QUANTERA

QuantERA Projects Catalogue

Call 2017 supporting the research topics of Quantum Information and Communication Sciences & Technologies

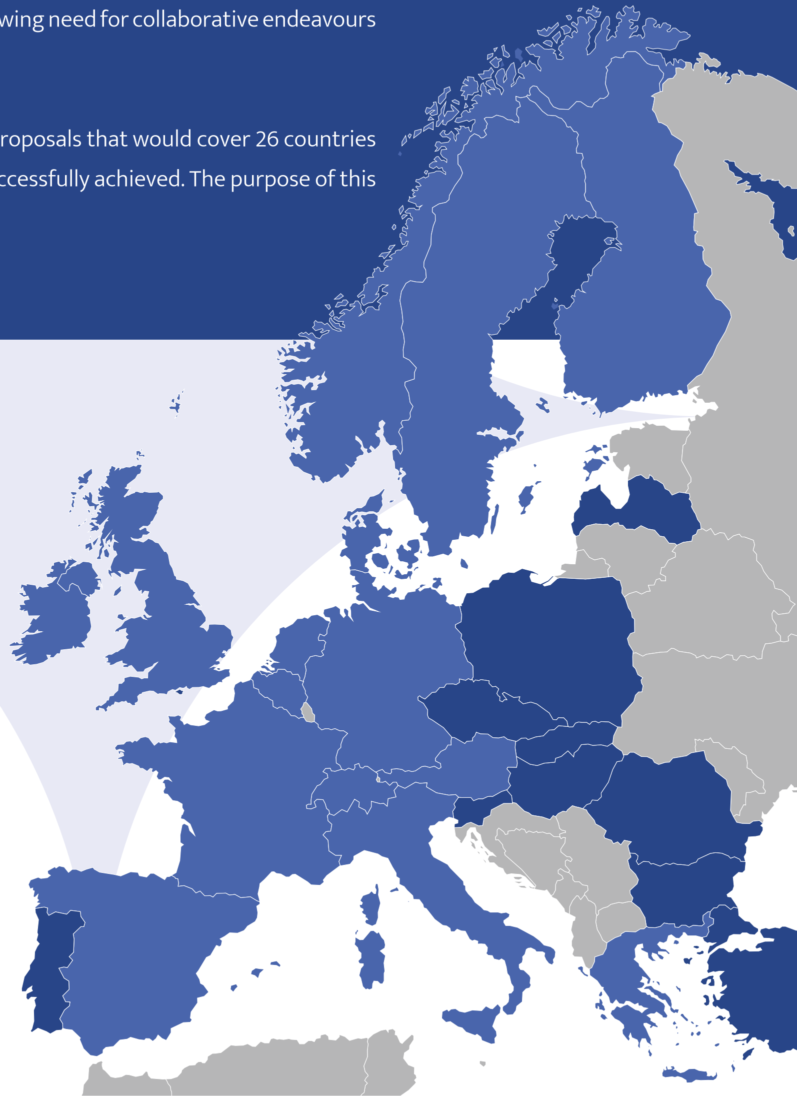
QUANTERA

Contents

QuantERA ERA-Net Cofund in Quantum Technologies

QuantERA is a consortium of 32 organisations from 26 countries, coordinated by the National Science Centre, Poland. It is a European Research Area Network (ERA-NET) in the field of Quantum Technologies (QT) established as an answer to the growing need for collaborative endeavours and a common funding scheme in this field of research.

The central objective of the QuantERA Programme was to launch a transnational Co-funded Call for proposals that would cover 26 countries and contribute to further integration of European research in quantum technologies. The aim was successfully achieved. The purpose of this Projects Catalogue is to provide an overview of these research projects.



Spreading Excellence

QuantERA aimed at spreading research excellence across European Research Area by encouraging consortia to include partners from the *widening countries* participating in the network (Bulgaria, Czech Republic, Hungary, Latvia, Poland, Portugal, Romania, Slovakia and Turkey). Finally, 70% of the successful projects involve research teams from *widening countries*.

Join us

QuantERA is open to new partners. If you are interested in joining us please contact the Programme Coordinator, Mrs. Sylwia Kostka (sylwia.kostka@ncn.gov.pl).

QuantERA Call 2017

Quantum technologies hold the promise of exploiting specifically quantum phenomena, such as superposition and entanglement in information processing, communication, sensing, metrology, and beyond. These applications are enabled by enormous progress in the ability to manipulate individual quantum systems, such as photons and atoms. Practical utilization of this potential requires a concerted effort involving different fields of research and expertise that often could not be found in a single European country. This provided rationale to launch the QuantERA Call 2017 with objective to fund cutting-edge transnational research in the field of quantum technologies.

QuantERA Co-funded Call, announced in January 2017, attracted unexpectedly high attention of the research community. 1087 applicants were involved in the preparationof 221 pre-proposals submitted in the first stage of the Call. Budget requested at this phase exceeded EUR 235 M. At the second stage of the Call, QuantERA Call Secretariat received 91 full proposals involving 490 applicants from all 26 countries, requesting funding of about EUR 107 M.

Thanks to the joint funding provided by the European Commission and the QuantERA member organisations, in November 2017, QuantERA finally recommended 26 excellent international proposals for funding of over EUR 32 M. The projects involve 128 research teams from 23 countries.

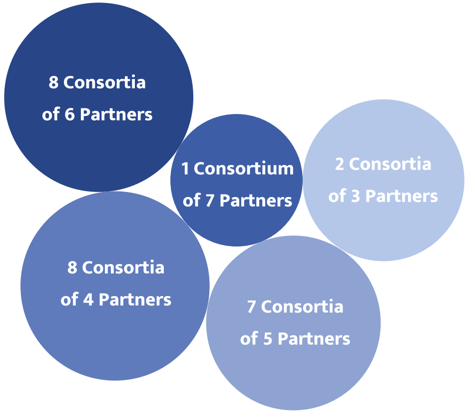
Topics Addressed

Selected projects aim in particular to develop novel physical platforms for quantum communication, sensing and computing, advance architectures and algorithms for future quantum information processing systems, and push for hardware scalability. Research results are expected to address a number of societal challenges, such as cybersecurity and healthcare.

Thematic scope of the QuantERA Call 2017 encompassed the following areas:

- Quantum communication
- Quantum simulation
- Quantum computation
- Quantum information sciences
- Quantum metrology sensing and imaging
- Novel ideas and applications in quantum science and technologies

Size of Project Consortia



QuantERA Call 2017

Funded Projects

CEBBEC

Controlling EPR and Bell correlations in Bose-Einstein condensates

We bring together researchers on quantum information theory, Bose-Einstein condensates and atom interferometry to create, detect and exploit Einstein-Podolsky-Rosen and Bell entanglement in atomic Bose-Einstein condensates. These represent much stronger forms of entanglement than the non-classical correlations created so far and are largely unexplored. Our purpose is both to gain a deeper understanding of quantum information in many body systems as well as to develop practical approaches for manipulating and exploiting it. The main targets are (i) to take advantage of this type of quantum correlation, (ii) to implement device-independent entanglement witnesses, (iii) to explore fundamental aspects of quantum mechanics, and (iv) to realize proof-of-principle implementations of quantum information and quantum measurement protocols with atomic many-body systems.

Atomic interactions in BEC's constitute a non-linearity highly analogous to four-wave mixing or parametric down-conversion in optics, and hence can create strong entanglement. Two separate lines of research have been pursued in the past; on the one hand, one can use the spin degrees of freedom of an atom to produce atom pairs whose spins are entangled, and on the other hand one can entangle the motional degrees of freedom in a spirit close to that of the original EPR proposal. In the CEBBEC project, these two lines of research will be brought together in both the technological sense (using one kind of entanglement to make another) and conceptual one (for example studying complex situations in which both spin and motion are entangled) giving rise to new possibilities for applications and new theoretical challenges. The participating partners have developed sophisticated detection technologies which allow us to make new types of measurements. We intend to respond to the great need for theoretical work to understand and exploit them. Finally, we will address practical applications and explore their metrological validity.

