QUTEGA
Quantentechnologie –
Grundlagen und Anwendungen

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

QUANTUM TECHNOLOGY
Basics and Applications

Concept paper of the National Initiative for the
Promotion of Quantum Technology from Basics to Applications (QUTEGA)

imprint

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January 2017

Machine Translated by Google

Table of contents

1. Summary 2. 4
Introduction 5
3. Application-oriented topics 6
3.1 Quantum communication 7
3.1.1 State of research and 7
technology 3.1.2 Research needs, challenges and 8
goals 3.2 Computing with quantum 9
computers 3.2.1 State of research
and technology 3.2.2 Challenges 9 10
and goals 3.3 11
Quantum -Sensor technology 3.3.1 11
State of research and technology 12
3.3.2 Challenges and 12
goals 3.4 Quantum simulation 3.4.1 13
State of research and technology 14
3.4.2 Challenges and goals 4. Methodological cross-sectional platforms 16
4.1 Overarching theoretical models and concepts 16
4.1.1 Quantum communication 17
4.1.2 Quantum computing and algorithms 18
4.1.3 Quantum 18
sensors 4.1.4 Quantum simulation 18
4.2 Hardware 18
systems 4.2.1 Solid-state 19
based systems 4.2.1.1 19
Superconducting systems 21
4.2.1.2 Nanoscopic 21
systems 4.2.2 Photonic systems 22
4.2.2.1 State of research and 22
technology 4.2.2.2 Challenges and goals 4.2.3 Atomic and molecular systems 24
4.2.3.1 State of research and 24
technology 4.2.3.2 Challenges 25
and goals 5. Key technologies 27
5.1 Quantum compatible data acquisition, fast electronics and cryogenics 27
5.2 Lasers, detectors, sources and interfaces 28
5.3 Materials, components and quantum technological 29
devices 5.4 Quantum 30
measurements 6. Standardization 31
7. Structure of the National Initiative 32
7.1 Research funding instruments 33
7.1.1 Research and development funding 33
7.1.2 Structural measures 34
7.1.3 Outreach and Educational Efforts 7.2 34
Recommendations 35

QUTEGA

1. Summary

In the spring of 2016, the European Commission announced that it would set up a flagship project on the subject of "quantum technology" with the four pillars of quantum communication, quantum sensors, quantum computers and quantum simulation computers as part of its research funding, which should start in 2018. A large part of the flagship funding comes from the European Commission, while another part is provided by the participating cou
In May 2016, the BMBF in Germany decided to set up a national initiative **"Quantum Technology -** Basics and Applications" (QUTEGA). The aim of this initiative is to promote the transfer of research results to indus
This goal has two facets: on the one hand, joint research and further development of quantum technology by research institutions and industry in cases where the application is already tangible. On the other hand, research is also to be funded on topics for which a possible application lies in the distant future and direct, active participation by industry is still premature. The all-encompassing goal is to make quantum technology usable in an economically relevant way. To this end, the BMBF has contacted both industry and science. This concept paper contains the scientific recommendations.

2 Introduction

In science, the field of "quantum technology" has been able to establish itself as a new type of research over the last few decades, which has the potential to revolutionize a large number of technical devices in the future. Current Limitations of today's metrology or structuring methods, which often form the backbone of our classic technologies, can be overcome using quantum effects. Examples of applications include interferometry, microscopy, lithography, imaging, sensors and time synchronization.

Quantum components combined with quantum light fields also offer a fundamentally new perspective for the secure transmission of information and thus for telecommunications.

Historically, one of the first proposals for using quantum technology in correlated systems concerns the simulation of complex tasks, a notorious weakness of classical computers. Even a very complex problem can be solved efficiently if it can be mapped onto a quantum system that is itself easily controllable. An example of such an application is the optimization of magnetic and superconducting materials. In the ultimate case, complex computing and simulation tasks are performed by a universal, freely programmable quantum computer.

The National Initiative "Quantum Technology - Basics and Applications" (QUTEGA) aims to gradually bring the special properties of quantum physics from the laboratory into industrial practice over the long term. The great advances in laser technology and in the unique control of atomic, photonic and solid-state systems have already brought parts of quantum technology close to application. Among other things, atomic clocks can be realized with this with an uncertainty of only a few parts in 1018, corresponding to about 1 second gear deviation over the age of the universe. As small as this number may seem, there are applications that require such accuracy. By the methods of moder With quantum technology, the intrinsic quantum uncertainty in the measurement process can be controlled and higher resolutions can be achieved in interferometers, for example. In complex, interacting many-body systems, quantum correlations provide information about the quantum state. The state of research and an outlook are described in the study on quantum technologies, which was published jointly by the Leopoldina1 and the other academies of science in 2015 . With the ability to control and manipulate quantum properties, traditional limitations and limitations can be overcome. After two decades of active basic research, the first attractive industrial applications are emerging.

