Slovak National Research Platform for Quantum Technologies

PLATFORM ACTION PLAN

Mário Ziman, Miroslav Grajcar, Tomáš Samuely, Martin Gmitra
2018

The goal of the Slovak National Research Platform in Quantum Technologies **(the QUTE platform)** is to create conditions for increasing the competitiveness and excellence of Slovakia in research and innovation in the field of quantum technologies, which will play a key role in future industrial and security applications.

The action plan elaborates the details of how to initiate and support their development in Slovakia, and in collaboration with the research teams of the platform to achieve long-term sustainability of research and development in this area.

The key activities of the QUTE Platform are:

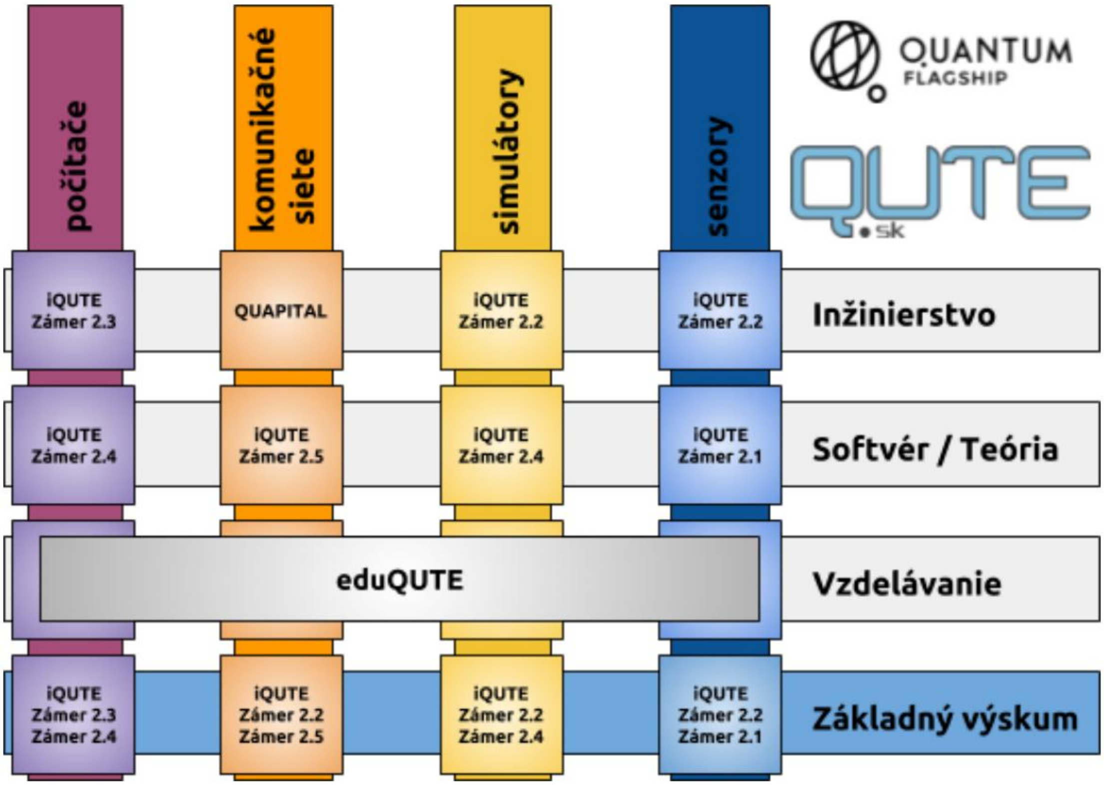
- the creation of an educational study program and the establishment of an international **education center eduQUTE,** which has the ambition to become an international training center of European importance
- the creation of a virtual **institute of quantum technologies iQUTE,** which will bring together individual research teams working on the research goals of the quantum initiative
- building **a quantum communication network** in cooperation with foreign partners **QUAPITAL** connecting Central European capitals

Only **excellent** research has the ability to compete in international project challenges. The action plan will help involve individual research teams in excellent international consortia, which will subsequently bring new possibilities and, last but not least, financial resources for further research. In addition to participating in international project programs, the QUTE platform will intensify existing communication with relevant industrial partners such as IBM, Dell, Slovak Telekom, Eset, and others.

The action plan for Slovakia **is conceptually in line with the European initiative** Quantum Technologies Flagship (QT Flagship, http://qt.eu/), which has four strategic technological goals: **quantum computer, quantum communication network, quantum sensors and metrology and quantum simulator.** all based on basic research. Activities creating tools for achieving strategic goals are an important part of the strategy. They focus on the development **of quantum engineering** (materials and control), **quantum software** (theory), and **the education system** of a new generation of quantum physicists and engineers capable of transferring research results to industrial practice.

In other parts, this action plan describes the specific activities and research objectives of the QUTE platform, the estimated budget that will enable these objectives to be fulfilled in the next five years, the structure of the QUTE platform and individual research teams.

The QUTE platform unites seven institutions: •
Institute of Physics SAS (FÚ SAS), •
Institute of Electrical Engineering SAS (ELÚ SAS),
• Institute of Mathematics SAS (MÚ SAS), •
Institute of Experimental Physics SAS (ÚEF SAS), •
Faculty of Mathematics, Physics and Informatics UK (FMFI UK), •
Faculty of Science UPJŠ (PF UPJŠ), • Faculty of
Electrical Engineering and Informatics STU (FEI STU).



The individual objectives (described in the next section) are based on the pan-European strategy of the quantum flagship (see picture) and contribute to the achievement of its goals. Achieving the goals of this action plan rests on two pillars: ensuring staffing and strengthening experimental equipment at already existing workplaces.

Estimated costs for the QUTE platform for a period of 5 years are EUR 8.725 million. Thanks to this support, it will be possible to carry out the activities of the action plan and to establish Slovak research and the school in an international context. The most important long-term result will be the preparation of competitive human resources that have the potential to build a modern and innovative industry.

Financial support will enable us

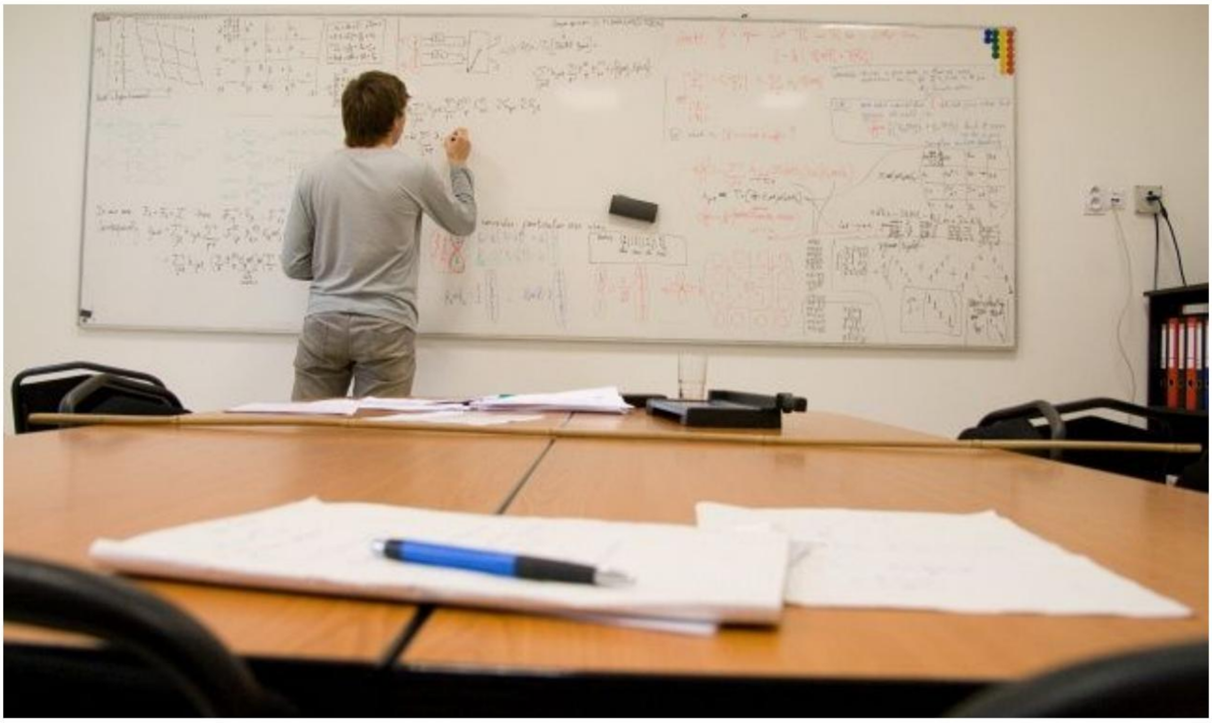
• create an internationally established educational center in the field of quantum technologies
• retain high-quality students and young scientists in Slovakia • attract new high-quality scientists to Slovakia • significantly contribute to the development of quantum innovations and technologies • increase success in international project challenges and strategic consortia
• create a scientific research background and infrastructure for emerging quantum industry

PLANNED ACTIVITIES

1. eduQUTE ACTIVITY: SCHOOL OF QUANTUM TECHNOLOGIES

Goal: Creation of a national educational center eduQUTE

Slovakia has been facing a "brain drain" in recent years, which affects all levels of higher education. One of the reasons is the decreasing attractiveness of the Slovak research area, especially its financial instability, low flexibility and non-existence of additional funding sources, and low wage competitiveness (even compared to the V4 countries). In support of the coming revolution in the field of quantum information technology, we see the possibility of creating a pilot program to support science and research, which, thanks to existing expertise, has the potential to reverse this unfavorable development. We want to create a modern educational and research program with a stabilized financial model that will be attractive to quality applicants on an international scale as well.