CONSORTIUM

Coordinator: Christoph Westbrook, Institute of Optics, Charles Fabry Laboratory, France

Carsten Klempt, Institute of Quantum Optics, Leibniz University of Hannover, Germany

Marie Bonneau, Technical University of Wien, Austria

Géza Tóth, University of the Basque Country, Spain

Augusto Smerzi, National Research Council (CNR), Italy

CUSPIDOR

CMOS Compatible Single Photon Sources based on SiGe Quantum Dots

The efficient generation of quantum states of light is a vital task in Quantum Photonics. Current approaches are bulky and expensive with low generation rates and the few commercial single photon sources are either not compatible with telecoms standards, require cryogenic temperatures or are bulky benchtop devices.

CUSPIDOR will develop a novel integrated photonic platform relying on a fully CMOS-compatible technology, which will provide compact and highly efficient sources of deterministic single photons at telecommunications wavelengths. Using quantum electro-dynamics principles, silicon-germanium quantum dots (QDs) in silicon will be optimized for high radiative efficiency at temperatures up to 300K. Ion implantation will be implemented during growth, modifying the electron wave function and improving the radiative recombination rate. Optimal and deterministic coupling of the QDs with high quality-factor resonators will be achieved by site controlled QD growth in combination with precisely aligned, lithographically defined photonic crystal resonators, allowing upscaling and a straight forward implementation of areas of identical single photon sources. Combining these sources with lateral p-i-n diodes will yield electrically triggered single photon emitters.

By using the QD to provide a strong optical nonlinearity, a single photon source (SPS) will be realized via the implementation of an on-chip photon blockade. Quantum interference in a photonic molecule increases the system's sensitivity providing a practical path to the first integrated photon blockade device - i.e a “holy grail” of the Quantum photonics community - and provide opportunities for coherent protocols not possible with a single quantum dot. The project will create a strong team of quantum photonics researchers proficient with material design and growth, advanced CMOS processes and nanophotonics design, who will become the basis of a new community spanning these diverse fields. A firm basis of design skills and fabrication expertise will be established that will provide a springboard for further innovation and the exploitation of quantum light sources. This consortium will exploit the state-of-art advances in CMOS processing to realize advanced photonic crystal components that will dramatically improve the functionality of the silicon-germanium devices. The final target is a demonstrator for a compact, integrated, and flexible source of quantum states of light ready for prototyping.

CONSORTIUM

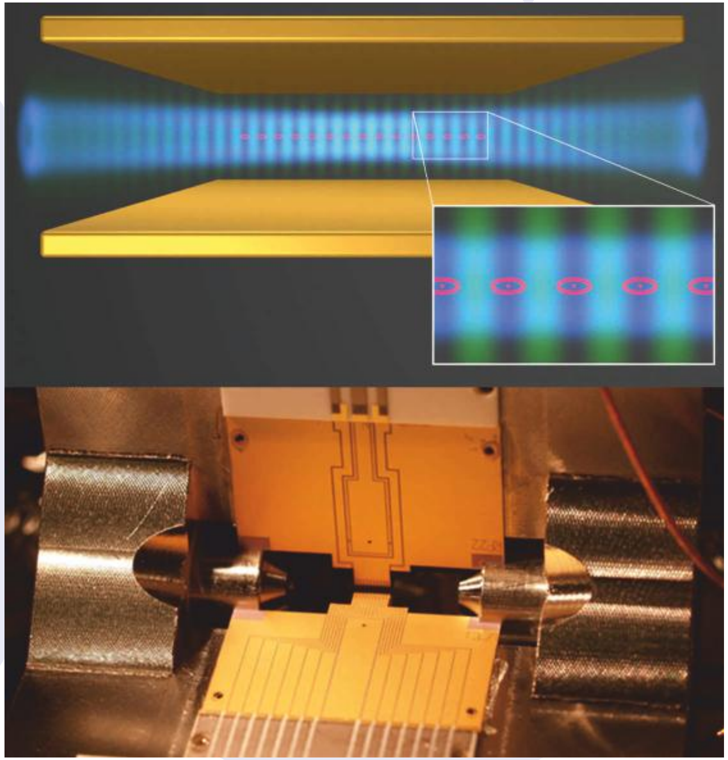
Coordinator: Thomas Fromherz, Johannes Kepler University Linz, Austria
Liam O'Faolain, Cork Institute of Technology, Ireland
Stephen Fahy, Tyndall National Institute, Ireland
Dario Gerace, University of Pavia, Italy
Petr Klenovsky, Masaryk University Brno, Czech Republic

ERyQSenS

Entangled Rydberg matter for quantum sensing and simulations

Owed to their remarkable properties trapped Rydberg atoms and ions are ideal systems for realizing quantum simulators and sensors. The strong and long-ranged dipolar interactions between Rydberg matter is the basis for entangling gates. The long lifetime of circular Rydberg states leads to long coherence times, enabling gates with high fidelity and quantum simulation over long times. Large transition dipole moments make Rydberg atoms and ions highly sensitive to electric fields, microwave and terahertz radiation.

In this project, we will exploit these unique physical features to build two devices: A Rydberg quantum simulator and a Rydberg-enabled quantum sensor. In particular, we will realize quantum gates based on dipolar Rydberg interaction, and bring their performance to a new level using coherent control methods. We will employ dipolar interactions for realizing quantum simulators and apply them to simulate coupled spin and spin-boson systems through digital and analogue approaches. This will enable the investigation of quantum-controlled structural phase transitions as well as the simulation of the motional mode structure of molecules. We will develop highly sensitive probes for electric fields and microwave radiation based on Rydberg-excited ions that can be positioned with nanometer precision and cooled down to micro-Kelvin temperature. This will enable local measurements of electric and microwave fields with high sensitivities that will be further improved through the use of entangled quantum states and dynamical decoupling schemes. Our research will deliver the enabling steps for a future Rydberg-enhanced quantum technology base thereby securing the competitiveness of the European Research Area.



CONSORTIUM

Coordinator: Markus Hennrich, Stockholm University, Sweden

Ferdinand Schmidt-Kaler, Mainz University, Germany

Peter Ivanov, Sofia University, Bulgaria

Jean-Michel Raimond, National Center for Scientific Research (CNRS), France

Weibin Li, University of Nottingham, United Kingdom

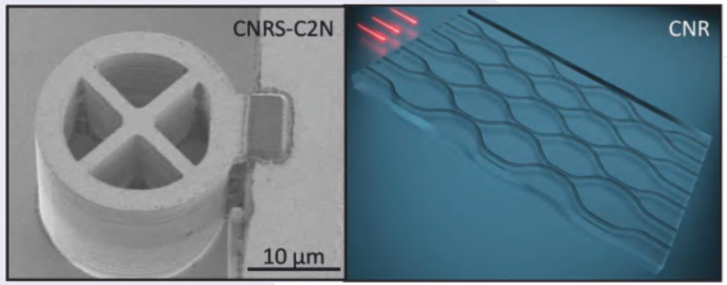
HiPhoP

High dimensional quantum Photonic Platform

Today, photonics is among the very few platforms that can reach very high levels of complexity in quantum communication, computation and sensing. This is made possible by the mobility of photons and the large variety of their controllable degrees of freedom. The quantum optics community has already obtained spectacular achievements, yet using quite inefficient sources and bulk optics, limiting the number of particles involved, the explored Hilbert space dimension and the fidelity of the protocols.

Very recently, a new generation of single-photon sources and high complexity integrated optical circuits have emerged, promising to drastically scale up quantum optical technologies. In this project, experts in solid-state single-photon sources, integrated photonics, quantum optics and complexity theory join their expertise to develop a whole new platform to perform high-fidelity quantum protocols, involving a large number of particles (>8) and large number of modes (>40) in high-dimensional Hilbertspaces (108).

We will develop near-optimal single-photon sources based on semiconductor quantum dots, and couple them to highly reconfigurable two- and three-dimensional photonic glass chips to implement multi-photon multi-mode quantum walks. With this new platform, we will implement high photonnumber Boson sampling measurements, develop new certification protocols and head toward the threshold for quantum advantage. The platform will also be used to demonstrate new secure quantum computation schemes such as homomorphic encryption, and quantum communication tasks based on so-called quantum enigma machines. The richness of applications for our developed photonic platform will be further demonstrated by new advanced metrology tasks that enable simultaneous multiparameterestimation. Our interdisciplinary consortium and work methodology gives us the ideal condition to tackle these challenges and thus to establish a new generation of photonic quantum platforms.