QUTEGA is intended to flank the quantum technology program planned at European level , the goals of which were laid down in the Quantum Manifesto2 . The four application-oriented pillars of the Quantum Manifesto and the horizontal methodical cross-cutting issues are described below.

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http://www.leopoldina.org/uploads/
tx_leopub1lication/2015_Quantentechnologie_LE_DE_kort.pdf

http://qurope.eu/system/files/
u7/93056_Quan2tum%20Manifesto_WEB.pdf

3.Application-oriented topics

Quantum technologies can be used in a wide variety of areas and in many areas they enable the improvement of known technologies and open up new ones
on the other hand, fundamentally new possibilities. For the first time, quantum communication makes it possible to secure communication even against future, currently unknown attacks (Chapter 3.1). The increased performance of quantum computers due to the parallelization of calculations means that the solution to previously unsolved problems is now within reach (Section 3.2). Quantum sensors can determine the most diverse types of physical parameters with previously unattainable accuracy (Section 3.3). And the behavior of complex quantum systems can be simulated with the help of other, highly controlled quantum systems. This procedure is referred to as quantum simulation (Chapter 3.4).

The current status of research and development as well as future challenges and goals for the future in these four subject areas of quantum communication, quantum computing, quantum sensors and quantum simulation are presented below .

3.1 Quantum Communication

Quantum communication deals with the construction of quantum-physically secured connections and the distribution of quantum states. The secure connections can be reached point-to-point or distributed with trustworthy nodes.

A future quantum internet promises not only physical instead of algorithmic security in communication, but also the complete networking of quantum computers for decentralized calculations on distributed machines. It requires methods of quantum communication that are based on quantum teleportation and that allow quantum properties to be loaded into quantum memories that are far away.

3.1.1 State of Research and Technology

Physically and thus verifiably secure communication is possible for the first time through the use of quantum states as information carriers. According to the laws of quantum physics, every eavesdropping attack causes a verifiable change of state on the line, if the quantum states used are chosen skilfully, which could be described as quantum noise. Since such proof is based on a law of nature, it cannot be overcome even by technologies that are not yet available today. The quantum key distribution (QKD for quantum key distribution) makes it possible for the first time, by measuring the quantum states, to draw conclusions about the actions of the eavesdropper and the knowledge he has acquired in the process, and thus the security of the communication on a funda to quantify mentally. The first systems are commercially available, but still offer a wide range of improvements in terms of range, rate, transmission medium and standardization before this security concept can conquer practice.

Since light can be transmitted with the lowest possible losses, the quantum states of the light field, for example individual light quanta (ie photons), have emerged as the tool of choice. In fibre-optic based systems, secure keys are exchanged over distances of up to 400 km, very high key rates of around 1 Mbit/s are achieved up to 50 km. Open space systems can be used, for example, for mobile devices or for short connections in cities.

Over longer distances, for example, networks from the Battelle Institute (USA) in cooperation with the Swiss company ID Quantique in the Northeast of the USA or in China over a distance of 2000 km between Beijing and Shanghai from point-to-point QKD links and secure Network nodes set up and tested. Satellite connections even make it possible to bridge intercontinental distances. The quantum satellite launched by China in August 2016 is an example of this scenario.

A quantum repeater adopts principles known from telecommunications. By dividing the connection into individual segments, the losses and noise in The range limitation caused by the optical fibers can be overcome. The individual segments can be efficiently concatenated using quantum logic gates and, where appropriate, quantum memories at the nodes. The principle of point-to-point entanglement distribution, for example, has been demonstrated in Munich over 400 m at currently two qubits per minute, over 1.3 km in Delft at a lower rate.

Principles of quantum communication can also be applied to a number of other communi cation methods are used, e.g. for “quantum tokens”, physically secure seals, for efficient communication, or for distributed calculations, scheduling and quantum authentication. So far, however, there have only been proof-of-principle experiments for all of these processes .

The security of most of the asymmetric algorithmic encryption methods used today may be at risk in the future for two reasons. For one thing, the safety of these methods has not been mathematically proven. However, the probability of the resulting danger is estimated to be extremely low. On the other hand, these methods no longer provide security as soon as a quantum computer is available. For this reason, around 10 years ago, research was started into new algorithms in asymmetric cryptography that can hold their own against well-known quantum computer algorithms. Such new processes must be made ready for use in the next few years in order to guarantee the long-term security of our IT systems, such as those used in Industry 4.0, critical infrastructures, autonomous driving or in mobile communication. This requires research in the areas of algorithms, efficient implementations and security against both algorithmic and physical attacks. As in the past, security will no longer be guaranteed in the future due to algorithmic complexity when the performance of classic computers has increased accordingly. In combination with classical cryptography, quantum key distribution is the most suitable method for long-term security. The first steps towards the standardization of such methods are being taken at ETSI, for example, in the 'WG Quantum-Safe Cryptography' working group.