Objective 1.1 Creation of an education system in the field of quantum technologies (from bachelor's to postdoctoral level) *(coordinator: Gabriel Semanišin)*

Partners: FMFI UK, FEI STU, UPJŠ, FÚ SAV, ÚEF SAV, MÚ SAV, ELÚ SAV,
Responsible solvers: Miroslav Grajcar, Pavol Zajac, Gabriel Semanišin

Description of the purpose: Quantum technologies are an intersection of engineering, physics, mathematics and IT fields. The creation of such an educational program therefore goes significantly beyond the faculties and even beyond the capabilities of individual universities. The QUTE national platform will ensure the cooperation of the Slovak Technical University, the Comenius University, the PJ Šafárik University as well as the relevant SAS institutes on the development of an interdisciplinary study of quantum technologies. We will create a scholarship awarding system with the aim of motivating students to choose a field of study in quantum technologies.

Objectives: **C 1.1.1 Creation of a master's/engineering/doctoral study program** We plan to have the first students in the prepared program in September 2021. The promotion of the research and study direction at selected high schools and universities will begin in 2019.

C 1.1.2 Creation of a scholarship system Thanks to support in the form of union motivational scholarships, we anticipate an increase in the attractiveness of the study program of quantum technologies, which should ensure quality students at the second and third level of study in this field. Until the new program is approved, students from research teams from the platform will be able to apply for this scholarship. We plan 300 euros/month for the second degree and plus 400 euros/month (600 euros/month) for the basic doctoral scholarship (after the dissertation exam).

Objective 1.2 Creation of a doctoral school and Flagship training center *(coordinator: Vladimír Bužek)*

Partners: FMFI UK, FEI STU, UPJŠ, FÚ SAV, ÚEF SAV, MÚ SAV, ELÚ SAV,
Responsible solvers: Vladimír Bužek, Mário Ziman, Miroslav Grajcar, Tomáš Samuely, Martin Gmitra

Description of the intention: Doctoral students of the platform's partners will form a doctoral school, within which education will take place in the form of summer schools, which will be open to foreign participants, and at which lectures will be given mainly by foreign lecturers. It will also include full financial support for a four-month internship (for domestic doctoral students) at a foreign workplace. As part of edu-QUTE, with this activity we will try to create a European educational center in the field of quantum technologies, which would provide theoretical education for the entire Quantum Flagship and would be co-financed from European sources.
There are already conditions for such an educational center to be established on the basis of the Center for Quantum Information Research, a scientific workplace of the FÚ SAS, which has experience in organizing scientific events, including summer and winter schools. The goal of the creation of such a center is a qualitative shift in the level of education of Slovak students. Lectures by leading European experts in the given field will be invaluable to the students of the platform, and at the same time will make Slovak science and Slovakia itself visible.

Objectives: **C 1.2.1 Joint master's/engineering and doctoral courses**
Teaching in the form of short-term intensive courses of more general subjects on quantum technologies optimizes the expenditure on education. By bringing together students from several institutions, a critical mass necessary for the meaningfulness of the course will be achieved. The courses will initially be organized face-to-face, but we are planning a gradual transition to online courses.

C 1.2.2 Summer schools
eduQUTE Summer doctoral schools will be focused on specific courses in current areas of quantum technologies in the range of 6-10 h/course in the number of 4-6 courses per summer school. The courses will be conducted mainly by foreign lecturers. The schools will also be open to foreign participants. The duration of the schools is expected to be 10-14 days and will include exercises and discussions with the lecturer. Participants will have an active presentation in the form of a poster.

C 1.2.3 Involvement in the educational activities of Flagship
QT The created national training center at FÚ SAS will be actively involved in the quantum flagship with the ambition of becoming an educational center for Flagship, at least for the countries of Central Europe. As part of the credit system, courses and completed summer schools will be accepted as part of a doctoral program in quantum technologies throughout Europe.

Objective 1.3 Creation of support for fellowQUTE postdoctoral fellows *(coordinator: Miroslav Grajcar)*

Partners: FMFI UK, FEI STU, UPJŠ, FÚ SAV, UEF SAV, MÚ SAV, EIÚ SAV,
Responsible solvers: Miroslav Grajcar, Mário Ziman, Tomáš Samuely, Martin Gmitra

Description of the purpose: In Slovakia, there is practically no way to support postdoctoral positions, despite the fact that postdoctoral fellows are the main research force. Our goal is to create a system that would enable the opening of internationally competitive postdoctoral positions. Individual partner organizations will apply for these places in an open competition.
Postdoctoral positions will be for a maximum of three years. We envisage the gradual creation of at least 12 such positions (running simultaneously) that will cover the research objectives of iQUTE.

Objectives: **C 1.3.1 Quality fellowQUTE postdoctoral fellows** Basic selection criteria, the method and form of calls and the creation of selection committees will be defined by the executive board of the QUTE platform. Its proposal will be approved by the Board of Directors of the QUTE platform.

C 1.3.2 QUTE workshops At these workshops, all platform groups will meet, except for the supported postdoctoral fellows. They will be organized once a year. At the meeting, the achieved results of individual postdoctoral students and groups will be presented and the fulfillment of the platform's objectives will be evaluated. In addition to research, organizational issues and tasks of the platform will also be discussed. These workshops will be predominantly internal in nature, but relevant foreign specialists will be invited to them in order to enrich the QUTE Platform with new expertise and potentially new research tasks.

C 1.3.3 Training of postdoctoral fellows in soft-skills
As part of the QUTE workshop, a one-day satellite training of postdoctoral fellows and doctoral students in writing projects, in copyright and patent law, in improving presentation skills and the way of communicating research results to the public, etc. will be organized.

2. iQUTE ACTIVITY: INSTITUTE OF QUANTUM TECHNOLOGIES

Goal: Establishment of a virtual institute and sustainability of excellent research

The iQUTE Institute covers the research objectives of the QUTE platform. It is a virtual structure that is organizationally based at the SAS FÚ, and in addition to **research activities ,** it also carries out **expert and popularization activities.** It is composed of research teams from individual institutions of the QUTE platform. The team leaders form the iQUTE Council, headed by the QUTE coordinator.

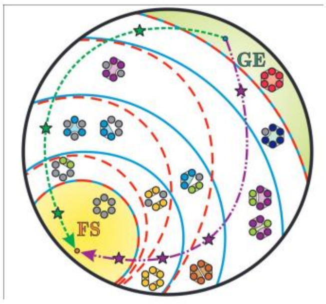
The theoretical research of iQUTE is focused on basic research of qualitatively new quantum information structures, certification and optimization of quantum technologies, development of effective algorithms for simulations of quantum systems, analysis of computational complexity of physical systems, designs of secure communication protocols. The key strategic goals of the QUTE platform are focused on the theoretical modeling and experimental development of quantum hardware in superconductor and semiconductor systems, on the implementation of quantum memory and quantum "repeater" and other technologies for the global quantum network (quantum internet). In the field of quantum computers and simulators, the iQUTE research teams will investigate several possibilities for implementing quantum bits - elementary elements of quantum technologies.

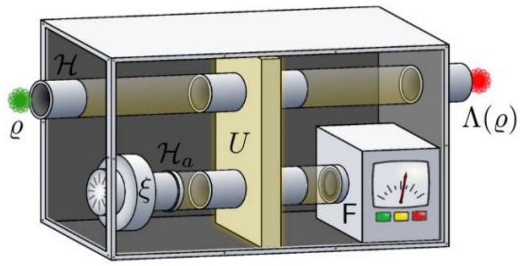
List of research teams: • G1
Group of Quantum Information Structures and Networks (M. Ziman) • G2
Group of Quantum Simulations and Algorithmic Methods (A. Gendiar) • G3
Laboratory of Quantum Measurements (M. Grajcar) • G4
Laboratory of Quantum Magnetism (E. ÿižmár) • G5 Laboratory
of Low Temperature Physics (P. Skyba) • G6 Laboratory
of Topologically-Protected Quantum Bits (T. Samuely) • G7 Laboratory of Post-
Quantum Cryptography (P. Zajac) • G8 Group of Quantum
Computing and Algorithms (M. Gmitra)

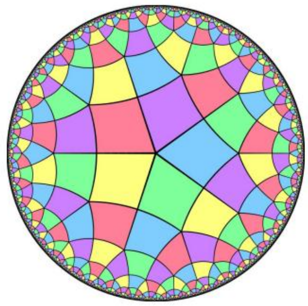
Objective 2.1 Quantum information structures and metrology *(coordinator: Anna Jenÿová)*

Partners: FÚ SAS, MÚ SAS
Responsible solvers: Mário Ziman, Anna Jenÿová, Michal Sedlák, Vladimír Bužek, Daniel Reitzner, Peter Rapÿan

Description of the purpose: Research in the field of quantum information structures defines the basic theoretical framework for quantum technologies, i.e. creates concepts and methods that allow us to define quantum technologies at all, determine the basic theoretical as well as practical boundaries of their functionality, and finally certify their implementations.