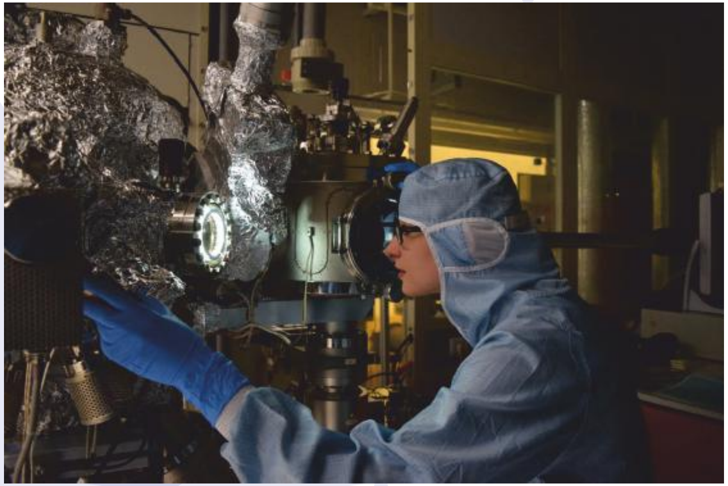
CONSORTIUM

Coordinator: Pascale Senellart, National Center for Scientific Research (CNRS), France
Philip Walther, University of Vienna, Austria
Roberto Osellame and Fabio Sciarrino, National Research Council (CNR), Italy
Ian Walmsley, University of Oxford, United Kingdom
Mario Ziman, Institute of Physics, Slovak Academy of Sciences, Slovakia

HYPER-U-P-S

Hyper-entanglement from ultra-bright photon pair sources

We will fabricate and exploit an entirely novel photonic device platform for the generation of highly indistinguishable and entangled photon pairs with near-unity extraction efficiency.



The envisioned implementation consists of a quantum dot embedded in engineered photonic environment. We predict that this device will generate very high rate of polarization entangled photons pairs and, in combination with time-bin entanglement, hyper-entangled quantum states.

Last but not the least, we will investigate the performance of this device in both free space and fibre based quantum networks, getting therefore closer to the establishment of an operating quantum system for real-life quantum communication.

CONSORTIUM

Coordinator: Ana Predojevic, Stockholm University, Sweden

Christian Schneider, University of Würzburg, Germany

Rinaldo Trotta, Johannes Kepler University Linz, Austria

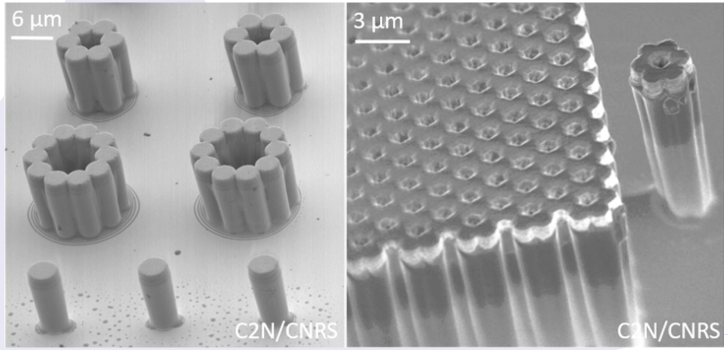
Niels Gregersen, Technical University of Denmark, Denmark

Miroslav Jezek, Palacký University Olomouc, Czech Republic

InterPol

Polariton lattices: a solid-state platform for quantum simulations of correlated and topological states

Quantum simulators allow to address quantum systems that are difficult to study in the laboratory and impossible to model with even the most powerful supercomputer. They are special purpose devices designed to provide insight about specific problems difficult or often impossible to address by any other means. The development of quantum simulation, however, lacks compact on-chip scalable platforms. The consortium, consisting of partners in the UK, France, Germany, Poland and Israel, will aim to develop the world-first polariton quantum simulator, an entirely new platform. Polaritons are half-light half-matter particles with unique properties, which can be created in semiconductors, and which exhibit quantum properties up to room temperatures while their photonic component allows easy integration with other interfaces. The project will combine the expertise in semiconductor physics and technology of four experimental groups and the input of three theoretical groups to push polariton nonlinearities into the strongly interacting regime. It will provide the first quantum simulation platform using scalable lattices at optical wavelengths, and enable simulations of some of the most fundamental strongly interacting quantum models.



CONSORTIUM

Coordinator: Marzena Szymańska, Department of Physics and Astronomy, University College London, United Kingdom

Jason Smith, University of Oxford, United Kingdom

Dimitrii Krizhanovskii, University of Sheffield, United Kingdom

Paulo Santos, PDI-Berlin, Germany

Jacqueline Bloch, Centre for Nanoscience and Nanotechnology, France

Eytan Grosfeld, Ben Gurion University of the Negev, Israel

Michal Matuszewski, Institute of Physics, Polish Academy of Sciences, Poland

MICROSENS

MICROwave quantum SENSing with diamond color centers

Detection and spectroscopy of weak microwave (>GHz) signals is of pivotal importance for key areas of modern technology, including wireless communication, radar, navigation and medical imaging. Solid state spins could be attractive sensors for both tasks since they have transition frequencies that can be tuned across the 1-100 GHz range. However high-frequency sensing by solid state spins has remained underexplored so far, and most demonstrations of spin sensing have focused on low-frequency (<10MHz) signals.

The main reason is that well-established quantum sensing protocols suffer from a low efficiency in the high frequency domain. Furthermore, implementation of spin quantum sensors is not as mature compared to highly integrated microwave electronics. The purpose of the MICROSENS proposal is to use the well-known Nitrogen-Vacancy (NV) diamond colour centre as a tool to address these issues. We will build two different prototypes of microwave sensors based on the NV spin properties: a single microwave photon detector and a wideband quantum spectrum analyser. Theoretical aspects will also be jointly addressed by the MICROSENS proposal since understanding the ultimate limits of noise for high-frequency spin sensing will be one of the main objectives of the MICROSENS proposal.

Led by an industrial partner, MICROSENS federates leading European groups of experimental materials science, solid-state spin sensing and cavity QED. MICROSENS thereby brings together all the necessary blocks to achieve the ambitious target of producing MW detectors with outstanding performances occurring from the quantum properties of the probe.

CONSORTIUM

Coordinator: Thierry Debuisschert, Thales Research & Technology, France

Alexandre Tallaire, LSPM, France

Jan Meijer, University of Leipzig, Germany

Friedemann Reinhard, Walter Schottky Institute, Technical University of Munich, Germany

Fedor Jelezko, University of Ulm, Germany

Johannes Majer, Wolfgang Pauli Institute/ Atominstitut, Technical University of Wien, Austria

CEBBEC
CUSPIDOR
ERyQSenS
HiPhoP
HYPER-U-P-S
InterPol
MICROSENS
NanoSpin
NAQUAS
ORQUID
Q_Magine
Q-Clocks
QCDA
QTFLAG
QuantAlgo
QUANTOX
QuaSeRT
QuompleX
RouTe
Si QuBus
SQUARE
SUMO
SuperTop
TAIOL
TheBlinQC
Topoquant

NanoSpin

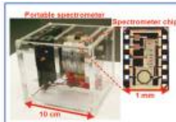
Spin-based nanolytics – Turning today's quantum technology research frontier into tomorrow's diagnostic devices

Magnetic resonance spectroscopy (MRS) is a diagnostic tool that is routinely used in biomedical and pharmaceutical research to analyse the chemical composition of a mixture or to even investigate the structure and dynamics of molecules. MRS draws it strengths from a quantum mechanical property of electrons and many nuclei called "the spin". Conceptually, the spin can be thought of as a tiny bar magnet that senses its environment inside a molecule with very high precision, turning the spin into a nanoscopic probe of the molecule. Unfortunately, today, MRS suffers from long measurement times and high instrument costs that prevent its wide usage outside dedicated lab environments.

The goal of the NanoSpin project is to overcome the existing limitations of MRS by using an intriguing property of colour centres in diamond that allows to shorten the required measurement times by several orders of magnitude and at the same time to drastically reduce the required instrument costs. Colour centres are impurities in the diamond lattice such as nitrogen vacancies that absorb light of a certain wavelength and thereby equip the naturally transparent diamond with colour. By irradiating the colour centres with a laser one can align almost all "bar magnets" associated with the spin of the colour centre (a state called hyperpolarization) and even transfer this alignment to other nearby spins in a sample of interest. In this way, the weak MRS signal can be boosted by several orders of magnitude, resulting in drastically reduced measurement times.