Another aspect of quantum communication is reaching the quantum limit in information transmission. Today's optical technology is still a few powers of ten away from the minimum energy consumption given by the quantization limit. The transition to the quantum limit will only be possible with a new generation of quantum-limited component concepts.

3.1.2 Research needs, challenges and goals

The applications in quantum communication have two goals. On the one hand, a secure quantum key distribution between two or more partners. These processes are already very close to being ready for the market. What is important here is the achievement of high key rates in realistic environments. To do this, processes must be developed that are compatible with existing telecommunications environments and can be easily integrated into existing security architectures. The development of satellite-based methods is suitable for bridging very large distances, ie both the development of suitable satellites and ground stations.

On the other hand, quantum communication aims to transmit superposition states from one node to another in networks and to establish quantum correlations between different locations. The Challenges are based on the fundamental requirements of all communication networks: Quantum and classic information has to be sent, transmitted and received, and not just in simple point-to-point connections, but in networks. This requires the development of reliable, highly efficient interfaces that link hybrid systems made up of technically different components, such as quantum memory and photonic communication channels.

It will be important to replace complex demonstrators made up of individual components from previous basic research with integrated and miniaturized components. The goals of future quantum technology as a basis for quantum communication applications include, for example, the development of powerful single-photon sources, quantum memories and various systems for efficient, secure key exchange and communication with robust components for a wide variety of communication scenarios. In future networks

Quantum communication can only be successful with protocols that are closely matched to the available hardware.

In order to approach the quantum limit in energy efficiency, attojoule technologies and concepts must be researched. This includes, for example, reducing the optically active volume by powers of ten and consequently avoiding electrical/optical conversions.

In principle, post-quantum methods should be researched for cryptography, which can be integrated compatibly into the existing infrastructure and which can be implemented efficiently and are resistant to physical attacks. Post-quantum means immunity to attacks using a quantum computer. The post-quantum methods include both classical, algorithmic and quantum technological methods.

For the classic methods, it is helpful to use quantum phenomena to generate unique random numbers and cryptographic keys or identities that are uniquely assigned to the object (physical unclonable functions). It is also important to develop suitable procedures for secure key management.

3.2 Computing with quantum computers

In a quantum computer, information is not stored in binary form with bits, i.e. in the values of zero or one, as in a classic computer, but with quantum bits that are present in a superposition of zero and one. This means that massively parallel calculations are possible on a quantum computer, which allows its performance to increase exponentially with the number N of quantum bits, such as 2N . Many algorithms have already been worked out that use this quantum parallelism for previously unsolved problems

Zen.

3.2.1 State of Research and Technology

Experimental platforms have already shown the basic function and first quantum algorithms have been successfully demonstrated, but so far only with a comparatively small number of less than 10 quantum bits and logical operations with a fidelity of less than 99.9%. Computer architectures in which the number of quantum bits is in principle scalable have already been implemented in smaller prototypes with trapped ions or atoms, but also in solid-state-based systems or superconducting circuits. The discovery of topological materials also offers innovative concepts for the development of novel hardware for solid-state-based quantum computing. The quantum state of these topological qubits is expected to be protected by the two-dimensional topology. Even a quantum computer in which information is stored and processed in 50 quantum bits would outshine any classic supercomputer when it comes to suitable computing tasks. Quantum computing thus represents perhaps the most far-reaching innovation of all quantum technologies. However, it is at the same time technically and scientifically the most challenging and complex task, quantum logical operations with sufficiently high fidelity on a scalable system of ultimately hundreds of quantum bits carried out in order to be able to carry out fundamental mathematical problems or safety-relevant algorithms. These challenges also stimulate advances in all other quantum technologies: Any digital quantum simulation of a complex problem can be carried out on a quantum computer. Quantum communication links with repeaters require a large number of small quantum computers at the nodes in order to be able to carry out and process local Bell measurements

Run entanglement distillation protocols.

3.2.2 Challenges and Goals

The central scientific and technological challenges for a quantum gate-based quantum computer can already be foreseen from the advanced work on experimental platforms and prototypes:

- The fidelity of quantum logic operations should be better than 0.99999 in order to provide the prerequisite for quantum error correction algorithms. The coherence time of quantum bits is further improved, as is the speed of logical operations ones.

- Initialization, readout quality and readout speed for quantum bits should be further improved so that a measurement result can control the sequence of operations.

- With these improvements, quantum error correction algorithms are to be implemented.

- Scalable architectures are implemented and further optimized to enable large numbers of quantum bits . The production of corresponding chips and prototypes is just as necessary here as the classic control of operations in the quantum computer using optimized control voltages such as laser, radio frequency or microwave pulses. Ultimately, optimized classic hardware in a quantum computer works closely with the Quantum software for technological or mathematical-scientific application problems.