The physics of quantum systems forces us to rethink many of our ideas about how the world works. Not only standard physical quantities cannot have arbitrary values (they are quantized), but we also cannot talk about them with certainty. This randomness must be accepted as part of the quantum world. Quantum information theory looks for added value precisely in this quantum randomness and tries to use it to improve existing technologies.

By analyzing quantum models, it is possible to identify and quantify those quantum properties whose values we can talk about with certainty, but the question is how to obtain these quantities (effectively) from experimental data. These quantum quantities are closely related to the development of quantum technologies, because they quantify those manifestations of the quantum world that allow us to push the boundaries of communication and computing technologies. We say that these quantities create the so-called quantum information structures.

Our specific intention will be to explore the quantum-technological potential of higher-order quantum structures, in which information is encoded into transformations of quantum systems that we can directly work with experimentally. These structures allow us to create hypothetical interferences between causal orders, which have been shown to increase computational efficiency over (first-order) quantum computing.
Their realized experimental demonstration is still a subject of discussion, but other qualitatively new properties of such information processing are shown.

Verification and comparison of the quality of functionality of quantum devices is an important part of quantum technologies. Current quantum metrology is mainly devoted to the improvement of metrological procedures and accuracy in the measurement of classical physical parameters of systems, i.e. physical units. Our goal will be to identify and standardize universal procedures for effective characterization of quantum properties of systems, or to measure quantum information units such as non-locality, incompatibility, non-Markovianity, and others. In other words, to create quantum metrology standards, specifically for quantum processes and measurements themselves. An important task is the certification of measuring devices, which is non-trivial in that the verification of the correct functionality of the measuring device requires complete knowledge of the measured object (standard). However, such knowledge we can obtain from the definition only when we measure the system with certified measuring devices. An important question (with an impact on the security aspects of quantum technologies) is to what extent we can, or we have to make ***ad hoc*** assumptions about the properties of the devices and systems used.

Main research objectives

C 2.1.1 Quantum computing and higher order communication

In this research program we aim to analyze the potential contribution of higher orders to quantum computing acceleration. In the case of quantum security, we are interested in whether quantum protocols are resistant to attacks using higher order structures. This research opens up a whole new field of information processing and has the potential to revise the foundations of quantum information technology.

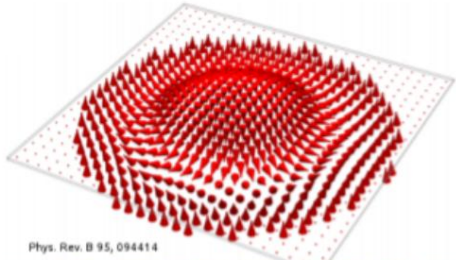
C 2.1.2 Metrological standards for quantum processes and measurements The development of standards represents a tool for the quantum industry that will be able to evaluate and certify quantum technologies. This is a long-term goal involving many sub-research tasks. These are interesting both from a practical and a conceptual point of view of the theory itself, because they give concrete meaning to abstract mathematical concepts.

C 2.1.3 Optimization of quantum structures and information processing

Systematic research into the existence and optimal solutions for individual tasks of quantum information processing, such as protocols for optimal cloning, programmable processors and decision protocols, has a direct impact on all quantum technologies.
Solving these model tasks is useful for understanding the possibilities that appear when solving the previous objectives, and their subsequent use in applications.

Objective 2.2 Quantum electronic devices for quantum communication and computing

(coordinator: Miroslav Grajcar)



Institutions: FMFI UK, FÚ SAV, ElU SAV, UEF SAV

Responsible solvers: Miroslav Grajcar, Daniel Manca, Pavol Neilinger, Ján Greguš, Richard Hlubina, Peter Markoš, Peter Skyba, Peter Szabo, Peter Samuely, Vladimir Cambel

Description
of the purpose: The goal is the construction of top electronic devices using quantum technologies, at a level comparable to the most advanced European research institutes. Currently, we are already working on this issue within the APVV project QUTEMAD and we are trying to get involved in the projects of the QT Flagship initiative. In the document "Quantum Technologies Roadmap 2016", superconducting circuits are directly mentioned as a promising platform for quantum devices with optimal properties. These devices can work up to the so-called quantum limit. In the project, we will focus on **the realization of specific devices based on superconductors,** or superconducting circuits operating near the quantum limit. One of the main goals of the project is the realization of a functional parametric signal amplifier, which would bring a real improvement compared to amplifiers based on HEMTs - transistors with high electron mobility.

Part of this intention is also research in the field of new materials, as progress in quantum technologies is tied to progress in the realization of non-traditional quantum as well as classical materials. One example of such promising materials is topological insulators. They are typical in that, although they are non-conductive inside, they are conductive on the surface or edges. These conductive states are extremely durable (almost indestructible, it is called topologically protected), which offers many practical applications for these materials.

Our next strategy is to focus on the field of quantum communication. We will investigate hybrid schemes combining microwave and optical frequencies. The goal is the construction of the so-called quantum repeater, as a key element of quantum communication. It would enable secure data transmission over long distances over already existing (and unsecured) optical lines. In addition to the repeater, such a quantum communication infrastructure also requires high-efficiency single-photon detectors. Among the most effective today are detectors based on disordered superconductors WSi, NbN, MoC, MoRe, with which we have experience and are the subject of our research. The last component we want to focus on in this area are the so-called NV centers in the diamond. These could be used to transform the quantum information encoded in an optical photon into a microwave photon, which would allow the use of superconducting quantum bits in the construction of quantum repeaters.

There are only two laboratories in Slovakia that operate mixing refrigerators and have experience in working at ultra-low temperatures and are therefore suitable for quantum measurements, detection and simulations on superconducting quantum systems. Both are part of the QUTE platform. The Laboratory of Quantum Measurements (joint workplace of FÚ SAV and FMFI UK) in Bratislava and the Center for Low Temperature Physics (joint workplace of ÚEF SAV and UPJŠ) in Košice will work together to achieve the set research goals. In the construction of microwave amplifiers working at high frequencies, we also rely on the expertise of ELÚ SAV, which has extensive experience in the development of prototypes of HEMT transistors using new materials and technologies for their preparation.

Main research goals:

C2.2.1 Quantum-limited amplifiers for quantum communication and computing The goal is the realization of a functional prototype of a parametric signal amplifier reaching top parameters: gain greater than 10 dB, noise temperature close to the quantum or even subquantum limit. Such a parametric amplifier is crucial for efficient quantum measurements and opens up the possibility of realizing quantum feedback. Top-of-the-line HEMT amplifiers cooled below 20 K have a gain of >20 dB and a noise temperature of TN~2 K in the 4-8 GHz band.

Amplifiers operating in the quantum limit should be able to achieve a noise temperature comparable to the energy of quantum fluctuations kBTN~ÿ/2, i.e. less than 0.2 K. Another order of magnitude improvement can be achieved with superconducting microwave parametric amplifiers. Superconducting circuits, the production of which is easy thanks to electron lithography, are an attractive base because of the low losses that allow reaching the quantum noise limit in the GHz band. The peak parameters of superconducting parametric amplifiers are >10 dB and TN~0.2K, which is sufficient to manipulate and measure the quantum states of the microwave photon field. But the processing of quantum information requires such a high efficiency that only amplifiers working in the so-called of the subquantum limit with kBTN<< ÿ/2. Such microwave amplifiers are still not available, and their design and implementation will be one of the goals of our project. The way to reach them leads either through the improvement of standard materials used in the production of these devices, or in the use of non-traditional quantum materials.

C2.2.2 Single-photon detectors in the optical and microwave range with an efficiency above 90%.

We will test different systems capable of detecting a single photon such as quantum dots, superconducting detectors based on disordered superconductors, superconducting bolometers. We are currently testing a new type of superconducting detector based on disordered superconductors.

C2.2.3 Transmission of quantum information from the optical to the microwave region and back with the aim of constructing a quantum repeater.

This is the most ambitious goal, since such a transmission has not been implemented with sufficient efficiency so far. In cooperation with the Leibniz Institute of Photonic Technologies (Jena, Germany), we want to try to implement such a transmission via a high-frequency field in which the foreign partner has many years of experience.

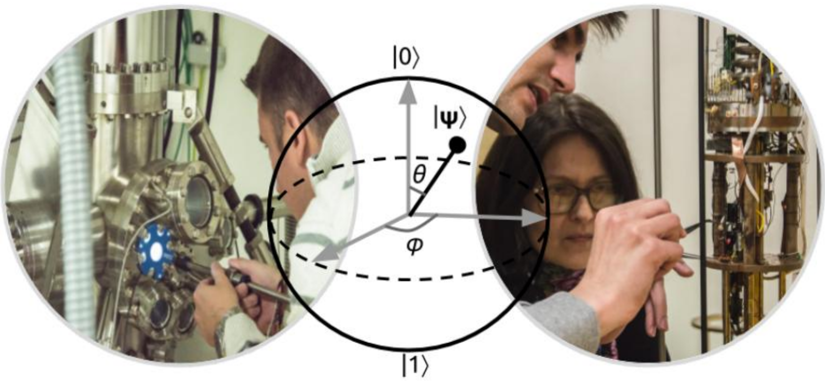
C2.2.4 Using skyrmions to store classical and quantum information.

The use of skyrmions as a memory cell capable of storing quantum information appears to be very progressive. ELÚ SAS works on the issue of skyrmions for classical computers, and as part of this task we will try to show that it is also possible to store quantum information using a skyrmion.