In NanoSpin a group of researchers from widely different disciplines ranging from physics, chemistry, materials science and engineering will work together on all aspects of diamond-hyperpolarization enhanced MRS to make this powerful method available in portable instruments that provide the same analytical strength as today's room filling MRS equipment.

The vision of NanoSpin is to establish the required hardware and software tools, which are necessary to further push today's research frontier in colour centre based quantum sensing for MRS. Then, with those tools available in the next generation of instruments, MRS with its great diagnostic power will be turned into an easy-to-use, in-field method, which will have transformative effects on the emerging fields of personalized medicine and home diagnostics.



NMR spectro-meter	22 T high resolution NMR spectrometer at NIMS	1 T portable combined ESR/DNP-enhanced spectrometer with on-chip polarizer
Sensitivity	**100-fold higher than 1T benchtop spectrometer**	**1000-fold higher than 1T benchtop spectrometer with 0.4% polarization**
Size	3-story building	Portable (10 cm)^3
Cost	> €10 m	< €10k for spectrometer including on-chip diamond DNP

CONSORTIUM

Coordinator: Jens Anders, Institute of Smart Sensors, University of Stuttgart, Germany

Martin Plenio, University of Ulm, Germany

Fedor Jelezko, University of Ulm, Germany

Ilai Schwartz, NVision, Germany

Milos Nesladek, Hasselt University, Belgium

Adam Gali, Wigner Research Centre for Physics, Hungary

Aldrik Velders, Wageningen University, Netherlands

Petr Cigler, Institute of Organic Chemistry and Biochemistry of the Czech Academy of Sciences, Czech Republic

NAQUAS

Non-equilibrium dynamics in Atomic systems for QUAntum Simulation

In a quantum simulator, the time evolution of a quantum system should be controlled to reach the desired outcome of the simulation. Quantum simulators, more precisely quantum annealers, start to appear in the market (at very prohibitive prices for an individual person) but an efficient manipulation of such systems still requires fundamental progress in our basic understanding of quantum systems. First, the dynamics of a quantum system in which many particles interact altogether is a complex problem. Second, quantum simulators are often facing the presence of phase transitions during their time evolution which makes their control difficult.

In our consortium we gather theoreticians with a large expertise in out-of-equilibrium dynamics of quantum many-body systems and in the physics of phase transitions together with experimentalist studying these problems with ultracold quantum gases. Quantum gases are unlikely to be a platform for commercial simulators but they are ideal test systems which are well-controlled and tunable. We will explore in this project the dynamics of quantum systems around phase transitions in synergy between state-of-the-art experiments and computational tools to provide a comprehensive picture of this subject that could be applied to quantum simulators prototypes in the next future.

CONSORTIUM

Coordinator: Jérôme Beugnon, Kastler Brossel Laboratory, France

Giovanna Morigi, Saarland University, Germany

Gabriele Ferrari, National Institute of Optics, National Research Council (INO-CNR), Italy

Jacek Dziarmaga, Jagiellonian University, Poland

Zoran Hadzibabic, University of Cambridge, United Kingdom

Nikolaos Proukakis, University of Newcastle, United Kingdom

Tilman Esslinger, Swiss Federal Institute of Technology, Switzerland

ORQUID

Organic QUantum Integrated Devices

Our society relies on secure communication, powerful computers and precise sensors. Basic science has shown that huge improvements in these capabilities are possible if we can utilise many single quantum objects working in concert. We can then see how to store and process huge amounts of information in a fully secure way and how to make exquisitely sensitive measurements of fields and forces.

Specific types of quanta – photons, electrons, phonons – already bring new specific functions, but to realise the full promise of quantum technologies, it will be necessary to interface these systems with each other in a way that is practical and scalable. This is the focus of our programme. ORQUID will explore the exciting new possibility of using single organic molecules as the interface between these three quanta so that they can work together as required. First, single molecules will interact with light in waveguides and cavities to generate and detect single photons, providing immediate impact in quantum photonics. Second, single molecules will detect single moving charges in nano-electronic circuits to provide quantum coherent information exchange between these charges and the external world. Third, molecules embedded in nanomechanical devices and two-dimensional materials will measure nanoscale forces and displacements, which are key to developing mechanical quantum systems and understanding nanomachinery. By developing these three interfaces on a common platform, we will create a versatile hybrid system. By allowing the user to draw simultaneously on the most sensitive quantum aspects of light, chargé and sound, we anticipate that this hybrid will be a major advance in the technology of quantum devices.

CONSORTIUM

Coordinator: Costanza Toninelli, National Research Council (CNR), Italy

Wolfram Pernice, University of Münster, Germany

Frank Koppens, Institute of Photonic Sciences, Spain

André Gourdon, National Center for Scientific Research (CNRS), France

Michel Orrit, Leiden University, Netherlands

Boleslaw Kozankiewicz, Institute of Physics, Polish Academy of Sciences, Poland

Edward Hinds, Imperial College of Science Technology and Medicine, United Kingdom

Q_Magine

Scalable Electrically Read Diamond Spin Qubit Technology for Single Molecule Quantum Imagers

Ground-breaking progress in quantum metrology using NV diamond single spin qubits operating at room temperature led to imaging of single molecules carrying nuclear (1) or electron spin (2) and ultra-weak magnetic and electric fields (3)(4)(5). It is further anticipated that diamond quantum sensors will be one of the first quantum technology devices on the market, with applications in magnetic field sensing and sensors for medicine, biology, and chemistry.

Q-Magine comes with a disruptive approach for NV spin projection measurements, by developing hybrid photoelectric detection of NV electron spin resonances at room temperature, introduced jointly by the applicants (6)(7)(8) and used for constructing single qubit matrix sensors. This technique radically increases the Signal to Noise Ratio (SNR) compared to optical readout methods (6)(7)(8)(9). The electrical readout provides additionally device scalability and compatibility with semiconductor processing methods, which is one of the bottleneck issues for pushing forward the quantum technologies. The combination of photoelectric detection with a sub-millihertz spectra resolution Nuclear Magnetic Resonance spectroscopy using single NV qubit sensor (10), demonstrated by consortium very recently, will be used to establish a breakthrough in single molecular protein structural analysis on a quantum chip. These devices have high application potential in biology, e.g. as a quantum lab-on-chip proteome sequencer.

This approach will progressed towards single molecular NMR imaging, resolving the structure of individual molecules without requiring averaging, and determining their chemical fingerprints by measuring the chemical shift. At the same time there is a wide span of industrial applications for the ultrasensitive detection using the magnetic field, that can profit form the imagers developed in Q-Magine, e.g. in the consumer electronics, automotive, medical diagnostics,and aerospace sectors.

CONSORTIUM

Coordinator: Milos Nesladek, Hasselt University, Belgium

Emilie Bourgeois, IMEC, Belgium

Fedor Jelezko, University of Ulm, Germany

Michael Trupke, University of Vienna, Austria

Adam Gali, Wigner Research Center, Hungary

Q-Clocks

Cavity-Enhanced Quantum Optical Clocks

The "Atomic Quantum Clock" is a milestone of the European Quantum Technologies Timeline. Q-Clocks seeks to establish a new frontier in the quantum measurement of time by joining state-of-the-art optical lattice clocks and the quantized electromagnetic field provided by an optical cavity. The goal of the project is to apply advanced quantum techniques to state-of-the-art optical lattice clocks, demonstrating enhanced sensitivity while preserving long coherence times and the highest accuracy.

A three-fold atom-cavity system approach will be employed: the dispersive quantum non-demolition (QND) system in the weak coupling regime, the QND system in the strong collective coupling regime, and the quantum enhancement of narrow-linewidth laser light generation towards a continuous active optical frequency standard. Cross-fertilization of such approaches will be granted by paralel theoretical investigations on the available and brand-new quantum protocols, providing cavity-assisted readout phase amplification, adaptive entanglement and squeezed state preparation protocols. Novel ideas on quantum state engineering of the clock states inside the optical lattice will be exploited to test possible quantum information and communication applications. By pushing the performance of optical atomic clocks toward the Heisenberg limit, Q-Clocks is expected to substantially enhance all utilizations of high precision atomic clocks, including tests of fundamental physics (test of the theory of relativity, physics beyond the standard model, variation of fundamental constants, search for dark matter) and applied physics (relativistic geophysics, chrono geodetic leveling, precision geodesy and timetagging in coherent high speed optical communication). Finally, active optical atomic clocks would have a potential to join large scale laser interferometers in gravitational waves detection.