In order to deal with the challenges of a quantum computer, close cooperation between experimental and theoretical physicists with engineering and industrial working groups will be necessary in the future.

Global IT companies have shown increased interest in computing with quantum computers over the past decade. This great technological interest is motivated by the obviously foreseeable end of Moore's law, after it became clear that further improvement of conventional approaches beyond 7nm technology will be severely limited. Advances in quantum computer design, fault-tolerant or corrective algorithms and new quantum processor manufacturing technologies have transformed this scientific approach into a realistic technological goal of far outperforming classical computers in special applications on a time horizon of ten to twenty years.

For example, leading companies such as Intel, HRL Laboratories and NTT support the implementation of spin quantum bits in semiconductors; Google, IBM, D-Wave and Intel are investing in superconducting quantum bit architectures, both using the gate-based approach and, in the case of D-Wave, the adiabatic optimization approach. Microsoft relies on topological quantum bits; Lockheed Martin, IONQ Massachusetts, SANDIA Albuquerque, INFINEON and others support research or work with quantum bits in trapped ions and their interface to photons. Due to the world-leading research in quantum computing in Europe, many IT companies have academic partners in Eu

ropa chosen for their R&D efforts.

For the increased expansion of core technology Quantum computing in Europe will require synergies between industrial and academic partners over a ten-year period, as well as the participation of institutes such as the Fraunhofer Society or the Helmholtz Association in multidisciplinary consortia. Such hardware efforts should be flanked by the development of quantum software to optimize quantum algorithms for application problems of interest. Europe is a leader in the development of

Software for classic high-performance computing applications and therefore well positioned to establish itself in the new field of quantum software engineering.

3.3 Quantum Sensors

The precise recording of physical variables is the basis of all natural sciences and a necessary prerequisite and driving force for almost all further technical developments.

Although classic sensor principles are currently being refined, miniaturized and combined, it is foreseeable that no significant increase in the key parameters achieved so far, such as sensitivity and specificity, can be achieved.

Quantum phenomena such as coherence, superposition and entanglement, on the other hand, can be used to detect variables such as pressure, temperature, position, time and movement or acceleration, location, gravitation or electric and magnetic fields with unprecedented accuracy. Quantum sensors use different quantum systems, each of which has specific strengths.

3.3.1 State of Research and Technology

Atomic quantum sensors have the potential to become a key technology not only for next-generation optical clocks, but also for accurately determining a body's acceleration and rotation. With 18 significant digits, frequency measurements on optical clocks are the most precise measurements in all areas of technology and research. While in a clock the interference of the internal states of the atoms indicates the beat, acceleration sensors detect the interference of atomic matter waves that have experienced different accelerations, for example in the Earth's gravitational field. Atomic quantum sensors now surpass their classic counterparts in almost all performance indicators. Improvements in the performance indicators by at least two more orders of magnitude are expected in the future. This allows a variety of applications open up applications ranging from earth observation and earth exploration to satellite navigation and the synchronization of large networks to questions in basic research, such as physics beyond the standard model.

Solid-state quantum sensors, on the other hand, achieve outstanding properties in the combination of spatial resolution and sensitivity. Different sensor principles can be combined in this form of quantum sensors and, in principle, allow very compact designs up to the complete device. Spin quantum sensors, for example, detect small amounts of magnetic moments up to individual electron or nuclear spins under ambient temperature and even physiological conditions. Among other things, they detect magnetic and electric fields or pressure and temperature with a spatial resolution of a few nanometers. Due to the combination of different materials and designs (hybrid quantum sensors), solid-state quantum sensors are suitable for the sensitive detection of mass, position or rotation. Multiqubit quantum sensors improve the sensitivity and spectral resolution as well as the bandwidth of spin quantum sensors using quantum algorithms. Semiconducting and superconducting solid-state quantum systems play a fundamental role in the field of electrical quantum metrology. Single electron pumps based on semiconductor quantum dots are to be used in the future as quantum current standards with strongly non-classical current properties and as single photon sources. In optical quantum metrology, non-classical properties of light are used to increase the resolution of measurements or to make them possible in the first place. By so-called "squeezing" of light, noise contributions can be reduced in a targeted manner, for example in gravitational wave detectors, or the resolution can be increased in imaging processes. Entangled photons of different wavelengths enable so-called “quantum imaging”, in which images of objects

3.3.2 Challenges and Goals

In basic research, quantum sensors have been developed from a number of different physical platforms. The individual approaches complement each other and each face system-specific challenges.
The following are some key cross-platform challenges. For example, complex state preparation and rapid dephasing often prevent a sensitivity advantage through highly correlated quantum sensor states. Here, the development of specific quantum algorithms and research into robust quantum states in suitable physical systems can play a key role in improving the sensitivity of quantum sensors. In addition, sensor principles that have already been developed in basic research have only been sporadically put into practice. One of the reasons for this is that the sensor principles used to date are not sufficiently robust and that the not