Objective 2.3 Implementations of quantum bits *(coordinator: Tomáš Samuely)*

Institutions: UPJŠ, FÚ SAV, ElU SAV, UEF SAV

Responsible solvers: Martin Gmitra, Jozef Streÿka, Ondrej Hutník, Tomáš Samuely, Vladimír Komanický, Pavol Szabo, Peter Samuely, Jozef Kaÿmarÿík, Zuzana Vargaestokova, Erik ÿižmár, Martin Orendáÿ, Alžbeta Orendáÿová, Alexander Feher, Róbert Tarasenko, Vladimír Tkaÿ, Karol Flachbart, Slavomír Gabání, Gabriel Pristáš, Peter Staÿo



Description of the purpose: We have clear theoretical ideas about the quantum computer. For now, however, we lack suitable quantum hardware for **the realization of quantum bits** (also ***qubit).*** The complexity of its development in a real environment requires joint theoretical and experimental efforts. It turns out that the most suitable candidates for quantum bits are hybrid systems based on superconductors or semiconductors. While superconductor prototypes (experimentally covered by objective 2.2) are currently experimentally better managed, semiconductor ones are close to already existing computer hardware.

The main strategic advantage of semiconductor quantum bits is the possibility of integration with silicon chips and with existing standard hardware. Several of their variations have been the subject of research for a long time, but in the last period (2-3 years) significant changes have taken place in this field: several research groups have succeeded in reproducing several key experiments with prototypes in silicon structures. This started intense scientific research interest in silicon quantum bits at the level from government agencies to private IT companies (e.g. Intel). Our intention is to participate in the research of theoretical models for **"quantum dots" in silicon** in cooperation with experimental groups. Technologically, it is possible to produce a quantum dot in a special semiconductor nanostructure and trap one electron in it, which represents a quantum bit.

In addition to the spin states of individual electrons, the collective spin degrees of freedom originating from the bound states of the multi-electron system of low-dimensional magnetic materials and nanostructures can also be used for quantum calculations.
Molecular nanomagnets, which from a magnetic point of view represent the experimental realization of small electron spin clusters, have two very important properties for quantum computing: (i) their properties can be tailored by molecular engineering, while they remain almost unchanged even when they are placed on a substrate. ; (ii) due to the stronger interaction between electron spins, the operating time of quantum gates (on the order of nanoseconds) can be significantly shorter than the "lifetime" of such quantum bits (on the order of microseconds).

The advantage of high-spin molecules and isolated ions is that they offer the possibility of placing multiple quantum bits in one set of energy levels of the spin system and easily address multi-qubit quantum logic operations by changing the applied magnetic field, or microwave pulse frequency. In Košice there is a strong tradition of experimental research into such spin systems. In addition, magnetic ions can also be used in quantum calculations as **a quantum memory,** when a molecular magnet located in a microresonator can directly form part of a quantum bus consisting of superconducting mesostructures. An important parameter that will need to be achieved is the strong coupling of the spin ensemble to the microwave resonator necessary for the coherent transmission of quantum information. For the successful transmission of information, not only the appropriate design of the resonator is important, but also the selection of a suitable set of spins.

One of the most pressing problems that significantly affects the development of quantum computers is that the physical implementation of quantum bits in any system is subject to quantum errors - decoherence of quantum systems, quantum noise in unitary operations, and so on. An intuitive solution to this problem, similar to classic computers, is redundancy, i.e. the use of multiple bits for the same operations. However, for quantum computers, such a method of error correction is complicated by several fundamental obstacles, e.g. the technical difficulty of increasing the number of linked quantum bits, or the impossibility of cloning an unknown quantum state. However, there is a possibility to completely avoid quantum errors - to implement the so-called **topologically protected quantum bits.** Theoretical works indicate that such topologically protected bits can be realized in the form of one-dimensional spin-polarized nanostructures created on the surface of some specific superconductors. At ***the Center for Very Low Temperature Physics*** in Košice, we have been engaged in cutting-edge research on superconducting materials for decades, some of which have properties suitable for the implementation of these systems. Our goal will be to prepare such systems and study their properties from the point of view of realizing quantum bits.

Main research goals:

C2.3.1 Implementation of quantum bits in silicon

In the first phase, the established scientific group will investigate the properties of silicon quantum dots using computer simulations based on microscopic models with the aim of identifying quantum noise mechanisms in isotopically pure silicon and in silicon with hole conductivity. Although there is no laboratory experimenting with semiconductor quantum chips in Slovakia, the contacts of the researchers enable relevant theoretical research in cooperation with leading foreign experts in this field (for example, in Japan and Germany).

C2.3.2 Entangled quantum bits in molecular nanomagnets We investigate the resistance of quantum entanglement to temperature fluctuations in selected low-dimensional quantum spin systems including, among others, molecular nanomagnets. We will carry out a complex analysis starting with a theoretical calculation from first principles to the subsequent theoretical modeling of the available, or of newly measured experimental data.

C2.3.3 Quantum teleportation and communication using spin chains From the point of view of quantum communication and quantum information processing, the teleportation of quantum bound states is also important, which we plan to investigate in a system of communication channels formed by two quantum spin chains. We will characterize the reliability of the standard teleportation protocol consisting of a system of two quantum channels using the overlay of the input pure quantum of the bound state of the first spin chain with the mixed quantum state obtained at the output of the second spin chain.

C2.3.4 Materials with topologically-protected quantum bits
The high-end equipment of our laboratories enables the preparation and characterization of spin-polarized nanostructures. The goal is to prepare and test one such system – a superconductor with Ising spin-orbit coupling with a ferromagnetic nanochain on the surface, on which we want to experimentally demonstrate the existence of topologically protected Majorana bound states using spin-polarized scanning tunneling microscopy.

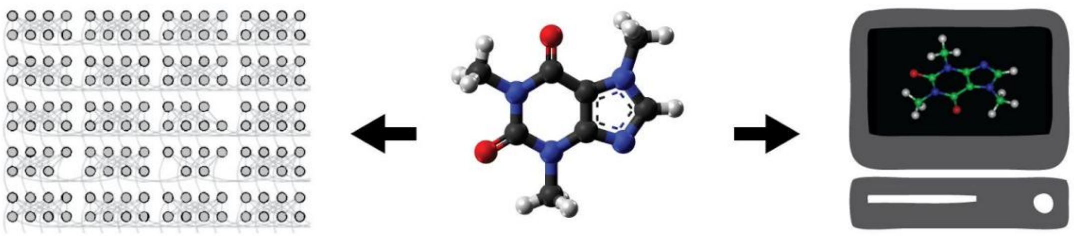
C2.3.5 Quantum bits stored in magnetic ions In the first phase, we will identify a spin system suitable for circuits with quantum memory based on magnetic ions, and then we will design and build a microwave resonator suitable for such circuits. In the last phase, we will look for a combination of a spin system and a microresonator with optimal coupling. The properties of the magnetic system (massive sample, dilute sample or thin layer) that need to be known to create a quantum bit or memory object can be determined using standard electron paramagnetic resonance. In order to contribute to the development of quantum electronics, we will use the knowledge of our experts in the field of magnetic resonance and an excellent technical base for the lithographic preparation of mesoscopic structures when designing our own resonators.

Objective 2.4 Quantum simulations and computational complexity *(coordinator: Andrej Gendiar)*

Partners: FÚ SAS, ÚEF SAS, UPJŠ

Responsible solvers: Andrej Gendiar, Daniel Nagaj, Daniel Reitzner, Peter Rapÿan, Roman Krÿmár, Hana ÿencaríková, Gabriel Semanišin,

Description of the intention:



Our goal is the development of state-of-the-art simulation methods for large quantum mechanical systems and their application in solid state physics and quantum chemistry. Quantum simulations are one of the pillars of the Quantum Flagship, and the area where medium-sized and slightly noisy quantum chips developed in the near future are expected to have the greatest application. They will help us to virtually, quickly and relatively cheaply **simulate and investigate production-intensive systems or classical computer simulation.** The results that the methods developed here will help us to achieve could be new superconducting materials for electrotechnical applications, topologically protected quantum memories, modeling of nuclear reactions, understanding of the structure of space-time or new drugs developed thanks to the understanding of the three-dimensional structure and chemical activity of proteins.

The task of physics is to develop from the first principles and equations to an effective description of the entire system. With the development of computer technology, enormous progress has also been made in the possibilities of numerical simulations, and many times we can explain properties only thanks However, the complexity of simulating quantum systems increases extremely with the number of particles, and it is the physics of such multi-particle quantum systems (modeling molecules and materials) that typically interests us.

The goal of our quantum simulations is the analysis and very accurate solution of problems from quantum physics for such many-particle systems. Simulations connect quantum theory with experimental measurements and allow us to investigate real quantum systems using numerical calculations, classical or quantum, depending on what hardware we implement them on. Experimentally demanding measurements can thus be investigated in advance thanks to the fact that the simulated system behaves according to the equations of quantum theory. With this procedure, we can predict completely new physical phenomena and design experiments that, if successful, can later be applied to industrial production. On the other hand, unknown phenomena or effects encountered by experimenters need to be justified using a suitable theory that can be easily verified by computer simulations.