CONSORTIUM

Coordinator: Filippo Levi, National Institute of Metrological Research, Italy

Roberto Franzosi, National Institute of Optics, National Research Council (INO-CNR), Italy

Jan W. Thomsen, University of Copenhagen, Denmark

Morgan Mitchell, ICFO - the Institute of Photonic Sciences, Spain

Jérôme Lodewyck, National Center for Scientific Research (CNRS)/ Time Space Reference Systems (SYRTE), France

Michal Zawada, Nicolaus Copernicus University in Torun, Poland

QCDA

Quantum Code Design and Architecture

Errors in quantum computers are unavoidable. Controlling quantum bits (qubits) stored in individual electrons or photons is significantly more challenging than controlling bits in traditional computers. Direct use of physical qubits typically only yields very short lifetimes such that information is lost before any meaningful computation can be executed. Fortunately, we can use quantum error correcting codes to make a logical qubit that is protected against errors. This approach allows us to extend the lifetime as long as is needed to complete a computation. Although the longer we extend the lifetime the more physical qubits will be needed for each logical qubit. Maybe hundreds or thousands of physical qubits will be needed per logical qubit. Current hardware supports fewer than 50 qubits so this cost is substantial.

Kitaev's surface code is a popular idea in quantum error correction that has captured the hearts and minds of many hardware developers since it is a much more practical approach to quantum error correction than its predecessors. The discovery of the surface code is one of the main drivers behind the recent excitement that quantum computation is a realistic prospect, nearly within our grasp. Major industrial hardware developers including Google, IBM, and Intel are all currently working toward a quantum computing architecture based on the surface code. Unfortunately, however, a detailed analysis points towards substantial hardware requirements using the surface code approach, possibly millions of qubits for commercial applications.

Therefore, a fundamental rethinking of how we design quantum computers is a pressing near-future issue. We need to search for alternatives to the surface code that are still practical but do not need so many physical qubits. This is particularly crucial since sufficient time is required for hardware developers to react and adjust course accordingly. The QCDA project will initiate a European co-ordinated approach to designing a new generation of logical qubits and quantum error correction codes. The ultimate goal is the development of high-performance architectures for quantum computers that offer significant reductions in hardware requirements; hence accelerating the transition of quantum computing from university labs to the wider world. The project is composed of two core directions.

The first core direction is the development of qubit codes that exploit an economy of scale offered by large blocks of logical qubits. The most efficient codes in conventional information technology systems are called low-density parity check codes and are used in all Wi-Fi networks and mobile communication networks. The QCDA project will explore the different ways that these highly efficient classical techniques can be converted into highly efficient quantum codes.

The second core direction is the development of codes that go beyond qubits. In many hardware systems, the physics is not naturally that of a qubit but of a quantum oscillator or resonator. This is especially the case when the quantum computer uses light or superconducting circuits as the elementary building blocks. Developing quantum codes based on the natural physics of quantum oscillators rather than qubits offers the hope of more easily experimentally realisable devices.

CONSORTIUM

Coordinator: Earl Campbell, University of Sheffield, United Kingdom

Dan Browne, University College London, United Kingdom

Robert Koenig, Technical University of Munich, Germany

Anthony Leverrier, National Institute for Computer Science and Applied Mathematics (Inria), France

Barbara Terhal, Delft University of Technology, Netherlands

QTFLAG

Quantum Technologies For LAttice Gauge theories

Some of the most fundamental and intriguing phenomena occurring in nature, ranging from the interaction of elementary particles to conventional and exotic matter, are described by *gauge theories.* The study and understanding of such phenomena in most cases is only possible by means of numerical simulations as analytical solutions are not available. These numerical simulations are one of the most complex challenge that physicists have undertaken in the last decades, attacking the problem mostly by means of Monte Carlo methods. Unfortunately, despite the enormous efforts performed and the successes achieved, many significant physical phenomena remain beyond the field of applicability of *Monte Carlo methods* due to a fundamental limitation, the *sign problem.*

As R. Feynman already pointed out when he first proposed the idea of a quantum computer, fully developed quantum technologies will be extremely effective to attack the problems currently out of reach. The goal of the QTFLAG project is to make significant two steps along this path: the first one is to develop classical simulation methods inspired by quantum information science *(tensor network methods)* that do not suffer from the sign problem. The second step is to develop and run quantum software on quantum simulation platforms, that is, to replace classical numerical simulations with experiments where a quantum systems in the lab mimics the physics of the lattice gauge theory of interest, allowing its study in a controlled environment.

This interdisciplinary project will exploit the knowledge from experimental and theoretical quantum optics; atomic, molecular and optical physics; quantum information science; high energy physics and condensed matter. Its results will potentially impact different fundamental and applied fields of science ranging from materials science and quantum chemistry to astrophysics. From the technological point of view, among many different potential applications, the results of this project will enable, in the long run, the study and design of novel materials with *topological error* correcting capabilities, which will play a central role in the quest for building future quantum computers.

CONSORTIUM

Coordinator: Simone Montangero, Saarland University, Germany
Ignacio Cirac, Max Planck Institute of Quantum Optics, Germany
Christine Muschik, Innsbruck University, Austria
Frank Verstraete, Ghent University, Belgium
Leonardo Fallani, National Institute of Optics, National Research Council (INO-CNR), Italy
Jakub Zakrzewski, Jagiellonian University, Poland

QuantAlgo

Quantum algorithms and applications

During the 20th century, the development of information technologies had a huge impact not only on science but also on society as a whole. This unprecedented revolution revealed a need to improve the speed and efficiency of data processing, as well as to strive for better security and privacy. One ultimate limitation of current information processing models is that they assume a simplified representation of physics, relying on classical mechanics. Quantum information technologies promise to break this barrier by achieving the highest security and efficiency allowed by the laws of physics, hence leading to a new revolution in information technologies, in the form of a large-scale network of classical and quantum computing devices able to communicate and process massive amounts of data both efficiently and securely using quantum resources. Despite steady experimental progress, we are still far from this long- term vision, not only due to technological limitations but also to the still-narrow range of applications of current quantum algorithms.

The vision of this project is to combine research on the fundamentals of quantum algorithms with the development of new applications targeted at areas of extreme practical importance and timeliness such as big data and machine learning. The project will complement ongoing experimental efforts in quantum technologies by providing new software tools in order to help lead to a revolution in information technologies, harnessing the power of quantum resources to go well beyond today's capabilities, while maintaining a secure digital society.

CONSORTIUM

Coordinator: Jérémie Roland, Free University of Brussels (ULB), Belgium

Matthias Christandl, University of Copenhagen, Denmark

Miklos Santha, University of Paris Diderot, France

Cyril Allouche, Bull SAS, France

Andris Ambainis, University of Latvia

Ronald de Wolf, Centrum Wiskunde & Informatica (CWI), Netherlands

Ashley Montanaro, University of Bristol, United Kingdom

QUANTOX

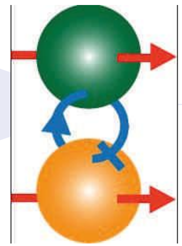
QUANtum Technologies with 2D-OXides

Quantum computation has been conceived to face problems which classical computer cannot solve and that can revolutionize our society, alike modelling of global economy, of the climate changes and implementation of more secure (quantum encrypted) communication schemes. Among other promising fields, quantum computer can establish a "quantum supremacy" in the solution of complex quantum physics, quantum chemistry and biology problems for drug design, which require the simulation of the interactions between many electrons. The solution of these fundamental problems promises a real revolution, whose positive benefits are even unpredictable.

As critical step towards scaling up quantum computers, researchers are trying to encode the quantum bit in a kind of quasiparticle, called Majorana fermion, which take their name from the italian phisicist Majorana, which theorized their existence at the beginning of the 20th century. This particle-like object emerges from the interactions inside materials which are characterized by exotic topological properties. David Thouless, Duncan Haldane and Michael Kosterlitz won the 2016 Nobel Prize in Physics for their theoretical study of topological phases in two-dimensional materials, A qubit working trhough the control of Majorana particles have the characteristic to be insensitivity to decoherence, which is the main problem that quantum computation is facing.