Agile integration into sensor systems requires the new development of a number of key components, also in the sensor periphery (Chapter 4, Methodical Cross-Sectional Platforms). Specifically, we identify the following challenges and goals:

- Investigation of new physical systems and areas of application for quantum sensors

- Development of sensors and sensor principles that achieve an effective gain in sensitivity and selectivity through multi-particle effects through to entangled sensor networks

- Development of quantum algorithms for Improvement of sensors

- Further development of current laboratory systems into demonstrators or prototypes through miniaturization and integration of the sensor peripherals

Quantum sensory systems require not only the detection of the physical or chemical properties but also a conversion into processable, ie electrical or photonic signals. Especially when using quantum effects for measurement acquisition, 'transducers' downstream of the detector are required, which generate a measurement signal from the detected quantum state. This can be achieved in atomic and molecular sensors by coupling them to well-controllable quantum systems. In solid-state systems, material development for sensory elements must take into account signal conversion and signal transmission in the sensory system. It is important to integrate the detector element into existing micro and

Coupling or integrating nanotechnologies.

3.4 Quantum Simulation

The idea of a quantum simulator goes back to Richard Feynman, who first suggested that interacting quantum systems can be efficiently simulated using other highly controlled quantum systems. This is ins

special also possible in such cases where simulations on classical computers

architectures are inefficient and therefore largely unfeasible.

In general, the simulation of quantum systems requires exponentially large computational resources since the dimension of the underlying Hilbert space scales exponentially with the size of the system to be simulated. In certain cases, such a scaling can be circumvented by a clever representation of the quantum states.

So-called tensor network methods, such as the density matrix renormalization group (DMRG) or quantum Monte Carlo methods, make it possible to determine the ground state properties of many-particle quantum systems in certain situations.
However, such classical simulation methods can only be applied to a limited number of problems

does not represent a general solution. With the help of quantum simulators, there is hope to overcome such limitations in order to solve such important problems in physics and quantum chemistry, and even to extend simulations to other fields of science beyond physics. After the various approaches to a quantum simulator are discussed below, some important examples that could be solved with the help of a quantum simulator will be presented.

3.4.1 State of Research and Technology

The term quantum simulator refers to closely related concepts of new physical computer architectures, the aim of which is the simulation of complex quantum many-body systems using highly controlled other quantum systems. A distinction is made between:

- Static quantum simulators that examine the static properties of interacting quantum many-particle systems, such as their ground states, and

- dynamic quantum simulators that examine the properties of quantum systems that are, for example, far from equilibrium and have a pronounced and complex time evolution.

Quantum simulations can be carried out in different ways.

- Digital quantum simulators are based on discrete quantum circuits that can be implemented on a quantum computer – in principle also error-tolerant.

- Analog quantum simulators are simulators that can, for example, predict the time evolution of an interacting quantum many-body system under well-controlled conditions. The potential of such analogue quantum simulators is very large, especially in the near future, since promising large ones are in here Systems could already be realized with current technologies that even surpass the computing power of modern supercomputers.

Quantum simulators open up a new insight into complex many-body quantum phenomena, with far-reaching applications from solid state physics to statistical physics, high-energy physics, energy transfer in molecules or in biological systems to gravitational physics or cosmological issues. The fundamentally new experimental approaches to investigating these many-particle systems open up radically new possibilities for studying these fields of science. On the one hand, theoretical work deals with how the physical platforms can be used to simulate physical phenomena. On the other hand, conceptual questions need to be clarified, such as how the correctness of the simulation can be certified without being able to efficiently simulate the system in the

In recent years, several physical platforms have emerged as promising for realizing a quantum simulator. The various systems offer various advantages and disadvantages and differ, among other things, in the size of the quantum systems that can be simulated and their control. To the also in Germany often high he Successfully represented systems include the following platforms:

- Ultracold atomic or molecular quantum gases, especially systems of cold atoms in optical lattices or continuous Systems in optical traps or so-called atomic chips

- Ultra cold trapped ions

- Polariton and photon condensates eg in semiconductor nanostructures

- Circuit cavity QED systems made of superconducting elements and resonators in the microwave range

- Quantum dot networks

- Josephson Junction Networks

- Photonic platforms made of discrete optical elements or also photonic grids and crystals

3.4.2 Challenges and Goals

Almost every quantum problem for which no adequate analytical solution exists or which cannot be efficiently calculated using a classical computer is a possible candidate for a quantum simulation. These include e.g

- Ground states of quantum many-particle systems, especially of frustrated spin systems or quantum systems that cannot be simulated with quantum Monte Carlo methods. Paradigmatic examples in this area are Heisenberg antiferromagnets on a Kagomé lattice or so-called anisotropic triangular lattices.