Our expertise and core contribution is the tensor network method. We (Dr. Gendiar's group at FÚ SAS) stood at its birth and designed and published several new algorithms for the description of many-particle systems with high accuracy. This method is based on the fragmentation of quantum states into smaller objects - tensors. These tensors they are interconnected and usually represent a network of interactions between particles. They thus create a mathematical structure, with the help of which we represent the state of the system and can effectively develop or optimize it. Our goal is the development of this field and the design of new algorithms for the study of properties of quantum phases (topological arrangements), for the analysis of hyperbolic geometries of spacetime (quantum theory of gravity), for fractal structures and multidimensional quantum states of particles.

Since simulations are inherently demanding, the second goal of this project is **to understand the computational complexity of simulation and optimization tasks** that appear in industrial applications (designs of transistor layouts on a chip, image recognition) but also in solid state physics (searching for states with the lowest energy, understanding correlations). We have to look at this complexity in the light of quantum computing. The result will be not only basic research at the border of theoretical informatics and quantum physics, but also practical, more efficient optimization algorithms that will make full use of available quantum resources (binding, superpositions, tunneling).

Fundamental tools for understanding complexity are mapping problems between different areas of theoretical computer science and quantum physics. In this area, we (Dr. Nagai's group at FÚ SAV) brought fundamental results for the area of quantum complexity of local Hamiltonians - contributed to the development of optimization adiabatic algorithms, understood the possibilities of universal quantum computing for many interaction models, and discovered several interesting, simply described physical systems with surprisingly complicated properties. For further such discoveries, we will apply our understanding of the mappings required for simulations of one system to another, effective interactions, and various methods of encoding and repairing quantum information.

The current development in the field of artificial intelligence and machine learning (so-called machine learning) is largely determined by technological possibilities. It is therefore high time to use and apply these possibilities also in the field of quantum technologies. This can be approached in two ways. One of them is to use classic machine learning tools to optimize quantum mechanical tasks and thus contribute to their efficiency. In the second method, we want to deal with the possibility of **quantum machine learning,** ie such networks that would either be quantum or could handle quantum states. This field is a hot topic at the moment with not entirely clear benefits (high-risk-high-gain), but with the potential to explain quantum mechanisms in a radically different way.

Today, there are many open problems related to determining the computing power and limits of quantum computers as a new type of computing tools. From the point of view of the long tradition of research on classical automata and formal languages (UPJŠ), it is natural to expand and capitalize on the acquired knowledge in the context of quantum automata. By studying operator algebras in synergy with theoretical physicists, we want to try to develop the existing mathematical models of quantum computing, so far based mainly on finite-dimensional Hilbert spaces. However, as it turns out, quantum flows can be semantically characterized as infinite tensor products of von Neumann algebras, which are necessarily infinite-dimensional, which gives rise to the need for a deeper study of their structures.

Main research goals: **C**

2.4.1 From tensor networks to quantum gravity simulations We will develop tensor network algorithms for systems of interacting particles with multidimensional degrees of freedom and variable geometry of interactions. Such a discrete space can have an interesting curved space geometry, e.g. near a black hole.

By analyzing the binding entropy in curved space, we will contribute to the unexplored area of quantum gravity from the point of view of the correspondence between the so-called Anti de-Sitter (hyperbolic) space and conformal field theory.

C 2.4.2 Dominance of quantum computing

The goal is to obtain a quantum system whose computing capabilities far exceed the capabilities of classical computers and simulations. In this highly competitive field, research teams are currently working with a budget and human potential that far exceeds the capabilities of the Slovak platform. It competes on two fronts: technological and conceptual, which does not necessarily require such huge investments. As proponents of innovative ideas, we are involved in international projects in which experimental partners are ready to implement them. This goal has applications in quantum technology in general, and is also important for understanding the computational complexity of quantum tasks and developing new optimization algorithms.

C 2.4.3 Machine learning methods in optimization of quantum information processing

We will develop machine learning techniques for quantum systems and develop techniques for rapid recognition of quantum states, operations and processes, and their subsequent implementation and optimization. This goal has two paths, classical machine learning and certification of quantum systems, and on the other hand purely quantum information processing and related computational complexity.

C 2.4.4 Quantum walks on non-lattice systems Our goal is to use quantum walks - propagation of excitations in quantum systems - for the development of new search algorithms. They may be conceptually similar to classical Markov chains, but the use of quantum superpositions will enable an order-of-magnitude acceleration of the number of necessary steps. We will specifically focus on walking on non-lattice systems, similar to those in objective C 2.4.1.

C2.4.5 Mathematical models of quantum algorithms

The aim is to combine knowledge from classical computational complexity, mathematical analysis, algebra, combinatorial optimization and algorithm design together with models of quantum computing in order to create new quantum algorithms for known problems with high computational complexity.

Objective 2.5 Quantum and post-quantum communication networks *(coordinator: Mário Ziman)*

Institutions: FEI STU, FÚ SAV, MÚ SAV

Responsible solvers: Pavol Zajac, Mário Ziman, Daniel Reitzner, Vladimír Bužek, Otokar Grošek, Karol Nemoga, Tomáš Fabšiÿ

Description of intent: Communication protocols can gain an additional level of protection using the principles of quantum mechanics. In theory, this security is perfect, but in an imperfect world, many influences need to be taken into account. Quantum protected communication must be able to identify and eliminate these effects. Recently, the so-called device-independent cryptographic schemes that, thanks to quantum non-locality (pseudo-telepathy), can also eliminate situations where the supplied devices are not trustworthy, i.e. they may contain Trojan horses unknown to users in the form of side communication channels through which these devices potentially communicate without user control. Some of these approaches are also based on our previous research on quantum incompatibility and non-locality, which are a necessary condition for the reliability of such protocols.

From the point of view of the security of quantum protocols, the key stage is the distribution of the quantum key, which subsequently enables communication via the quantum communication network, or it also defines it to a certain extent. The question is how to eliminate the influence of attackers, but also possible noise, and thus enable distribution over arbitrary distances. In the case of two-user protocols, distillation and quantum amplifier are ideal solutions. Our primary goal is to look at efficient (in terms of communication complexity) multi-user key distribution that tolerates the existence of noise.

An alternative to quantum cryptography is the so-called post-quantum cryptography, which aims to develop new technological standards and methods of classical encryption that are immune to any quantum attack. These schemes have been known for a long time, but the computational complexity of encryption and decryption was too complicated for computers of the past.

Main research goals:

C2.5.1 Implementation-safe practically device-independent quantum communication We will perform an analysis of non-locality tests (so-called Bell inequalities) for multidimensional systems. Subsequently, in addition to securing the information itself, we will also focus on device-independent protocols for secret sharing, anonymous channels, and quantum anonymous voting.

C2.5.2 Secure distribution of multi-user quantum keys Part of the solution is a mechanism for creating a stable bound state, which can be transformed into a state enabling the implementation of the required quantum protocol.
Limitations on certification options, or state purification, de facto limit the possibilities of quantum communication technologies themselves.

C2.5.3 Efficient and unconditionally secure post-quantum cryptography
We will focus on the development and use of asymmetric cryptography algorithms that are secure against an attacker with access to a quantum computer and efficient for use in communication protocols (post-quantum algorithms). Also of interest is the question of a secure combination of standard symmetric and post-quantum asymmetric cryptography with quantum key distribution and the use of combined protocols.

3. ACTIVITY OF QUAPITAL

Goal: Creation of a large-scale quantum communication network QUAPITAL.

This activity aims to build a quantum cryptographic network between the capitals of the European Union enabling secure communication between embassies and state institutions of individual EU countries. It is an international infrastructure project and in 2018 the international consortium of European research and industrial institutions QUAPITAL (https://quapital.eu/) began to form. The financing of this part of the project itself is extremely expensive, and therefore already in the first stage we will look for other (European and private) sources for its implementation.

Objective 3.1 Creation of a quantum line between Vienna and Bratislava *(coordinator: Peter Rapÿan)*

Taking into account the technological know-how at the University of Vienna (Professor Rupert Ursin's group), the existing cooperation between the workplaces in Vienna and Bratislava (CVKI FÚ SAV) and the geographical proximity of these two cities, it is completely natural for the first quantum line of the QUAPITAL network to be created right here.

Objective 3.2 Creation of a quantum communication network between the main Central European cities *(coordinator: Vladimír Bužek)*

This objective is a natural continuation of objective 3.1 and will create a unique infrastructure that will be a significant scientific and research contribution.

ESTIMATED BUDGET

The fulfillment of activities and the achievement of the objectives of the QUTE platform counts on a budget of **8,725,000 euros** for 5 years. Of this, roughly a third to cover experimental needs (capital and material) and the rest to personnel costs (wages, travel and services).

The total amount is allocated for individual activities as follows:

eduQUTE activity

3,835,000 euros

• Salary costs (2,304,000 euros) cover in each year of the solution one competent administrative force, approx. 8 postdoctoral students (3,000 euros/month) and scholarship support for 16 doctoral students (plus 600 euros/month) and 16 second-degree students (300 euros/month monthly). These costs (together with the costs derived) will be distributed to the partners according to their success in distributing the respective scholarships.

• Levy (811,000 euros) is related to wage costs. • Travel expenses
(80,000 euros) cover postdoctoral fellows for their conferences and research stays. • The material covers the material
needs of postdoctoral fellows (80,000 euros) and administration (10,000 euros) for the promotion of quantum technologies and the presentation of platform results.