QUANTOX propose a novel material technological platform for the for the realization of topological quantum computers. It is based on two-dimensional electron gas which are formed at the junction between two insulating oxide materials, namely the $LaAlO_3$ (LAO) and $SrTiO_3$ (STO) oxides. This platform has all the characteristics for the practical realization of theory-based proposals for topological quantum computation, and important fundamental and technological advantages. Like the possibility to scale the technology to complex systems including a large number of qubits and the possibilty to incorporate in the device layout all the element necessary for the operation of the qubit.

The project, leaded by the Italian researchers of the CNR-SPIN institute, joined together theoretical and experimental groups among the most active and expert groups in the physics of oxide 2DEGs in the extended European Research Area (ERA), and comprises the participation of theoretical groups expert in Majorana Physics and topological quantum computation.



Our project is aimed at establishing oxide 2DEGs as a viable platform for the realization of topological quantum computers, thus launching a new technological approach to the realization of "fault tolerant" quantum computation technology.

For more information see the QUANTOX website: www.quantox.spin.cnr.it

CONSORTIUM

Coordinator: Marco Salluzzo, National Research Council - SuPerconducting and other INnovative materials and devices institute (CNR-SPIN), Italy
Jacobo Santamaria, Complutense University of Madrid, Spain
Manuel Bibes, Joint Physics Unit CNRS/Thalès, France
Nicolas Bergeal, ESPCI Paris, France
Beena Kalisky, Bar Ilan University by Birad R&D Co. Ltd., Israel
Andrea Caviglia, Delft University of Technology, Netherlands
Alexei Kalaboukhov, Department of Microtechnology and Nanoscience - MC2, Chalmers University of Technology, Sweden

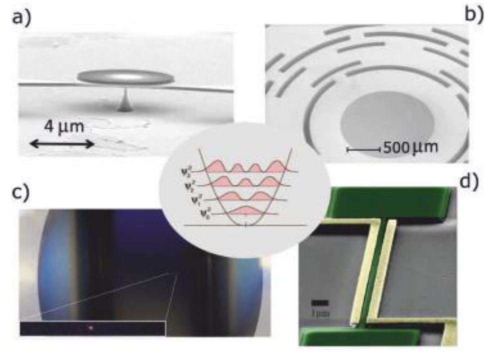
QuaSeRT

Optomechanical quantum sensors at room temperature

The research in cavity optomechanics has recently achieved a major breakthrough: the first observation of quantum phenomena in cryogenic, optically cooled mechanical resonators (i.e., actually in macroscopic objects), as well as in the electromagnetic field interacting with such resonators. These results open the way to the exploitation of optomechanical systems as quantum sensors.

The main target of this project is indeed the creation of optomechanical sensing devices achieving the quantum limit in the measurement process, and exploiting peculiar quantum properties, of both the mechanical oscillator and the interacting radiation field, to enhance the efficiency of the measurement and to integrate the extracted information in quantum communication systems. We will develop three different platforms that, according to the present state of the art, are the most suitable to achieve our goal: (i) semiconductor nano-optomechanical disks (ii) tensioned dielectric membranes (iii) levitating nanoparticles. This parallel approach allows increasing the success probability, to extend the operating frequency range and diversify the systems for a larger versatility. Moreover, in order to study specific quantum protocols, we will exploit nano-electro-mechanical systems which have been shown to be the most suitable classical test-bench for this purpose thanks to their long coherence even at room temperature and their unprecedented control. Mechanical and optical properties of the different resonators will be improved, choosing innovative paths to advance the state of the art, in order to increase the coherent coupling rate and reduce the decoherence rate, eventually achieving quantum performance of the devices at room temperature, a crucial requirement for a realistic application scenario as sensors. Producing and manipulating quantum states of a sensor is an important pre-requisite for the quantum revolution, e.g., for implementing a quantum network that collects information from the environment and transfers it into quantum communication channels.

We will produce prototype portable sensing systems, evaluate and compare the performance of the different platforms as acceleration sensors, study the possibilities of system integration and of functionalization for future extended sensing capability.



a) GaAs waveguide/disk integrated optomechanical device; b) High-stress silicon nitride membrane (100 nm thick) with on-chip mechanical filtering system; c) Silica nanoparticle trapped in an optical cavity; d) High-stress silicon nitride nanobeam with electrodes used to polarize and resonantly excite the beam.

CONSORTIUM

Coordinator: Francesco Marin, National Institute of Optics, National Research Council (INO-CNR), Italy

Eva Weig, University of Konstanz, Germany

Nikolai Kiesel, University of Vienna, Austria

Ivan Favero, Laboratory of Materials and Quantum Phenomena, France

Kjetil Borkje, University College of Southeast Norway, Norway

Pasqualina Sarro, Delft University of Technology, Netherlands

QuompleX

Quantum Information Processing with Complex Media

When we look into a mirror, we see a perfect image of ourselves that is formed by light reflecting off the mirror surface. In contrast, when light is incident on an uneven surface such as a layer of paint or a sugar cube, it scatters in many directions, usually leading to a scrambling of any information carried on the light beam. In recent years, scientists have achieved a staggering amount of control over how light propagates through such complex media, demonstrating feats such as looking through opaque scattering walls, and sending an entire image through a tiny optical fiber. The QuompleX project aims to use such techniques for the delicate task of manipulating quantum information carried by particles of light.

Quantum technologies such as quantum encryption and quantum computers promise as yet unattainable levels of information security and computing power. Such technologies rely on our ability to carefully control and transport quantum states of light, tasks that are usually achieved by conventional optical elements such as beam splitters or integrated photonic circuits. However, as the quantum states in question get more complex, the devices required to control them become harder and harder to use. In QuompleX, we turn this problem around by using commonly available scattering media such as multi-mode fibers as complex linear optical networks for generating, manipulating, and transporting multi-level quantum states of light.

In this manner, QuompleX will study the theoretical limits of quantum transformations possible with complex media, and apply them for designing multi-level quantum logic gates for light. In addition, the technologies developed in QuompleX will be used for the generation of complex, multi-photon entangled states of light and for implementing noise-robust quantum communication protocols with unprecedented levels of information security.

The consortium members at the QuompleX kickoff event in Vienna.

CONSORTIUM

Coordinator: Mehul Malik, Institute for Quantum Optics and Quantum Information in Vienna, Austria
Claudio Conti, National Research Council (CNR), Italy
Pepijn Pinkse, University of Twente, Netherlands

RouTe

Towards Room Temperature Quantum Technologies

Quantum technologies relying on pure quantum effects such as many-body quantum correlations and entanglement hold the promise to outperform their classical counterparts in key tasks, such as correlation and information transfer and processing. Standard applications of Quantum Science and Technology (QST) operate at very low temperatures, as exposure to hot environments typically leads to the quick degradation of quantum correlations. It is therefore the goal of RouTe to lay the foundations for a quantum technology that can operate at room temperature, thus taking a first major leap towards exploiting fundamental quantum phenomena in light-matter interaction for real-world applications. The enabling physical systems are organic materials that display quantum properties even at room temperature when coupled resonantly to cavity modes or plasmonic structures.

The objectives of RouTe include the realization of: i) Room temperature quantum simulator setups for many-body lattice models and topological states of matter with polaritons; ii) Strongly coupled light-matter interfaces with applications to quantum communication and robust quantum information storage at room temperature; and iii) Enhanced material properties and chemical reactivity by making use of strong coupling of organic materials to photonic or phononic modes prepared in their vacuum state.