- Fermionic lattice models, such as the paradigmatic Hubbard model, which cannot be analyzed with value-free quantum Monte Carlo methods due to the "sign problem". The Hubbard model is considered a promising model that could contain the essential components of high-temperature superconductivity. However, the phase diagram of even this simple model is still a matter of controversy today.

- A similar situation arises in quantum chromodynamics at high densities and temperatures, such as quark gluon plasma, which also makes this problem particularly interesting for quantum simulations.

- Bosonic and fermionic systems, the artificial magnetic fields among the most extreme Are exposed to conditions that are not generated in any real magnet today can. This offers the potential to discover entirely new, previously unrealized states of matter.

- Boson sampling describes a problem in which single photons are sent into n inputs of a linear optical network that has m inputs and m outputs, m > n. No classic, efficient algorithm is known for calculating the permanents required for this.

- Fundamental disordered quantum systems can already be inaccessible to classical simulations in molecular field approximation. Atomic systems, ions and photonic platforms offer opportunities to understand new fundamental effects of disorder and defects on matter phases and properties.

- New theoretical approaches also point to the potential of quantum simulations for understanding energy transfer in biological systems.

- Even problems inspired by gravitational and astrophysics can benefit from efficient quantum simulations, eg based on ultracold atoms and molecules or ions.

- Classic optimization problems can be represented as ground states of spin glasses with tunable interactions. Such ground states can be determined within the framework of quantum simulations ("Adiabatic QC").

- Non-equilibrium problems are also candidates for suitable problems for quantum simulators.

A key goal is the development of quantum simulators in different platforms with a sufficiently high level of controllability and complexity to be able to carry out relevant quantum simulations. These include, for example, controllable grid systems with flexible variable and programmable coupling strengths between lattice sites and the realization of new detection and control options. In doing so, detection qualities of >90% should be achieved, while at the same time the highest possible single station controllability. At the same time, controllable interactions of different ranges should be implemented and the highest possible number of qubits (>20 qubits, ideally >100 qubits) should be available in order to be able to carry out more complex quantum simulations.

A major challenge is to find out how reliable the results of a quantum simulation are, especially in areas that can no longer be simulated in the traditional way.
To this end, theoretical developments must be promoted that give the experiments opportunities for verification and ultimately certification. It is also necessary to develop classic simulation methods, for example based on tensor networks, in order to test quantum simulations in certain regimes under certain specifications.

4. Methodological cross-sectional platforms

The four pillars into which the application-oriented topics can be divided were discussed in the previous chapter. Despite all the variety and difference, within the pillars, similar me

methods resorted to. The theory, which forms the basis of all experimental approaches and all applications, is of fundamental importance. In experimental terms, for different An

Similar hardware systems based on solid bodies, light or atoms and molecules are used again and again in applications. For

Technical implementation requires numerous key technologies, which are also explained below.

4.1 Overarching theoretical models and concepts

Each of the four application-oriented topic pillars (quantum communication,

quantum computing, quantum sensor technology and quantum simulation) rests on the foundation of theory. This foundation

consists on the one hand of common methodological concepts, which thus provide a cross-connection between the four pillars, and on the other hand of specific fundamental questions that are different and individual for the four pillars.

Important common methodological concepts are quantum information theory, quantum resource theories, entanglement theory, quantum error analysis and correction, control theory and complexity theory. These concepts have the following questions and objectives:

- **Quantum information theory** forms the basis for understanding the differences between classical information processing and quantum information processing. The development of suitable quality measures for information-theoretical variables such as entropies is a goal, as is the calculation of channel capacities and the classification of quantum correlations.

- **Quantum resource theories** describe usable properties of quantum states not only qualitatively but also quantitatively. There are already some quantum resource theories, including those on entanglement, coherence and purity, but their further development and the search for additional resources is of great importance, especially with regard to experimental implementation.

- **Entanglement theory** has already contributed a great deal to understanding the fundamental advantages of computing with quanta. However, there are still important unsolved problems, such as the importance of entanglement for mixed-state quantum algorithms, or the characterization and dynamics of many-body entanglement in complex systems.

- In the **quantum error analysis and correction,** the unavoidable experimental conditions, such as noise and losses, are characterized and methods for correcting these quantum errors are developed and their performance is examined. Certain quantum states are used for coding, which are either immune to errors or whose errors can be removed later.

- In **control theory ,** one pursues the essential goal of keeping the fundamentally fragile quantum states stable for as long as possible (thus avoiding unwanted decoherence) and of carrying out the desired operations with great precision, ie quantum processes in a targeted manner influence.

- Finally, the **complexity theory** should be mentioned, in which one describes how large the resources (in terms of time, components, calculation steps, etc.) are that are required to solve a given problem. Depending on the type of information processing used (classical versus quantum mechanical), the level of complexity can vary; which problems can be solved more quickly using quantum information processing is far from fully know

The specific questions and goals of the theory within the four pillars are outlined below; a number of the topics described above also reappear here.

