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Review of the doctoral dissertation entitled

„Electronic transport and topological superconductivity in nanoscopic Josephson junctions"

by Dibyendu Kuiri

The reviewed doctoral dissertation was carried out by Dibyendu Kuiri at the Academic Centre for Materials and Nanotechnology, AGH University of Kraków, under the supervision of dr. hab. inż. Michał Nowak (prof. AGH). The dissertation consists of a collection of three scientific publications, with the reprints supplemented by a concise summary. The reprints are preceded by three introductory chapters on the studied phenomena, quantum transport, and the functionality of the KWANT software tool used for large-scale numerical simulations. The dissertation is written in English, as are all the included publications.

The dissertation addresses a fundamental problem at the intersection of condensed matter physics and quantum device engineering. Specifically, the doctoral candidate, in collaboration with his supervisor, aimed to analyze the nature of Andreev bound states and topological superconductivity in planar Josephson junctions under perpendicular magnetic fields. The ultimate motivation for the research lies in studying a platform that allows for efficient manipulation of Majorana bound states for quantum computing.

A key achievement of the dissertation concerns the investigation of planar Josephson junctions under perpendicular magnetic fields, with the aim of understanding experimentally observed transport characteristics, establishing robust detection of topological superconductivity, and engineering an enlarged parameter space for topological superconductivity. To accomplish this, the candidate used the quantum transport simulation tool KWANT, which is uniquely suited to modeling transport through complex heterostructures. More precisely, the original scientific contributions of the dissertation include theoretical analyses in planar Josephson junctions under perpendicular magnetic fields of:

(i) the effect of the spatially varying superconducting phase on the Andreev bound states and their spatial location in the sample,

(ii) the identification of nonlocal conductance sign changes as robust indicators of topological phase transitions, and

(iii) the engineering of elongated junctions to expand the accessible topological superconductivity parameter window.

These findings, supported by numerical simulations, are directly relevant to ongoing experimental efforts. This is clear, as one of the articles forming the dissertation is an experimental effort supplemented with the numerical analysis of the observations authored by the PhD candidate, Dibyendu Kuiri. Therefore, by bridging theory and experiment, the research presented in the dissertation provides clear guidance for the design and interpretation of measurements in modern quantum devices.

The doctoral dissertation consists of an introduction composed of three chapters, a chapter summarizing the works included in the thesis, three attached reprints of published scientific papers coauthored by Dibyendu Kuiri, a summarizing chapter, and a bibliography. The quality of the writing in this dissertation is high, and I did not spot any major issues with formatting, typos, or similar problems. The only thing that I noticed, and that could be improved in this respect, is the absence of page numbering starting from chapter 4, which somewhat makes it difficult to navigate between chapters.

Moving on to the more detailed part of the review, I will discuss the chapters that make up the dissertation one by one. In the first chapter, the doctoral candidate clearly and logically outlines the scope of the dissertation. In the same chapter, the candidate provides a theoretical introduction to the fundamental phenomena and techniques employed in the dissertation: the Bogoliubov–de Gennes formalism, Josephson effects, Andreev reflection (modeled using the BTK approach), and finally Majorana zero modes. The thematic coverage is rather appropriate. **However, at the end of section 1.5.1, the PhD candidate describes a critical problem linked to the misinterpretation of zero-bias peaks of various non-topological origin as Majorana bound states. It is not clear from the dissertation whether detection of Majorana bound states in Josephson junctions is presumably more unambiguous in this perspective. I would be glad to discuss this issue during the public defence.**

In the second chapter, the candidate presents an introduction to quantum transport. The focus is mainly on the Landauer-Büttiker theory, which is primarily used within the scattering matrix approach in the dissertation. The introduction to Landauer-Büttiker theory contains a comprehensive derivation of quantum transport through materials, with an extension to superconducting heterostructures and an explanation of how to frame the conductance within the scattering matrix approach. **To my personal taste, however, I am missing two elements in this section: (i) an introductory explanation of the recursive Green's function method for quantum transport, to which the PhD candidate refers several times in the dissertation, and (ii) a discussion on the difference in modeling local and nonlocal tunneling spectroscopy (both are addressed in the scientific publications). As part of the public defence, I would like the PhD candidate to discuss these points at least at a basic level.**

The third chapter introduces the KWANT software, which the PhD candidate used in the series of works forming the dissertation for numerical calculations of transport through the studied Josephson junction structures. In this chapter, the candidate presents the key elements necessary to understand how the software operates. He begins with a brief introduction, shows the tight-binding Hamiltonian used as input for KWANT, and then explains in a concise and transparent manner how KWANT computes conductance through a given structure. The chapter concludes with an illustration of the scattering formalism in the tight-binding model, using the example of a one-dimensional chain. **In this section, however, I found two elements missing. First, although in the Nano Letters article coauthored by the PhD candidate, the effect of disorder beyond the ballistic regime is studied, it is only briefly described in the supplemental material, and there is no information on how it is modeled by KWANT in the relevant section of the dissertation. Can KWANT also capture, for instance, diffusive transport or even Anderson localization? Second, I find the description of the method incomplete in terms of its limitations. For instance, what is the maximum size of systems that can be realistically simulated, or can electron-electron correlations be included at least partially? I would be glad to discuss these points further during the public defence.**