• The costs of organizing the school and the workshop (50,000 euros) cover the primary travel costs of the invited speakers and remuneration for their lecture courses (120 euros/hour)

iQUTE activity

4,890,000 euros

Current resources are distributed among individual partners according to the expected activity in the fulfillment of planned tasks and objectives. One person-month is valued at 1,600 euros.
Indirect costs are calculated as approx. 15% of current costs. Capital expenditures (in the total value of 3,000,000 euros) cover the necessary investments in the planned experiments and will be distributed according to the requirements of the individual partners.

Regular funds: •
Center for Quantum Information Research, FÚ SAS (540,000 euros)
It covers 180 person-months of solvers on individual objectives of the action plan, the related travel expenses of 30,000 euros and material costs of 30,000 euros. The amount of 18,000 euros is allocated to the guests.
• FMFI UK (360,000 euros)
It covers 120 person-months of solvers on individual objectives of the action plan, related travel expenses of 20,000 euros and material costs of 20,000 euros. The sum of 12,000 euros is allocated to guests at an estimated cost of 120 euros/day of stay.
• PF UPJŠ (360,000 euros)
It covers 120 person-months of solvers on individual objectives of the action plan, related travel expenses of 20,000 euros and material costs of 20,000 euros. The sum of 12,000 euros is allocated to guests at an estimated cost of 120 euros/day of stay.
• FEI STU (180,000 euros)

It covers 60 person-months of solvers on individual objectives of the action plan, related travel expenses of 10,000 euros and material costs of 10,000 euros. The sum of 6,000 euros is allocated to guests at an estimated 120 euros/day of stay.

- ÚEF SAS (180,000 euros)

  It covers 60 person-months of solvers on individual objectives of the action plan, related travel expenses of 10,000 euros and material costs of 10,000 euros. The sum of 6,000 euros is allocated to guests at an estimated 120 euros/day of stay.

- MÚ SAS (180,000 euros)

  It covers 60 person-months of solvers on individual objectives of the action plan, related travel expenses of 10,000 euros and material costs of 10,000 euros. The sum of 6,000 euros is allocated to guests at an estimated 120 euros/day of stay.

- ELÚ SAS (90,000 euros)

  It covers 30 person-months of solvers on individual objectives of the action plan, related travel expenses of 5,000 euros and material costs of 5,000 euros. The sum of 3,000 euros is allocated to guests at an estimated 120 euros/day of stay.

Capital expenditure (expenditure
estimates): • EUR 500,000 (FMFI UK) for 3D laser
lithography, • EUR 700,000 (UPJŠ) to upgrade the EPR spectrometer Bruker ELEXSYS model E500 to model E580 FT/CW with helium cryostat, two-year warranty with installation and by transport,
• 500,000 euros (ELÚ SAV) for an etcher and PECVD equipment for creating isolations of the created nanostructures, •
500,000 euros (ÚEF SAV) for a refrigerator and electronic devices, •
800,000 euros (FÚ SAV) for equipping the quantum optics laboratory

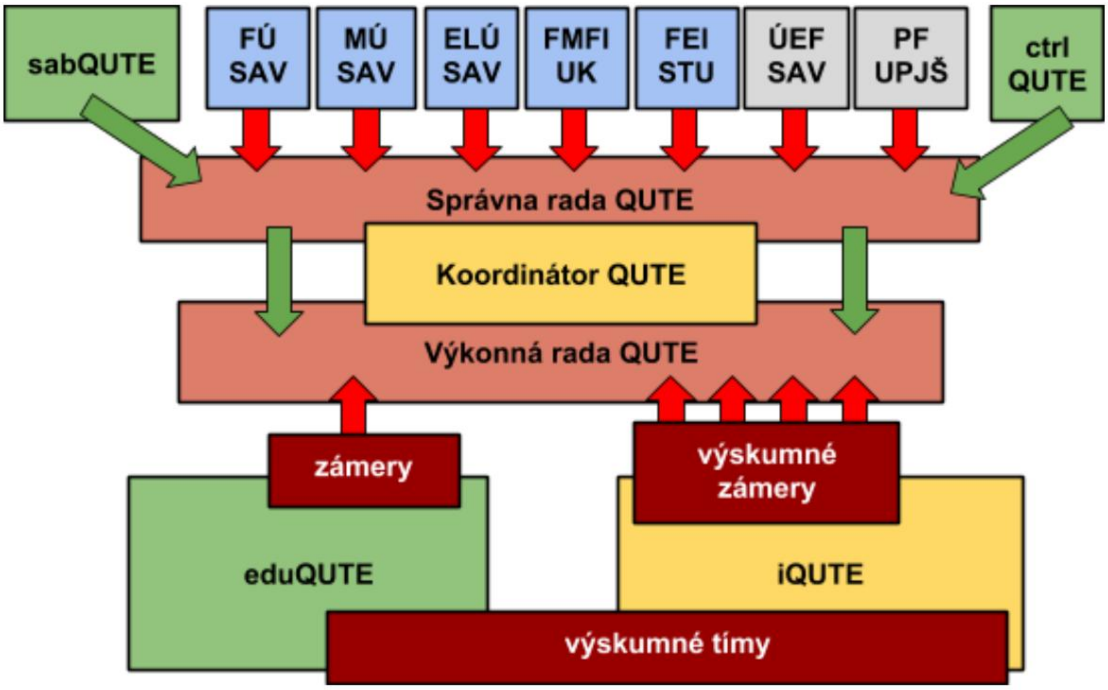
QUAPITAL activity

0

euros We plan to obtain funds for this application activity from other sources - both public and private.

NOTE: we propose the actual financing of the QUTE Platform Action Plan in two payments due to the most efficient way of using the proposed resources. In the first payment, pay out 75% of the project money for the first three years of solving the project objectives (capital expenditures are expected in this period), and then after the accounting of the results, i.e. after the research and financial report. After mastering the opposition of the results, we propose to pay out the rest of the budget in the next payment.

ORGANIZATIONAL STRUCTURE



The Board of Directors of the national platform QUTE (srQUTE) consists of representatives of individual institutions forming the platform. Representatives are nominated by the statutory body of the partner organization on the proposal of the solution teams of this organization, which are members of the QUTE platform. srQUTE appoints a coordinator of the QUTE platform, who becomes its member and administratively ensures its functioning and communication with other platform structures. The role of the board is to take strategic decisions regarding the direction and functioning of the QUTE platform, to decide on the admission/exclusion of new research teams, as well as partners, to the platform and to evaluate their activities. srQUTE works in cooperation with all components of the platform and forms a link between sabQUTE and ctrlQUTE with vrQUTE.

Current composition of

srQUTE: • Prof. RNDr. Vladimír Bužek,
DrSc. • RNDr. Vladimír Cambel, DrSc.
• Prof. RNDr. Alexander Feher, PhD. • Prof.
RNDr. Miroslav Grajcar, DrSc. • Assoc.
RNDr. Karol Nemoga, DrSc, • Prof.
RNDr. Peter Samuely, DrSc. • Prof. Ing.
Pavol Zajac, PhD • Doc. Mgr.
Mário Ziman, PhD

The Executive Council of the QUTE National Platform (vrQUTE) consists of the QUTE coordinator, iQUTE representatives (coordinators of individual objectives) and one representative from the eduQUTE Council. The QUTE coordinator is at the head of vrQUTE. The task of vrQUTE is to coordinate the activities of individual members, organize and carry out the planned activities. Executive Board

• proposes individual research and organizational activities of the platform, •
proposes procedural procedures for the distribution of financial resources of iQUTE and
eduQUTE,
• appoints the selection and organizational committees, prepares the annual report of the
project. vrQUTE's activity is monitored by srQUTE, which approves individual vrQUTE proposals.

Current composition of vrQUTE:

• Mgr. Andrej Gendiar, PhD • Prof.
RNDr. Miroslav Grajcar, DrSc. • Mgr. Anna
Jenÿová, DrSc. • Mgr. Tomáš
Samuely, PhD • Doc. Mgr. Mário
Ziman, PhD • Prof. RNDr. Vladimír
Bužek, DrSc.

The QUTE coordinator is the main point of contact for the platform. His task is to actively coordinate both the executive board, cooperation with the board of directors and the activities of the individual teams of the QUTE platform.

Coordinator: doc. Mgr. Mário Ziman, PhD

The Control Board of the QUTE National Platform (ctrlQUTE) will consist of three members whose task is to control the annual and financial reports.

The international scientific advisory board of the QUTE national platform (sabQUTE, Science Advisory Board) will be composed of five invited experts from abroad who are elected by srQUTE. Their task is to monitor the activities of the national platform, to comment critically and constructively especially on scientific research and organizational activities.

iQUTE is a virtual quantum institute that brings together individual **research teams** and coordinates their research and popularization activities. It ensures the exchange of information between them and organizes joint seminars and conferences in the field of quantum technologies. It is based at FÚ SAS and its activity is administratively provided by the Center for Quantum Information Research.
iQUTE activities are defined as research objectives, each of which has its own coordinator. Coordinators are part of vrQUTE. The leading researchers of individual research teams form **the iQUTE Council.** The task of this council is to coordinate research and popularization activities, control the fulfillment of research goals and define new scientific challenges. The iQUTE Board reports on the results and proposals of vrQUTE and sabQUTE.

eduQUTE is a training center of the QUTE platform located at the FÚ SAS, which administers resources for students, doctoral students and postdoctoral fellows, organizes selection procedures, summer schools and the national fellowQUTE workshop. eduQUTE activities are defined as intentions, each of which has its own coordinator. The goal coordinators together with the QUTE coordinator make up **the eduQUTE Council.** The eduQUTE board informs about the results and proposals of sabQUTE and vrQUTE.

iQUTE RESEARCH TEAMS

G1 Group of quantum information structures and networks

Institutions: FÚ SAS, MÚ SAS
Leader: Mário Ziman

Members: Anna Jenÿová, Michal Sedlák, Vladimír Bužek, Daniel Reitzner, Anatolij Dvurechensky

Expertise: Analysis and optimization of mathematical structures and properties of quantum information (e.g. cloning, programming, estimation, differentiation) and identification and verification of quantum information resources (e.g. entanglement, incompatibility, non-locality). Design of multi-user protocols for quantum secret sharing and anonymous voting.
Calculation of quantum capacities for communication channels and structure of channels with memory.

