# SEMESTER REPORT
1st semester, 2022/23/I

by **Róbert Németh** (nemeth.robert.1999@gmail.com)

PH.D. PROGRAM: Materials Science and Solid-State Physics
THESIS TITLE: Aharonov–Bohm Effect in Multiband Systems
SUPERVISORS: József Cserti, Gábor Széchenyi

## Introduction

In 1959, Yakir Aharonov and David Bohm studied the quantum mechanical scattering problem of spinless, charged particles on an infinitesimally thin solenoid (Fig. 1). They proved that the differential scattering cross section – unlike in classical mechanics – depends on the flux $\Phi$ of the coil. Since then, the phenomenon was experimentally verified, and is widely known as the *Aharonov–Bohm effect* [1]. These results are essential regarding the foundations of quantum mechanics.

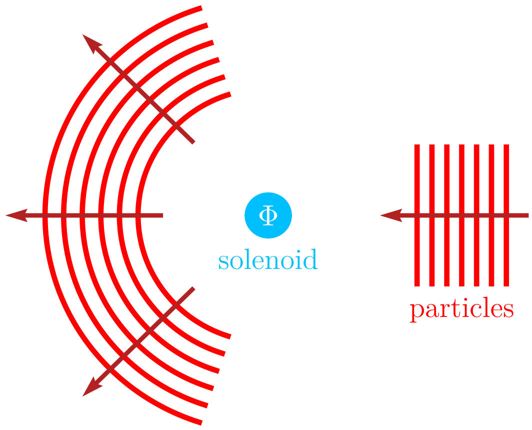


Figure 1: Schematic depiction of the Aharonov–Bohm effect.

Our main objective is to systematically extend the theory of the Aharonov–Bohm effect to the case of two-dimensional multiband electronic systems, which have a growing significance in modern solid-state physics. Such systems are *monolayer* and *bilayer graphene*, the *two-dimensional electron gas with Rashba spin-orbit interaction*, or the *pseudospin-1 system*. In the previous stages of our research, which were carried out during my MSc studies, we have discovered a general integral representation applicable to a wide class of isotropic multiband systems. Furthermore, we proved that the differential cross section is *the same* in all of these cases, and agrees with the results of Aharonov and Bohm. Our aim during the Ph.D. work is to further extend our results to the case of anisotropic systems, lattice models, or the non-Abelian Aharonov–Bohm effect.

In addition to the above, there is another branch of our Ph.D. research, concerning quantum technology and quantum information. As we live in the time of a "second quantum revolution", that is, the following years promise a fundamental breakthrough in the field of quantum information processing, we are confident about the importance of this area. Our plan is composed of the theoretical study of quantum algorithms, quantum codes and quantum computing architectures.

# Research Work in the Current Semester

Regarding the Aharonov–Bohm effect, the first months of the semester were spent working on the anisotropic extension of our theory. In the isotropic case, the scattering states $\mathbf{\Psi}^{(+)}_{s,k,\vartheta}$ are expressed using complex contour integrals with respect to a complexified version $\xi$ of the reciprocal space polar angle $\vartheta$. The integrand contains plane wave states $\mathbf{\Psi}_{s,k,\vartheta}$, where $s$ is the band index and $k$ is the wave number:

$$\mathbf{\Psi}^{(+)}_{s,k,\vartheta}(r,\varphi) = \sum_{m=-\infty}^{\infty} \frac{\epsilon(m+\alpha)}{2\pi} \int\limits_{\Gamma(m+\alpha,\varphi)} \mathrm{d}\xi\ \mathbf{\Psi}_{s,k,\xi}(r,\varphi)\mathrm{e}^{\mathrm{i}m(\xi-\vartheta)-\mathrm{i}\alpha(\varphi-\xi)}, \tag{1}$$

where $\alpha$ is a dimensionless flux parameter. In the anisotropic case, our main idea is to replace $k$ with the angle-dependent wave number $k_E(\vartheta)$ for some energy value $E$, or more precisely, its complexified version $k_E(\xi)$. This ansatz gives promising partial results but there are also mathematical subtleties regarding the branch cuts of the function $k_E$ leading to open questions. The significance of the anisotropic case lies in the shape of the differential cross section. Whereas for isotropic systems, we have proven that regardless of the concrete shape of the Hamiltonian operator, it takes the form

$$\sigma_{\mathrm{AB}}(\varphi) = \frac{\sin^2(\alpha\pi)}{2\pi k\cos(\varphi/2)}, \tag{2}$$

we expect a different, more general behaviour for anisotropic systems. The proof of this claim remains a problem to be solved.