CONSORTIUM

Coordinator: Thomas Ebbesen, University of Strasbourg & National Center for Scientific Research (CNRS), France

Vahid Sandoghdar, Max Planck Institute, Germany

Francisco Garcia-Vidal, Madrid Autonomous University, Spain

Paivi Torma, Aalto University, Finland

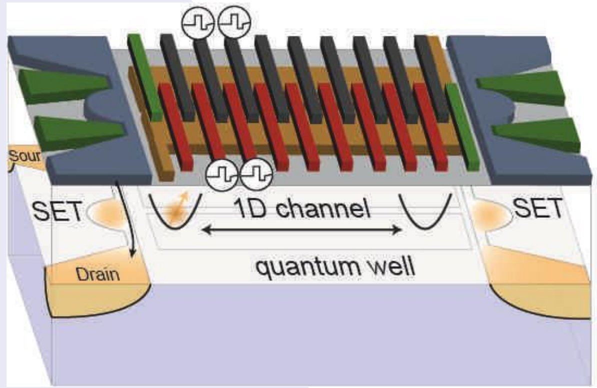
Boleslaw Kozankiewicz, Institute of Physics, Polish Academy of Sciences, Poland

Thilo Stoferle, IBM Research – Zurich Laboratory, Switzerland

Si QuBus

Long-range quantum bus for electron spin qubits in silicon

Using key concepts of quantum mechanics such as superposition and entanglement, quantum computers promise to solve problems, which are intractable for all classical computers. To operate a realistic quantum computer, the quantum information has to be encoded into several of the smallest physical quantum information elements, the qubits. Thus, a realistic quantum computer requires millions of qubits and must have a scalable architecture. The spin of a single electron can encode one qubit. We have learned how to trap a single electron in silicon, how to precisely manipulate its spin, to set it in a superposition and to entangle it with another qubit. So far, these functionalities were demonstrated in devices providing not more than only two qubits. Classical computer chips are made of silicon, based on the same technology as the electron traps and proofed to be highly scalable driving a large industry. Still, we cannot scale up a quantum chip as easily, because the qubits and thus the electrons have to be very close to each other in order to be able to interact. For a scalable architecture, we need space on the quantum chip for the required electrical connections or for embedding quantum chip elements with classical silicon electronics. Our idea is a new functional element, the quantum bus (QuBus), which shuttles a single electron and thus the quantum information across a distance of about 10 microns. The QuBus generates the space we need for designing a scalable quantum computer architecture. It is compatible with industrial fabrication and we benefit from industrial partners such as LETI, STMicroelectronics and Intel within the consortium. At the end of the project, we aim at the demonstration of quantum teleportation across a QuBus and explore branching of a QuBus to allow for building two-dimensional fault-tolerant networks of interacting qubits on a chip.



Schematic of a QuBus. A quantum dot is formed within a Si quantum well by multi-layer metallic surface gates. Pulsing the voltages to these gates the quantum dot, which carries a single electron, is shuttled across an electrostatically formed one-dimensional channel. Single electron transistors (SET) can detect a single electron and its spin state at the ends of the QuBus.

CONSORTIUM
Coordinator: Lars Schreiber, RWTH Aachen University, Germany
David DiVincenzo, Forschungszentrum Jülich, Germany
Tristan Meunier, Institute NEEL – National Center for Scientific Research (CNRS), France
Sylvain Barraud, Alternative Energies and Atomic Energy Commission, France
Lieven Vandersypen, Delft University of Technology, Netherlands
Łukasz Cywiński, Institute of Physics, Polish Academy of Sciences, Poland

SQUARE

Silicon Photonics for Quantum Fibre Networks

Nowadays secure communication is essential for exchange of sensitive information, while the security based on classical cryptography protocols cannot be absolutely guaranteed. Especially when a full-tolerant quantum computer will be available, the classical encryption and decryption methods will be no longer secure [1], posing a serious threat to cryptosystems. Quantum cryptography (QCy), a branch of Quantum Communications (QCs), has opened a new era in the security of information transmission.

Although big steps in QCs and Quantum Key Distribution (QKD) have been taken over the last 20 years, the future of QCs is stillchallenged by major barriers. The SQUARE project shatters these barriers by developing the next generation of quantum devices based on silicon photonics, enabling compact, reliable,and efficient components, allowing for the construction of fully connected long-reach, high-rate QKD-secured quantum communication networks.The SQUARE project develops a fully integrated transmitter (Tx) and receiver (Rx) for quantum communications and classical communication based on silicon photonics, which is a powerful means to combine the assets of integrated photonics with CMOS technologies. The driving force behind silicon photonics is that silicon represents a mature integration platform, which brings photonic circuits to a higher integration level allowing for mass-production [2,3] as it has done for electronic circuits. In this sense, we believe that silicon photonics will play a significant role in future QCs, allowing to build up powerful and cost-effective photonic circuits for quantum communication applications. SQUARE will develop the integrated quantum technologies necessary to breach the limits of current state-of-the-art, and furthermore integrate these technologies directly in quantum subsystems. Hence the components will be developed for specific applications in specific quantum network scenarios. The proposed novel network leverages on the strengths ofdifferent technologies to obtain global benefits in terms of reach, sensitivity, complexity,practicality and total power consumption.

CONSORTIUM

Coordinator: Karsten Rottwitt, Technical University of Denmark

Peter Tøttrup, IrSee, Denmark

Guang-Hua Duan, III-V Lab, France

Ségolène Olivier, Alternative Energies and Atomic Energy Commission, France

Alberto Tosi, Polytechnic University of Milan, Italy

Alessandro Ruggeri, Micro Photon Devices, Italy

Mark Thompson, University of Bristol, United Kingdom

Muhammet Ali Can, Tubitak Bilgem, Turkey

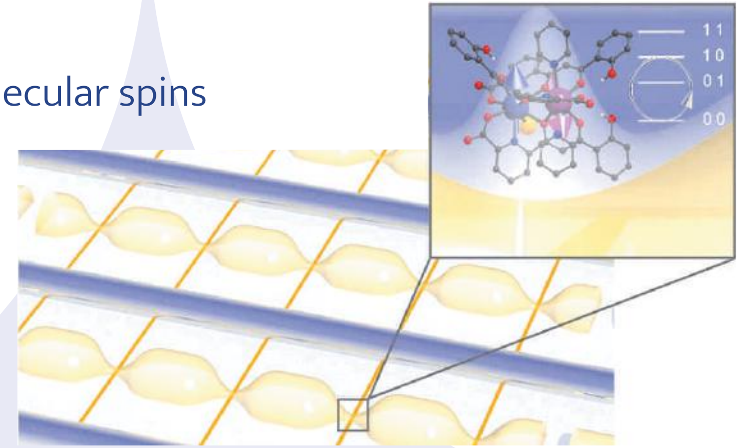
SUMO

Scaling Up quantum computation with MOlecular spins

Quantum computers use a new concept for processing information that is based on the principles of quantum mechanics. Employing fascinating effects that occur naturally in the realm of atoms and molecules, quantum processors can become vastly powerful machines that handle information in ways normal processors cannot. We expect them to solve computational problems that were once thought unsolvable.

Quantum computers can overcome today's most powerful computers. But to do so, they must reach a minimum level of complexity. They must contain a minimum number of quantum bits, qubits. Scaling up a quantum computer to reach this level while keeping it sufficiently isolated from external perturbations to preserve its pure, or coherent, quantum operation is a major challenge. The SUMO project will establish a novel architecture which hosts qubits in artificial magnetic molecules and connects them by superconducting circuitry. Molecules naturally obey quantum laws, are fully reproducible and many of them fit in a small device. They have tremendous potential for scaling up quantum resources.

The quantum behaviour of molecules is also highly tuneable: chemistry can modify their composition, structure and physical properties. We use this flexibility to integrate between 3 and 9 different spin qubits, each of them a single magnetic ion, in artificial molecules. Each molecule can then leverage quantum error correction codes internally and become a noise-resilient qubit. Superconducting circuitry in the form of microwave resonators can then connect all qubits coherently. This hybrid magnetic quantum processor will maintain coherence through a large range of scaling up.



Optimally interfacing these two components, the superconducting chip and the molecules, requires that some circuit regions are scaled down, using sophisticated nanofabrication techniques, to reach the molecular scale and that single molecules are integrated at these exact locations by means of nanopatterning and molecular recognition. The final goal of this multidisciplinary project is to perform basic quantum logical operations on individual molecules as a step towards the implementation of a full-fledged quantum architecture.

CONSORTIUM

Coordinator: Fernando Luis, National Research Council (CSIC)/ Aragón Materials Science Institute, Spain

Sebastian Loth, University of Stuttgart, Germany

Johannes Majer, Wolfgang Pauli Institute/ Atominstitut, Technical University of Wien, Austria

Stefano Carretta, National Interuniversity Consortium of Materials Science and Technology, Italy

Richard Winpenny, University of Manchester, United Kingdom

Ardavan Arzhang, University of Oxford, United Kingdom

SuperTop

Topologically protected states in double nanowire superconductor hybrids

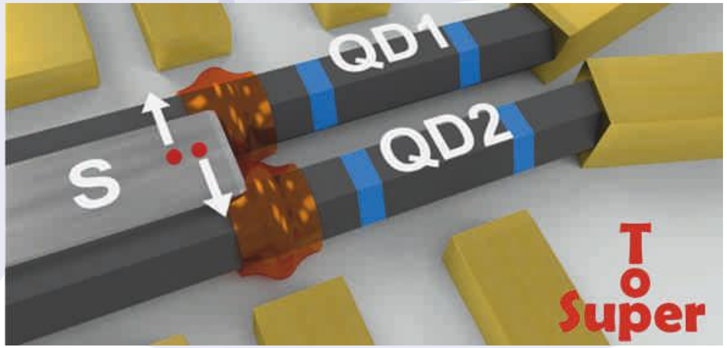
Topological quantum computing (TQC) is an emerging field with strong benefits for prospective applications, since it provides an elegant way around decoherence. The theory of TQC progressed very rapidly during the last decade from various qubit realizations to scalable computational protocols. However, experimental realization of these concepts lags behind. Important experimental milestones have been achieved recently, by demonstrating the first signatures of Majorana states which are the simplest non-Abelian anyons.