The most important results: •
M. Hillery, V. Bužek, and A. Berthiaume: Quantum secret sharing, Phys. Rev. A 59, 1829 (1999), 1700+ citations • V. Bužek and M.
Hillery: Quantum copying: Beyond the noncloning theorem, Phys. Rev. A 54, 1844 (1996), 700+ citations • F.
DeMartini, V. Bužek, F. Sciarrino, and C. Sias: Experimental realization of the universal NOT gate, Nature 419, 815 (2002), 130+ citations
• V.Scarani, M.Ziman, P.Štelmachoviÿ, N.Gisin, V.Bužek: Thermalizing Quantum Machines: Dissipation and Entanglement, Phys. Rev. Lett. 88 97905-1 (2002), 90+ citations ,

• M. Hillery, M. Ziman, V. Bužek, M. Bielikova: Towards quantum-based privacy and , pp 75-81 (2006), 50+ 349, Issues 1-4 • A. Jenÿová , D. Petz, Sufficiency citations voting, Physics Letters A
in quantum statistical inference, Commun. Math. Phys. 263, 259-276 (2006), 50+ citations • M.
Ziman: Process POVM: A mathematical framework for the description of process tomography experiments, Phys. Rev. A 77, 062112 (2008), 30+ citations

Mgr. Mário Ziman, PhD (41) was a doctoral student at the Institute of Physics of the SAS, completed a postdoctoral stay in the Czech Republic (FI MU, Brno), Slovakia (FÚ SAS) and Switzerland (ETH Zurich). He deals with the mathematical formalism of quantum theory, fundamental questions of quantum information structures, quantum cryptography and quantum metrology. He is the author of the book "The Mathematical Language of Quantum Theory" (Cambridge University Press), co-author of 71 articles that received a total of 850+ WOK citations, his h-index is 18.

G2 Group of quantum simulations and algorithmic methods

Institutions: FÚ SAS

Leader: Andrej Gendiar

Solvers: Daniel Nagaj, Daniel Reitzner, Roman Krÿmár, Peter Rapÿan, Peter Staÿo

Team expertise: Development of quantum search algorithms based on quantum walking. Quantum complexity theory and computational complexity of simulations of physical systems on classical and quantum computers. Development and analysis of quantum optimizations. Tensor network algorithms for many-particle quantum systems of interacting electrons.
Tensor product states of quantum Hamiltonians in the approximation of the renormalization group.
Analysis of phase transitions on fractal and hyperbolic quantum systems.
Higher order tensor renormalization group. Renormalization of density matrices. Theory of quantum hardware in semiconductors, designs and analysis of quantum bit implementations.

The most important publications:

- J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, I. Zutic, Semiconductor spintronics, Acta Physica Slovaca 57, 565 (2007), 600+ citations • J. Klinovaja, P. Stano, A. Yazdani, D. Loss, Topological Superconductivity and Majorana Fermions in RKKY Systems, Phys. Rev. Lett, 111, 186805 (2013), 200+ citations

- Rolando D. Somma, Daniel Nagaj, Maria Kieferova: Quantum Speedup by Quantum Annealing, Phys. Rev. Lett. 109, 050501 (2012), 35+ citations
- Sergey Bravyi, Libor Caha, Ramis Movassagh, Daniel Nagaj, Peter Shor: Criticality without frustration for quantum spin-1 chains, Phys. Rev. Lett. 109, 207202 (2012), 35+ citations

- Daniel Reitzner, Daniel Nagaj, Vladimír Bužek: Quantum walks, Acta Physica Slovaca 61, No.6, 603-725 (2011), 30+ citations
- Roman Krÿmár, Jozef Genzor, Yoju Lee, Hana ÿenÿariková, Tomotoshi Nishino, Andrej Gendiar: Tensor-network study of quantum phase transition on Sierpiÿski fractal, Phys. Rev. E 98, 062114 (2018). • Andrej Gendiar, Tomotoshi Nishino: Phase diagram of the 3D Axial-Next-Nearest Neighbor Ising model, Phys. Rev. B 71, 024404 (2005), 20+ citations **Mgr. Andrej Gendiar, PhD** (45) is

dedicated to the development of efficient algorithms for the simulation of quantum systems, with the help of which he investigates physical and chemical properties and processes in solid substances. He completed postdoctoral internships in Germany and Japan. He has co-authored 44 publications that have received 280+ WOK citations and his h-factor is 11.

G3 Laboratory of quantum measurements

Institutions: FMFI UK, ELÚ SAS, FÚ SAS
Leader: Miroslav Grajcar

Solvers: Richard Hlubina, Peter Markoš, Pavol Neilinger, Vladimír Cambel, Dana Gregušová, Marek ÿapajna

Expertise: Theory of metamaterials and wave propagation in disordered structures, construction of ultra-low-noise electronic amplifiers and detectors, superconducting quantum bits, microwave and optical spectroscopy, theory of solids and topological materials.

The most significant results:
- Patent US 2003/0224944 A1, Miles FH Steininger, Alexandre M. Zagoskin, Miroslav Grajcar, Evgeni Il'ichev, Characterization and measurement of superconducting structures
- Patent US 2005/0256007 - Mohammad HS Amin, Miroslav Grajcar, Andrei A. Izmalkov, Evgeni Il'ichev, Miles FH Steininger, Adiabatic quantum computation with superconducting qubits
- M. Grajcar, SHW Van Der Ploeg, A. Izmalkov, E. Il'ichev, H. -G. Meyer, A. Fedorov, A. Shnirman, G. Schoen Sisyphus cooling and amplification by a superconducting qubit Nature Physics 4, 612-616, (2008).
- G. Oelsner, P. Macha, OV Astafiev, E. Il'ichev, M. Grajcar, U. Hubner, BI Ivanov, P. Neilinger, and H.-G. Meyer Dressed-State Amplification by a Single Superconducting Qubit Phys. Rev. Lett. 110, 053602 (2013).
- Z. Medvecká, T. Klein, V. Cambel, J. Šoltys, G. Karapetrov, F. Levy-Bertrand, B. Michon, C. Marcenat, Z. Pribulová, and P. Samuely: Observation of a transverse Meissner effect in CuxTiSe2 single crystals, Phys. Rev. B 93, 100501(R) (2016).

Prof. RNDr. Miroslav Grajcar, PhD (52) is dedicated to superconducting quantum technologies and supersensitive quantum measurements. He is the co-author of 2 US patents, 84 publications, has 1600+ WOK citations, h-index 23.

G4 Laboratory of quantum magnetism

Institutions: ÚEF SAS, UPJŠ
Leader: Erik ÿižmár

Solvers: Martin Orendáÿ, Alžbeta Orendáÿová, Alexander Feher, Róbert Tarasenko, Vladimír Tkaÿ, Karol Flachbart, Slavomír Gabání, Gabriel Pristáš, Vladimír Komanický

Expertise: Technical basis for the lithographic preparation of mesoscopic structures for the design of custom resonators with a high Q quality factor based on thin films of classical and high-temperature superconductors, characterization using spin-polarized scanning tunneling microscopy and electron paramagnetic resonance.

The most significant results:
- SA Zvyagin, M. Ozerov, E. ÿižmár, D. Kamenskyi, S. Zherlitsyn, T. Herrmannsdörfer., J. Wosnitza, R. Wünsch, W. Seidel, Terahertz-range free-electron laser electron spin resonance spectroscopy: Techniques and applications in high magnetic fields, Rev. Sci. Instr. 80 (2009) 073102. 27 citations
- S. Zhou, E. ÿižmár, K. Potzger, M. Krause, T. Talut, M. Helm, J. Fassbender, SA Zvyagin, J. Wosnitza, H. Schmidt, Ferromagnetism in defective TiO2 single crystals, Phys. Rev. B 79 (2009) 113201. 120 citations
- K. Siemensmeyer, E. Wulf, H.-J. Mikeska, K. Flachbart, S. Gabáni, S. Mat'aš, P. Priputen, A. Efdokimova, N. Shitsevalova, Fractional magnetization plateaus and magnetic order in the Shastry-Sutherland magnet TmB4, Phys. Rev. Lett. 101 (2008), 177201. 70+ citations
- JDM Champion, MJ Harris, PCW Holdsworth, AS Wills, G. Balakrishnan, ST Bramwell, E. ÿižmár, T. Fennell, JS Gardner, J. Lago, DF McMorrow, M. Orendáÿ A. Orendáÿová, DM Paul, RI Smith, MTF Telling, A. Wildes, Er2Ti2O7: Evidence of quantum order by disorder in a frustrated antiferromagnet, Phys. Rev. B 68 (2003), 020401. 150+ citations
- J. ÿernák, M. Orendáÿ, I. Potoÿÿák, J. Chomiÿ, A. Orendáÿová, J. Skoršepa, A. Feher, Cyanocomplexes with one-dimensional structures: Preparations, crystal structures and magnetic properties, Coord. Chem. Rev. 224 (2002) 51-66. 300+ citations

Doc. RNDr. Erik ÿižmár, PhD. (45) completed a postdoc in the USA and in Germany, he studies quantum magnets and magnetic resonance. He is the co-author of 115 publications that have received 680+ citations, h-index 16.