4.1.1 Quantum Communication

With the help of quantum systems, private data can in principle (due to the laws of quantum physics) be transmitted securely. However, unavoidable additional technical noise during implementation means that perfect security is not achieved. Therefore, in connection with concrete implementations, security analyzes based on exact metrological characterization are necessary, which make quantitative statements about achievable safe key rates in the given experimental implementation. The security should be examined here without assumptions about the devices used - these are so-called device-independent scenarios. Satellite connections or quantum repeaters are required to enable quantum communication over long distances. A necessary resource related to quantum communications are real ones and unique random numbers whose efficient generation using quantum mechanical methods is also an important goal.

4.1.2 Quantum Computing and Algorithm men

It has been known since the 1990s that a quantum computer with a suitable algorithm can solve some tasks much faster than a conventional computer. However, it is still not fully understood which of the quantum resources entanglement, generalized quantum correlations, or coherence is responsible for this speed-up. This is an important theoretical question, also with regard to experimental implementation. Furthermore, various experimental realizations of quantum computers can be compared with methods of quantum information theory with regard to their overall performance: which error models or noisy channels occur, which quantum error correction methods can be used, and which quantum control methods lead to a stable quantum calculation?

4.1.3 Quantum Sensors

Quantum physics offers the possibility to build highly sensitive sensors. Here, principles such as superposition, entanglement and squeezing are used to achieve a level of precision in the determination of physical parameters that is fundamentally impossible in the classic way. An example is the phase determination in an interferometer. Important theoretical questions concern the algorithmic extension of coherence times and the identification of optimal quantum query protocols and states that promise a gain over non-entangled states in the case of application-specific noise and imperfections. Relevant applications in the form of the precise determination of natural constants (such as gravitational acceleration), of magnetic fields, or of time and space (e.g. in connection with gravitational wave detectors) are aimed at.

4.1.4 Quantum Simulation

Calculating the properties of complex physical systems is a long-cherished dream of physicists, chemists and engineers. However, the complexity of the calculations grows exponentially with the size of the parameter space to be examined, so that the limits of calculability are soon reached.

Even if you don't have a quantum computer at hand, quantum mechanics allows a solution in the form of quantum simulations: Instead of the system to be examined, a controllable system is used whose basic equations are formally identical, even if it consists of completely different physical building blocks . The properties of this simulator can now be specifically examined – a prominent example are atoms in an optical lattice, which formally behave analogously to electrons in crystal lattices and can thus provide information about the material properties of solids.

4.2 Hardware Systems

In order to practically implement the ideas and concepts for quantum technologies derived from theory, we need the appropriate hardware systems. These can be of very different nature and based on solids, light or atoms and molecules.

For use in quantum technology, it is crucial that these carriers of quantum information retain this information for as long as possible and how many logical operations can be carried out in this time. For this, any undesired interaction with the environment must be small enough. Free atoms in a vacuum, neutral or electrically charged and caught in a trap are good candidates even at room temperature. Photons are particularly suitable when their energy is well above thermal energy. At room temperature, visible photons fulfill this condition. A major difference is that free photons move at the speed of light, depending on the application this is a pre- or postpart. From the point of view of a commercial application, a highly integrated and compact implementation would certainly be advantageous. This speaks for one of the possible realizations in a solid body. The cost of decoupling from the environment is higher there, for example by cooling to cryogenic temperatures or by etching out free-standing nanostructures. The Out

Demands lie in completely different areas and the best solutions for certain quantum technological tasks still require considerable research effort. In the following, the possibilities offered by these systems are discussed in more detail and developments necessary for the future are pointed out grasslands.

4.2.1 Solid State Based Systems

Interest in solid-state hardware platforms has grown significantly over the past decade for a number of reasons:

- These are mainly **scalable architectures** that can be implemented using established techniques with great design flexibility analogous to classic integrated circuits.
- The region of **strong coupling** can be reached.
- The **coherence times** can be changed by materi al optimization, selection of the operating point and design of the environment can be optimized.
- Photonic systems **integrated on a chip** can be realized both in the visible and in the microwave range.

Overall, the future potential of solid-based systems is very high and the further development of the underlying manufacturing technologies is indispensable with regard to the realization of more complex systems. In the following, we will focus in particular on superconducting and nanoscopic systems.

4.2.1.1 Superconducting

systems Superconducting materials have a large number of specific advantages with regard to the realization of quantum circuits. At low temperatures, they lose their electrical resistance and the superconducting ground state is separated from the continuum of electronic excitations by an energy gap. Furthermore, the superconducting state is per se a macroscopic quantum state. The associated quantum phenomena such as fluxoid quantization and the Josephson effect can be exploited in a targeted manner to design tailor-made, linear and non-linear quantum circuits and with the help of established thin-film technology and nanostructuring processes. Superconducting systems are therefore very flexible and easily scalable systems.
Thanks to the development of high-performance and easy-to-use "push-button" cooling systems, the cooling that is still necessary is no longer a disadvantage.