However, to realize fully topologically protected universal quantum computation, more exotic anyons, such as parafermions are required. Thus, the unambiguous demonstration of parafermion states will have a great impact on the development of universal quantum computation. The experimental realization of parafermions is challenging, since they are based on the combination of various ingredients, such as crossed Andreev reflection, electron-electron or spin-orbit interaction, and high quality quantum conductors. Thus, the investigation of all these ingredients is essential and timely to achieve further experimental progress. The team of SuperTop is composed of six leading groups with strong and complementary experimental background in these areas with the aim to realize parafermions in double nanowire-based hybrid devices (DNW) for the first time.

The main objectives of SuperTop are: a) development of different DNW geometries, which consist of two parallel 1D spin-orbit nanowires coupled by a thin superconductor stripe and b) investigation of the emerging exotic bound states at the superconductor/semiconductor interface of the DNW.

SuperTop first grows state-of-the-art InAs and InSb based nanostructures, in particular InAs nanowires (NWs) with in-situ grown epitaxial superconducting layer, NWs with built-in InP barriers and InSb nanoflakes. Based on these high quality materials, different device geometries of DNW are fabricated and the emerging novel states are investigated. The topological character, quantum phase transition, coherence time, coupling strength to QED as key features of the engineered new states are planned to be addressed by various cutting-edge low temperature measurement techniques (e.g. non-local spectroscopy, noise, current-phase relationship measurement or integration into coplanar resonators).

The experimental team of SuperTop is supported by in-house theoretical experts of TQC, who will contribute to the interpretation of the results and development of technologically feasible topologically protected quantum architectures.



CONSORTIUM

Coordinator: Szabolcs Csonka, Budapest University of Technology and Economics, Hungary

Jesper Nygard, University of Copenhagen, Denmark

Takis Kontos, National Center for Scientific Research (CNRS), France

Lucia Sorba, Institute of Nanoscience, National Research Council (CNR), Italy

Attila Geresdi, Delft University of Technology, Netherlands

Christian Schönenberger, University of Basel, Switzerland

TAIOL

Trapped Atom Interferometers in Optical Lattices

The long-term vision of TAIOL project is to develop a novel class of quantum sensors based on trapped atom interferometry with performances that will overcome state of the art, and to extend their range of operation for high precision measurements in applied and fundamental physics.

In such sensors, atoms are split into a quantum superposition of two spatially separated states in the presence of an external force. The resulting difference in potential energy between the two spatial states leads to a differential phase evolution, which is read out by recombining them after some interrogation time, thus creating an atomic interferometer. In this measurement scheme, the sensitivity in the force measurement increases linearly with the spatial separation and the interrogation time. The use of trapped atoms allows here for reaching very long interrogation times, of up to several seconds, without having to increase the size of the physical package. This is a key advantage with respect to sensors based on freely falling atoms, for which such long interrogation times would imply free fall distances of tens of meters, which allows to envision the development of very compact sensors. In addition, it enables to perform local measurements of external fields with very high spatial resolution, of less than a micrometer.

The aim of TAIOL is to push the performance of sensors based on atom interferometry, using ultracold atoms confined in optical lattices, well beyond the levels reached by the few proof-of-principle experiments that have explored so far guided and trapped architectures. For that purpose, innovative approaches and methods will be explored for separating split atomic samples further apart, from tens of micrometers to millimeters, while maintaining the quantum coherence, and for taming harmful effects related to the interactions between the trapped atoms, by either controlling the strength of these interactions or using novel sources of ultra-cold atoms. The project outputs will open new possibilities for a wide range of applications, such as inertial sensing, inertial navigation, gravity field mapping, physical laws testing, surface interactions, with the perspective of future industrial implementations.

CONSORTIUM

Coordinator: Franck Pereira dos Santos, Paris Observatory/ Time Space Reference Systems (SYRTE), France

Andrea Bertoldi, LP2N, France

Ernst Rasel, Institute of Quantum Optics, Leibniz University of Hannover, Germany

Marco Fattori, National Institute of Optics, National Research Council (INO-CNR), Italy

Jan Chwedeńczuk, Faculty of Physics, University of Warsaw, Poland

TheBlinQC

Theory-Blind Quantum Control

Accurate control of complex quantum systems is of great importance for the development of quantum technologies, as it permits to achieve many goals with high accuracy despite inherent system imperfections. Realising this in practice, however, is a great challenge, since it requires precise models and numerically expensive simulations.

The central goal of this project is to develop and implement control techniques that do not require theoretical modelling, simulation or any knowledge of a systems' microscopic decomposition. Instead, all necessary information will be obtained directly from the experiment. We will identify control targets that characterise desired properties of quantum systems well, and that can be estimated accurately and efficiently in an experiment. Based on the assessment of these targets and their dependence on tunable control parameters, we will develop control algorithms such that an optimal control protocol is found within a minimal number of experimental measurements.

These methods will be developed in direct interplay between simulations of experiments with many-body systems and actual experimental implementations.

CONSORTIUM

Coordinator: Florian Mintert, Imperial College London, United Kingdom
Daniel Burgarth, Aberystwyth University, United Kingdom
Robert Loew, University of Stuttgart, Germany
Markus Aspelmeyer, University of Vienna, Austria
Krzysztof Sacha, Jagiellonian University, Poland
Jose Leitao, Instituto de Telecomunicações (IT), Portugal
Radim Filip, Palacký University Olomouc, Czech Republic

Topoquant

2D hybrid materials as a platform for topological quantum computing

The topological protection expected to hold in a Majorana qubit promises virtually decoherence-free and fault-tolerant quantum computation. Thanks to material and experimental advances achieved during the last years, realizing and observing individual Majorana zero modes has become routine in multiple research laboratories. Our project will bring research on Majorana modes to the next level in a twofold way.

First, we will develop cleaner InAs-based systems as well as novel InSb systems that allow the integration of multiple Majorana wires. Second, we will optimize fast electronic control and measurements techniques to be directly applied to study the physical properties of Majorana modes and in performing basic quantum operations.The new material system will be based on high quality III-V two-dimensional heterostructures where the superconductor, aluminum, will be grown in-situ, i.e. directly in the molecular beam epitaxy system. The devices we will fabricate and study will include elongated quantum dots hosting Majorana modes and coupled to charge detectors. Fast gate manipulation will allow us to deterministically change the coupling between Majorana modes. With this simple scheme, the braiding statistics of Majorana modes can be investigated, and elementary quantum operations performed. The results of the operations will be read out by changes in the charge state of the system. Here we will investigate and quantify quasiparticle poisoning, and suggest ways how to minimize it.

CONSORTIUM

Coordinator: Klaus Ensslin, ETH Zurich, Switzerland

Werner Wegscheider, ETH Zurich, Switzerland

Felix von Oppen, Free University of Berlin, Germany

Fabrizio Nichele, University of Copenhagen, Denmark

Ville Maisi, University of Lund, Sweden

Martin Leijnse, University of Lund, Sweden

QUANTERA

QUANTERA

Call Secretariat

FRENCH NATIONAL RESEARCH AGENCY

Mathieu Girerd
International Scientific Officer
mathieu.girerd@anr.fr

www.quantera.eu

Coordinator

NATIONAL SCIENCE CENTRE, POLAND

prof. Konrad Banaszek
Scientific Coordinator
konrad.banaszek@ncn.gov.pl

Sylwia Kostka
Programme Coordinator
sylwia.kostka@ncn.gov.pl

Marlena Wosiak
Coordination Office
marlena.wosiak@ncn.gov.pl

Funding Agencies

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POLAND

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