G5 Low Temperature Physics Laboratory

Institutions: ÚEF SAS

Leader: Peter Skyba

Solvers: Marcel ÿloveÿko

Expertise: The nuclear adiabatic demagnetization apparatus makes it possible to investigate the fundamental physical properties of superfluid helium-3 phases using mechanical micro and nanoresonators and radio spectroscopic methods (NMR). Superfluid helium-3 is one of the purest model systems. It allows simulating physical processes in cosmology, astrophysics, nuclear physics, etc.

The most significant results: • M. ÿloveÿko, E. Gažo, S. Longauer, E. Múdra, P. Skyba, F. Vavrek, M. Vojtko, Vacuum Measurements of a Novel Micro-resonator Based on Tin Whiskers Performed at mK Temperatures, J Low Temp. Phys. 175, 449 (2014) • SN Fisher, GR Pickett, P. Skyba, N. Suramlishvili, Decay of persistent precessing domains in He-3-B at very low temperatures, Phys. Rev. B 86, 024506 (2012) • P. Skyba, M. Kupka, BEC of magnons in superfluid He-3-B and symmetry breaking fields, Phys. Rev. B 85, 184529 (2012) • M. ÿlovecko, E. Gažo, M. Kupka, P. Skyba, New non-goldstone collective mode of BEC of magnons in superfluid (3)He-B, Phys. Rev. Lett. 100, 155301 (2008) • R. Blaauwgeers, M. Blazkova, M. ÿloveÿko, VB Eltsov, R. de Graaf, J. Hosio, M. Krusius, D. Schmoranzer, W. Schoepe, L. Skrbek, P. Skyba, RE Solntsev, DE Zmeev, Quartz tuning fork: Thermometer, pressure- and viscometer for helium liquids, J. Low Temp. Phys. 146, 537 (2007)

RNDr. Peter Skyba, DrSc. (60) has been dealing with the physics of superfluid phases of helium-3 for a long time. He is an expert in experimental methods of obtaining ultra-low temperatures and their measurement using spectroscopic methods (continuous and pulsed nuclear magnetic resonance), as well as with the help of mechanical resonators and other techniques. He is the author of 58 CC publications, for which there are more than 500 responses, h-index 11.

G6 Laboratory of Topologically Protected Quantum Bits

Institutions: UPJŠ, ÚEF SAS,
Leader: Tomáš Samuely

Solvers: Vladimír Komanický, Pavol Szabo, Peter Samuely, Jozef Kaÿmarÿík, Zuzana Vargaestokova

Expertise: Research and characterization of superconducting materials by macroscopic experimental methods. Preparation and characterization of superconducting and magnetic nanostructures using scanning probe microscopy.

The most significant results:

- G. Zhang, T. Samuely, Z. Xu, JK Jochum, A. Volodin, S. Zhou, PW May, O. Onufriienko, J. Kaÿmarÿík, JA Steele, J. Li, J. Vanacken, J. Vacík, P. Szabó, H. Yuan, MBJ Roeffaers, D. Cerbu, P. Samuely, J. Hofkens, and VV Moshchalkov, Superconducting Ferromagnetic Nanodiamond, ACS Nano 11, 5358 (2017) • G. Zhang, T. Samuely, H. Du, Z. Xu, L. Liu, O. Onufriienko, PW May, J. Vanacken, P. Szabó, J. Kaÿmarÿík, H. Yuan, P. Samuely, RE Dunin-Borkowski, J. Hofkens, and VV Moshchalkov, Bosonic Confinement and Coherence in Disordered Nanodiamond Arrays, ACS Nano 11, 11746 (2017)
- G. Zhang, S. Turner, EA Ekimov, J. Vanacken, M. Timmermans, T. Samuely, VA Sidorov, SM Stishov, Y. Lu, B. Deloof, B. Goderis, G. Van Tendeloo, J. Van De Vondel, and VV Moshchalkov, Global and local superconductivity in boron-doped granular diamond, Adv. Mater. 26, 2034 (2014).
- M. Timmermans, T. Samuely, B. Raes, J. Van De Vondel, and VV Moshchalkov, Dynamic visualization of nanoscale vortex orbits, ACS Nano 8, 2782 (2014).
- T. Samuely, S.-X. Liu, M. Haas, S. Decurtins, TA Jung, and M. Stöhr, Self-assembly of individually addressable complexes of C60 and phthalocyanines on a metal surface: Structural and electronic investigations, J. Phys. Chem. C (2009)
- P. Szabó, P. Samuely, J. Kaÿmarÿík, AG Jansen, A. Briggs, A. Lafond, and A. Meerschaut, Interlayer transport in the highly anisotropic misfit-layer superconductor $(LaSe)_{1.14}(NbSe_2)$, Phys. Rev. Lett. 86, 5990 (2001)

Mgr. Tomáš Samuely PhD (37) is an expert in scanning tunneling microscopy and spectroscopy of superconductors and nanostructures at low temperatures and in ultrahigh vacuum.
He completed his doctoral studies at the University of Basel, Switzerland, and later completed an eighteen-month postdoctoral stay at KU Leuven in Belgium. He is the co-author of 23 CC publications with more than 200 citations, h-index 9.

G7 Laboratory of Post-Quantum Cryptography

Institutions: FEI STU, MÚ SAV
Leader: Pavol Zajac

Solvers: Otokar Grošek, Karol Nemoga, Tomáš Fabšiÿ

Expertise: Design and implementation of secure cryptographic primitives and protocols. Cryptanalysis and mathematical cryptography. Practical post-quantum cryptography.

The most significant results:
- T. Fabšiÿ, V. Hromada, P. Stankovski, P. Zajac, Q. Guo, T. Johansson: A reaction attack on the qc-ldpc mceliece cryptosystem, International Workshop on Post-Quantum Cryptography, 51-68 (2017)
- T. Fabšiÿ, O. Grošek, K. Nemoga, P. Zajac: On generating invertible circulant binary matrices with a prescribed number of ones, Cryptography and Communications 10 (1), 159-175 (2018)
- P. Zajac, Upper bounds on the complexity of algebraic cryptanalysis of ciphers with a low multiplicative complexity, Designs, Codes and Cryptography 82 (1-2), 43-56
- P. Zajac, A new method to solve MRHS equation systems and its connection to group factorization, Journal of Mathematical Cryptology 7 (4), 367–381 (2013)
- P. Horak, O. Grošek, A new approach towards the Golomb–Welch conjecture, European Journal of Combinatorics 38, 12-22 (2014)

Prof. Ing. Pavol Zajac, PhD (38) deals with practical cryptography, cryptanalysis and implementations of post-quantum cryptography. He is the co-author of 20 CC publications with more than 34 citations, h-index 4.

G8 Quantum Computing and Algorithms Group

Institutions: UPJŠ
Leader: Martin Gmitra

Solvers: Jozef Streÿka, Gabriel Semanišin, Ondrej Hutník, Zuzana Bednárová, Ondrej Wing

Expertise: Computing measures of quantum entanglement, non-locality and reliability of teleportation. Design and implementation of quantum algorithms and computing.

The most important results: •

W. Han, RK Kawakami, M. Gmitra, J. Fabian: Graphene spintronics, Nature Nanotechnology 9, 794–807 (2014), 480+ citations

• J. Streÿka, O. Rojas, T. Verkholyak, ML Lyra, Magnetization process, bipartite entanglement, and enhanced magnetocaloric effect of the exactly resolved spin-1/2 Ising-Heisenberg tetrahedral chain, Phys. Rev. E 89, 022143 (2014). • J. Streÿka, RC Alécio, ML Lyra, O. Rojas, Spin frustration of a spin-1/2 Ising–Heisenberg three-leg tube as an indispensable ground for thermal entanglement, J. Magn. Magn. Mater. 409, 124-133 (2016).

• M. Hutníková, O. Hutník, Affine coherent states and Toeplitz operators, J. Phys. A: Math. Theor. 45(24) (2012), art. No. 244021.

• O. Hutník, E. Maximenko, A. Mišková, Toeplitz localization operators: spectral functions density, Compl. Anal. Op. Theory 10(8) (2016), 1757-1774. • Ondrej Krídlo, Manuel Ojeda-Aciego, Formal Concept Analysis and Structures Underlying Quantum Logics, International Conference on Information Processing and Management of Uncertainty in Knowledge-Based Systems, IPMU 2018: Information Processing and Management of Uncertainty in Knowledge-Based Systems. Theory and Foundations pp 574-584

• Ondrej Kridlo and Manuel Ojeda-Aciego, Relating Hilbert-Chu Correspondences and Big Toy Models for Quantum Mechanics, Accepted to book Computational Intelligence and Mathematics for tackling complex problems.

RNDr. Martin Gmitra, PhD. (40) postdoc A. Mickiewicz University in Poznaÿ, Poland (Marie Curie fellow), postdoc at the University of Regensburg, Germany (co-investigator of SFB projects), co-author of 87 publications, 2100 citations, h-index 17.

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