Topological properties of interacting systems

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Introduction (adapted from the proposal text)

Confined coherent quantum systems are characterized by a discrete energy spectrum. This spectrum depends on external parameters: for example, for a spin in a magnetic field, there are two energy eigenstates, and their separation in energy depends on the length of the magnetic field vector. The parameter-dependent energy eigenstates also carry a topological structure, which is characterized by concepts such as the Berry phase, the Berry curvature, the Chern number, and the quantum geometric tensor. These topological structures are fundamentally important for any application in quantum technology, since they can enhance the coherent control procedures and influence decoherence.

In this project, our primary goal was to foster breakthrough discoveries where these topological structures are measured in coherent quantum systems. We planned to capitalize on our recent joint theoretical-experimental results, where we have identified topologically charged magnetic degeneracy points (Weyl points) of a spin-orbit-coupled two-spin system realized in a double quantum dot. We planned to do new experiments, and to carry out theory work to find the best nanostructures and measurement methods providing smoking-gun signatures of the existence and qualities of these topological structures.

Short summary

We are thankful for the NKFIH for funding this project, which played an important role in our local research community, boosted our efforts along this research direction, and led to many exciting results that we published in journal publications and arxiv preprints, and disseminated through conference talks and research seminars.

Working through this project enabled a lively interaction between key senior researchers at the BME Department of Theoretical Physics (Gergely Zarand, Janos Asboth, Andras Palyi), young researchers of the Department (Peter Boross, Gyorgy Frank, Gergo Pinter, Vahid Derakhshan Maman, Zoltan Guba), and of the Department of Physics (Gergo Fulop), and strengthened inter-university links with Eotvos University (Gabor Szechenyi).

In total, we authored 29 publications funded by this project, out of which 18 are peer-reviewed papers in international research journals (including 4 Physical Review Letters, 1 Quantum Journal, 1 npj Quantum Materials), and 11 are arxiv manuscripts that are submitted to such journals for review. As testified by our publication list, this project fostered a high number of international collaborations with theoretical and experimental research groups from Denmark, Germany, Israel, Japan, The Netherlands, Norway, Poland, Slovenia, Sweden, Switzerland, and the United Kingdom.

Despite the covid pandemic, we carried out intensive dissemination activities of the results of this project. To illustrate this, we list the 7 most important talks of the PI in the funding period: (1) Invited conference talk at the APS March Meeting, (2021, online), (2) Invited talk at the triannual meeting of the Hungarian Physical Society (ELFT), Veszprém, Hungary (2022), (3) Invited conference talk at the Spin Qubit 5 Conference, Pontresina, Switzerland (2022), (4) Invited conference talk at the Hybrid Quantum Technologies Workshop, ISTA, Klosterneuburg, Austria (2023), (5) Invited seminar talk at the University of Basel, Switzerland (2023), (6) Invited seminar talk at IBM Research Zürich, Switzerland (2023), (7) Invited colloquium talk at the SFB1432 Colloquium, Konstanz, Germany (2023). Furthermore, the PI has been selected to give an invited conference talk at the APS March Meeting 2024 in Minneapolis.

The brief scientific summary of the project is as follows; more details with specific references follow in the Results section below. We focused on the theoretical investigation of the properties of energy degeneracy points (Weyl points) of parameter-dependent physical systems. We explored different physical settings where those Weyl points arise, e.g., band structures of crystalline materials, nanoelectronic circuits based on semiconductors and superconductors, and classical-mechanical ball-and-spring oscillator systems. Our work have led to key advances in understanding the universal properties of Weyl points, and we have also shown that this new understanding can be exploited for practical purposes, e.g., to foster efficient control and readout of quantum bits in spin-based quantum computer prototypes. Our work has extended further beyond this focus area, and established numerous new research results at the interface between nanoelectronics, topological condensed matter and quantum information.

Results

Below, we describe our results, following the structure of the Work Plan of the proposal.

WP1: Topological properties in different material systems

Year 1: Theoretical study of spin-orbit physics and degeneracy points in carbon nanotubes.
Year 2: Transition between different topological patterns of the magnetic degeneracy points in the two-tube setup.
Year 3: Theoretical description of magnetic degeneracy points in silicon and germanium nanostructures.
Year 4: Explore the magnetic degeneracy points of further experimentally relevant few-spin systems.

We have carried out analytical and numerical theoretical work to describe novel electronic bound states in carbon nanotubes, including their topology-related features [Moca2020] [Szombathy]. We have carried out extensive research on the magnetic behavior of few-spin systems [Bouman] [Gyorgy] [John] [Sen] [Kolok] [Moca2021], including the description of different topological patterns of the magnetic degeneracy points [Frank2020] [Frank2021]. We have revealed material-specific aspects of spin physics in silicon and germanium nanostructures in [John] [Sen] [Kolok]. We have explored the magnetic behavior of electronic bound states in different material systems, with a focus on superconductor-semiconductor nanostructures [Bouman] [Boross2022] [Boross2023] [Moca2021] [Malinowski] [Kurtossy] [Haller2022] [Haller2023] [Scherubl] [Kocsis].