Nevertheless, in the last months of the semester, me and my supervisor, József Cserti, wrote a paper summarising our previous results for isotropic systems. We included our general theory applicable to a wide range of multiband systems, our results regarding the invariance of the differential cross section, and five relevant applications to specific multiband systems (two-dimensional electron gas with and without Rashba interaction, monolayer and bilayer graphene, pseudospin-1 system). The manuscript is complete now, after some finishing touches, we are planning on submitting it in the following weeks.

In the current semester, I also began working on another project related to quantum computing architectures with the help of my supervisor, Gábor Széchenyi. Specifically, we are interested in the readout of spin quantum bits using other quantum bits, the latter functioning as a so-called quantum point contact (QPC). There were recent results in similar topics, such as those of J. F. Steiner et al [2], or J. Schulenborg et al [3]. In the preparations of our research, I revised these papers, and looked into others as well, in order to acquire knowledge in topics such as *weak and continuous measurements*, *stochastic master equations* or the *universal Lindblad equation*. In the following, our aim is to apply these techniques onto our specific problem of qubit readout.

# Publications in the Current Semester

A future publication with title *Unified description of Aharonov–Bohm effect in isotropic multiband electronic systems* is under preparation with the help of my supervisor, József Cserti. The manuscript of the paper is almost ready, we are planning on submitting it in the following weeks.

# Conferences in the Current Semester

I attended the conference called *Statisztikus Fizikai Nap 2022* organised by the Hungarian Academy of Sciences and the Roland Eötvös Physical Society, on the 25th of November. I also gave a short talk with title *Aharonov–Bohm Effect in Multiband Systems*. Furthermore, I briefly visited other colloquia at the Budapest University of Technology and Economics throughout the semester, namely, a presentation delivered by Michael Berry on the 6th of September, and a long talk given by David DiVincenzo on the 29th of November. I also took part in the weekly *Quantum National Laboratory seminar* at the Department of Physics of Complex Systems, and the *Quantum codes seminar* in the Budapest University of Technology and Economics.

## Studies in the Current Semester

I attended two courses this semester: *Quantum bits in solids* (FIZ/1/041E) and *Theories of open quantum systems* (FIZ/3/066E); I completed both of them with *Excellent* results.

## Teaching in the Current Semester

I contributed to the organisation of the MSc course *Solid-state and statistical physics* in the framework of the *Teaching activity* (FIZ/OKT/2) course. I gave five 90-minute long lectures (practice classes), prepared practice notes of 70 pages in total, handed out assignment problems for the students, and checked their solutions during the oral exams.

## Professional Activities

In addition to my studies, I tried to contribute to the promotion of physics and the Eötvös Loránd University as well. I took part in the organisation of the first round of the *Dürer Competition* as the main supervisor of the F+ physics category. Recently, I also participated in a video podcast related to *ELTE Online Open Day* by having a five-minute conversation about the opportunities of a Ph.D. student in the Instutitute of Physics.

## Awards

During the 2022/23 academic year, my research was supported by the ÚNKP-22-3 New National Excellence Program (ÚNKP-22-3-I-ELTE-836) and the Quantum Information National Laboratory of Hungary (Grant No. 2022-2.1.1-NL-2022-00004) of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

## References

[1] Yakir Aharonov and David Bohm: *Significance of Electromagnetic Potentials in the Quantum Theory*, The Physical Review **115**, 485 (1959)

[2] Jacob F. Steiner and Felix von Oppen: *Readout of Majorana qubits*, Phys. Rev. Research **2**, 033255 (2020)

[3] Jens Schulenborg, Michele Burrello, Martin Leijnse, and Karsten Flensberg: *Multilevel effects in quantum dot based parity-to-charge conversion of Majorana box qubits*, Phys. Rev. B **103**, 245407 (2021)