author's rationale for choosing this research topic is well-founded, citing the pressing issue in contemporary physics, namely the search for dark matter. In addition, fundamental concepts relevant to the study are introduced.

Chapter 2 is a central component, focusing on theoretical research questions regarding axions, their role in Lagrangian coupling, and the methods used to detect them. At this point, the author lists numerous previous or ongoing experimental initiatives and categorizes them according to differences in the axion coupling to standard model particles. However, the omission of the categorization of experiments according to their sensitivity leaves a lack of completeness.

Chapter 3 begins with the basics of spin and polarization, in particular vector and tensor polarization. It then moves on to the intriguing problem of elucidating the motion of a charged particle with spin in a magnetic field. The theoretical presentation of spin precession is commendably motivated, with the author consistently deriving relevant quantities in an understandable manner. Chapters 4 to 6 follow seamlessly from chapter 3, describing in clear detail the preparation of the deuteron beam, the process of polarization measurement, the technical challenges, and the verification of the experimental simulation with a Wien filter. These measurements were performed in the spring of 2019 with a deuteron beam with a momentum near 970 MeV/c at the Cooler Synchrotron in Jülich. The author's meticulous explanations facilitate a clear understanding of both, the measurement process and results as well as the control measurements conducted with the Wien filter.

Chapters 7 and 8 together form a cohesive unit covering simulation and data analysis. The author begins by describing the mathematical and conceptual methods used to simulate and calculate the spin orientation along the particle's trajectory in the accelerator. These calculations serve as a basis for calibrating the expected polarization shifts and converting the measurement results into upper bounds for the electric dipole moment (EDM) and exclusion limits for the axion coupling constants, assuming specific parameters for dark matter and axion mass. Notably, the author chooses to simplify the problem by using simple 3x3 matrix multiplications rather than complex lattice calculations for active accelerator components. While this simplification seems adequate, it would be valuable to assess the impact of inaccuracies, perhaps by randomizing the rotation terms in the matrices. In addition, the situation is complicated by the fact that COSY has a racetrack geometry and is not an elementary circle. However, the author has taken this into account by carefully placing the four circulating deuteron bunches.

To analyze the polarization measurement for shifts in magnitude depending on the rotation frequency, the author uses the Feldman-Cousins method, a wise choice for statistical analysis that yields unbiased results. Finally, the author derives an upper limit for the electric dipole moment within a certain frequency range, based on the absence of a clear polarization shift during data collection. This upper limit corresponds to an axion mass range of 495 peV/c^2 to 502 peV/c^2. Interestingly, the author uses the EDM exclusion limit to make a statement on upper limits for the ALP coupling to nucleons in the same mass range.

When it comes to citing the literature references, I've noticed a recurring pattern where Ms. Karanth tends to bypass citing the original work. Instead, she often relies on later authors who reference the initial studies. A more robust scientific approach would have involved the effort to engage with the original publications, which is considered good practice in reputable academic circles.

7. Conclusion and recommendation

Overall, I conclude that within the context of the present dissertation, Ms. Karanth has made significant contributions to the exploration of EDM, axions and ALPs. The methods she has developed allow for exclusion of axion-like particles in a mass range of between 495 peV/c^2 and 502 peV/c^2 and a coupling larger 1.7×10^{-7} GeV^{-2}. For this exclusion limit, Mrs. Karanth assumes Dark Matter consisting only of axions or ALPS and average Dark Matter density of 0.55 GeV/cm^3. Neglecting here potential Dark Matter streams or Axion Clusters is justified, because these objects are of speculative nature. In summary, the relevant answers to the research questions have been provided, and the work's objectives have been fully achieved.

The key merits of Mrs. Karanth's dissertation are as follows:

- The research topic was well-chosen, current, and intellectually engaging.
- The research topic and scope were accurately defined.
- The structure of the work is coherent.
- The interdisciplinary research approach bridging particle and accelerator physics deserves additional acknowledgment.
- The author has demonstrated an understanding of spin dynamics within the lattice of a storage ring.
- The methodology chapter is well described.
- The research results are accurate and can support initiatives for future storage ring-based EDM and axion search experiments.
- The author has exhibited a commendable knowledge and comprehension of the complexity of the entire experimental endeavor.
- The work highlights excellent theoretical and practical knowledge, along with a profound understanding of all subjects presented in the thesis.
- Proficient mastery of the research toolkits, highlighting the ability to pose scientific problems and to draw accurate conclusions.

The dissertation illustrates a logical sequence of individual research steps, and the addressed topics are pivotal to the formulated objectives. The conclusions and responses to the research questions demonstrate the capability to discern connections between complex phenomena and synthesize results. The work is an original solution to a specific scientific problem in modern particle physics, incorporating elements of both theoretical and predominantly empirical considerations. The presented research findings are logical, comprehensive, and innovative. Considering the empirical quality of the dissertation, the breadth of the research, and the interpretation of the achieved results, I am of the opinion that the doctoral candidate has exhibited a comprehensive theoretical and practical knowledge along with a profound understanding of the addressed subjects. In my assessment, Swathi Karanth possesses significant and ample potential to conduct independent scientific research.

I affirm that Swathi Karanth's dissertation, in accordance with the Higher Education and Science Act, Article 187 of July 20, 2018, concerning academic degrees and titles (Law Gazette 2020, point 85, in the amended version), fulfills both the substantive and formal requirements of a dissertation. Therefore, **I strongly recommend the acceptance of Ms. Swathi Karanth's dissertation entitled "Novel Method to search for axion-like particles in storage rings"** and propose that she proceeds to the next stages of the doctoral examination process.

Freiburg, 24th August 2023

Prof. Dr. Horst Fischer

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