WP2: Propose experiments to detect topological properties

Year 1: Model Landau-Zener spectroscopy experiments.
Year 2: Theoretical analysis of the Gritsev-Polkovnikov Berry-curvature experiment in the two-spin setup.
Year 3: Theoretical analysis of the Ozawa-Goldman quantum geometric tensor experiment in the two-spin setup.
Year 4: Generalization of Berry-curvature and quantum geometric tensor experiments for advanced quantum dot setups.

Results in line with the Work Plan. We have described Landau-Zener dynamics in the context of reflectometry-based spin readout in semiconductor nanostructures [Mahan] [Sen].

Results beyond the Work Plan. Instead of the theoretical analysis of specific measurement protocols (Gritsev-Polkovnikov, Ozawa-Goldman), we took the opportunity to theoretically explore the degeneracy-point structure and the topological aspects of a novel, emerging quantum coherent nanostructure platform: multi-terminal Josephson junctions. We have introduced and described the phenomenon of Weyl-point teleportation [Frank2021] in such setups, and revealed the universal geometrical characteristics of their Weyl-point phase diagrams [Frank2023], by invoking seminal results from a special branch of mathematics called singularity theory. We have also shown that certain features often associated to energy degeneracy points (Weyl points) of quantum systems do appear also as frequency degeneracy points of coupled classical mechanical oscillators [Guba], highlighting a way to study those phenomena in simple table-top experiments. Finally, we have proposed experiments to detect dephasing [Boross2022] and braiding-based quantum control [Boross2023] of topological quantum bits based on Majorana zero modes in super-semi hybrid systems.

WP3: Perform experiments to detect topological properties

Year 1: Optimize double quantum dot fabrication.
Year 2: Build and optimize the low-temperature reflectometry setup.
Year 3: Fabrication and measurement of double quantum dots with superconducting leads.
Year 4: Perform reflectometry measurements with hybrid super-semi quantum dot devices.

During the funding period, we have contributed to numerous experiments on nanoelectronic devices, some of them carried out at the Host Institute [Kurtossy], some of them at the labs of our international collaborators [Bouman] [Malinowski] [Haller2022] [Haller2023]. DC transport measurements on a double quantum dot with superconducting leads, pointing to the direction of topologically protected quantum bits, have been carried out and analyzed in [Kurtossy] and [Bouman]. In modern nanoelectronics, DC measurements are often substituted by the more time-efficient method of gate reflectometry. We have theoretically analyzed the roles of electric noise and overdriving effects for reflectometry [Maman], and utilized this modeling expertise to collaborate on an experiment [Malinowski] carried out by research of TU Delft and Microsoft with a hybrid super-semi quantum dot device.

WP4: Classification and stability analysis of the topological patterns of degeneracy points

Year 1: Finalize the classification of the topological patterns in the spin-orbit-coupled two-spin problem.
Year 2: Rigorous analysis of the topological patterns of the magnetic degeneracy points in the spin-orbit-coupled two-spin problem using differential topology.
Year 3: Generalization of the topological pattern classification problem to further experimentally relevant few-spin systems.
Year 4: Include dissipation in the topological pattern classification problem.

We have published the classification of the topological patterns of magnetic Weyl points, and transitions between different Weyl-point configurations, in [Frank2020], [Frank2021], [Frank2022], and [Sen]. Inspired by our results for the magnetic degeneracy points of few-spin system, we have studied further physical settings where the physics of Weyl points is relevant, including multi-terminal Josephson junctions [Frank2022] [Frank2023], electronic/phononic/photonic/magnonic band structures [Pinter], and coupled classical mechanical oscillators [Guba]. In these works, we predict and theoretically analyze universal features of Weyl phase transitions, i.e., sharp transitions between different Weyl-point configurations when control parameters are continuously varied.

Results beyond the Work Plan

The following results, albeit not planned explicitly in the Work Plan, are strongly connected to the scope of the project, i.e., topological properties of quantum systems. In [Penner], we discuss the Hilbert-space geometry of eigenstates of parameter-dependent random-matrix ensembles, and connect those to a statistical description of the quantum geometric tensor and the Berry curvature. In [Rozgonyi] and [Marton], we explore certain practical aspects of two quantum error correction codes (repetition code and surface code), that are equivalent to two different types of interacting quantum systems showing topological features. In [Grabarits] and [Liu], we present our results related to two aspects of topological insulator physics, revealing how disorder affects adiabatic (Thouless-type) charge pumping and the topological fine structure of an energy band. Our project also led to new results via cross-fertilisation with pure mathematics (singularity theory) [Pinter2023].

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