The fourth chapter provides a summary of the key results achieved in each of the works forming the dissertation. The summaries are concise and substantive, helping to trace the development of the research in a defined direction. The following three chapters are simply reprints of the articles coauthored by the PhD candidate. Next is the summary chapter, which ties the whole research into a coherent story with direct reference to the motivation to propose sensible hardware for a topological quantum computer. However, in my view, there is a missing, traditional part on the outlook on how the PhD candidate sees the potential directions along which his work could be further developed. On the other hand, it is worth noting that during the review process of this dissertation, a preprint authored by the doctoral candidate (arXiv:2511.11277) appeared online and thematically forms a coherent whole with the published works presented in the dissertation. Although it is not the subject of this review, I consider it an important element that demonstrates the doctoral candidate's active development of the research beyond the scope of this dissertation and, in some way, answers my reservation concerning the absence of the outlook. The last element of the dissertation is the bibliography, which I found suitable in both the scope of the cited articles and in size, proving that the PhD candidate has done proper literature research.

The research problem described in the dissertation is reflected in the three original scientific papers published by Dibyendu Kuiri. In two of these, the PhD candidate is the first author, while in one he is the fourth among ten authors. For the papers where the candidate is the first author, I have no reservations about including them as original publications forming part of the doctoral dissertation. The remaining article, in which the candidate is the fourth author, was carried out in collaboration with experimentalists, and the 'Authors' Contribution' section clearly states that D. Kuiri is responsible for the numerical simulations explaining the experimentally observed phenomena. Since the candidate's contribution to the analysis in this article is well-defined and important, I also have no reservations about including this work among the original publications constituting the doctoral dissertation. In the following, I will summarize the published articles constituting this dissertation.

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In "Controlling Andreev Bound States with the Magnetic Vector Potential" (Nano Letters, 2022), the authors explore how the magnetic vector potential affects the energy spectrum of Andreev bound states in planar Josephson junctions formed in two-dimensional electron gases. Using local tunneling spectroscopy at both ends of the junction, they show that the local superconducting phase difference induced by the vector potential is equal in magnitude and opposite in sign at the two ends. This finding is supported by microscopic numerical simulations performed by PhD candidate Dibyendu Kuiri. The study demonstrates that the tunneling current is mainly sensitive to Andreev bound states localized near the tunnel barriers, and that the spatially varying phase difference can be used to estimate the relative positions of Andreev bound states separated by hundreds of nanometers. These results provide insight into the spatial structure of Andreev bound states in planar Josephson junctions and are supported by both experimental data and theoretical modeling.

The article "Nonlocal transport signatures of topological superconductivity in a phase-biased planar Josephson junction" (Physical Review B, 2023) presents a theoretical investigation into detecting topological superconductivity in planar superconductor-normal-superconductor Josephson junctions using nonlocal spectroscopy. By modeling the transport properties of a two-dimensional electron gas proximitized with superconducting electrodes, the study shows that the sign of the nonlocal conductance at zero energy serves as a clear indicator of the topological phase transition. The analysis reveals that phase biasing, achieved via magnetic flux through a superconducting loop, is strongly affected by the Zeeman interaction, which can restrict access to the phase space crucial for realizing Majorana bound states at low magnetic fields. The authors discuss how device parameters such as loop inductance and junction transparency influence the feasibility of reaching the topological regime. The results offer practical guidance for experimental detection of topological superconductivity in planar Josephson junctions.

In "Enhancement of the topological regime in elongated Josephson junctions" (Physical Review B, 2025), the authors present a theoretical study of topological superconductivity in planar superconductor-normal-superconductor Josephson junctions, focusing on the impact of junction elongation. They demonstrate that increasing the length of the junction amplifies the Zeeman-induced phase shift of Andreev bound states. This in turn results in an expansion of the topological superconducting phase range around the superconducting phase difference equal to π. This enables possible emergence of Majorana bound states over a broader phase interval at lower magnetic fields. The work also shows that elongation leads to the appearance of trivial in-gap states that can suppress Majorana modes. This drawback however can be mitigated by further proximitizing the junction with additional superconducting contacts, which restores the topological gap. The authors demonstrate that the topological transition can be effectively probed via critical current measurements, with the critical magnetic field for the transition decreasing linearly with junction length.

Proceeding to the final evaluation of the candidate, I state that Dibyendu Kuiri meets all the criteria set out for PhD candidates in the Polish Law: Prawo o szkolnictwie wyższym i nauce (t.j. Dz. U. z 2020 r. poz. 85 z późn. zm.). The candidate has mastered an advanced tool, the KWANT software, for numerical simulations of ballistic transport in quantum structures, and the doctoral dissertation also demonstrates a solid understanding of the physics of the addressed phenomena. It should be emphasized that the results achieved have been published in reputable scientific journals: two in Physical Review B (IF: 3.7), and one in collaboration with experimentalists in Nano Letters (IF: 10.8). Taking all this into account, I strongly recommend that Mr. Dibyendu Kuiri be admitted to the public defence.

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