Due to their wide range of advantages, superconducting systems are now one of the most successful material platforms for quantum technologies. Since the first implementation of a superconducting qubit by NEC in 1999, superconducting quantum technology has developed at breakneck speed. For example, the coherence time of superconducting qubits has been improved by almost 6 orders of magnitude from a few nanoseconds to almost a millisecond today. The complexity of superconducting quantum circuits has evolved from single-qubit demonstrators to multi-qubit integrated circuits that have recently been able to implement quantum error correction.
This incredible advance has been made possible by an enormous global research effort, with superconducting quantum technology being heavily promoted, particularly in the United States, through several $10 million government and private programs. In the meantime, companies like Google and IBM have also started to invest in superconducting quantum technology.

The emerging areas of application for superconducting quantum circuits are broad and range from scalable universal quantum computers, quantum simulators, quantum limited amplifiers, sensors and single-photon detectors to the area of quantum metrology and quantum metamaterials.

Small digital quantum processors with up to 9 qubits were already realized by 2015, and further development to integrated quantum circuits with up to 100 qubits can be expected in the next 3-4 years. Even with this level of complexity, a universal quantum computer can surpass the performance of classical computers for some tasks. A promising application niche for superconducting quantum circuits will be analogue quantum simulators.

The combination of superconducting qubits with superconducting resonators forms a powerful platform for the realization of single photon sources and highly sensitive single photon detectors for the microwave range (Section 4.2.2). The range of applications of such systems in the field of sensor technology is currently being constantly expanded by coupling electronic, mechanical, magnetic and optical degrees of freedom in hybrid quantum systems. An important area of application for such hybrid systems is, for example, effective frequency converters. In addition, highly efficient, integrated single photon detectors for the optical sector can be realized with superconducting materials.

With superconducting quantum circuits, non-classical microwave states of the continuous variables can be realized, which are important for the communication between superconducting quantum processors.
These non-classical states can also be used for the realization of photonic quantum computers (Chapter 4.2.2.), the improvement of important microwave measurement methods (eg ESR, NMR) and for completely new applications such as quantum illumination or quantum radar.

Quantum metamaterials and lattices of nonlinear resonators for quantum simulation have been successfully realized with superconducting material systems. In turn, superconducting systems offer specific advantages here, since they can be manufactured in a scalable manner with great design flexibility and, with the Josephson junction, an intrinsi
ment is available.

Internationally, superconducting systems are regarded as a key platform for quantum technology. In terms of implementing quantum computing, they are among the most advanced of any scalable system. They are already being used successfully for quantum simulators and have great potential for quantum sensors, detectors and communication systems.

There is a particular need for development in the technology base required for these systems. This applies to material development and manufacturing technologies for superconducting quantum circuits as well as microwave technology (Section 4.2.2) and the development of special measurement methods.

Topological insulators are novel quantum materials that behave like normal semiconductors in volume, but have metallic states on the surface or at the edges. Under certain circumstances, novel bound states appear in these systems which have the character of two-dimensional quasiparticles and which were named after Ettore Majorana. These Majorana particles are neither fermions nor bosons, but something in between, which is called anyons. Anyons could, for example, be used as qubits in a topological quantum computer. This promising novel concept is attracting a great deal of attention worldwide. In the medium to long term, the aim is to detect the Majorana states and their anyonic character for the first time and to make them usable for quantum computer processes.

4.2.1.2 Nanoscopic systems

Semiconductors dominate the traditional information technologies and due to the established production and scaling methods they also represent very promising systems for quantum technologies. Semiconductor-based photon sources are already well developed for use in quantum technologies. Photon sources are central components for transporting quantum bits (qubits) with glass fibers or in free space over long distances (up to approx. 300 km), in order to enable the distribution of entanglement or to exchange entanglement between different locations . Semiconductor quantum dot sources are promising sources of single photons or entangled photon pairs, they offer high quantum efficiency, high repetition rates, optical or electrical control at the push of a button, etc. Quantum dots offer a high variability in terms of the operating wavelength, they can be used e.g. for direct Emission in telecom Tape can be configured or other components (quantum memory) are adapted to the. They are good candidates for long-distance fiber-based quantum communication. Many important fundamental milestones and demonstration experiments have already been achieved for semiconductor light sources: In the future, the focus will be on further improving physical and technical properties such as repetition rates, indistinguishability, bandwidths, etc. and achieving scalability. Semiconductors can also play an important role in other areas, starting with the provision of ultrafast electronics as an “enabling technology” through to the use of spin excitations in nanostructures for intermediate storage of quantum information or its manipulation. Spin qubits in lateral quantum dots are a well-developed, solid-state-based qubit realization. here single electrons are enclosed in quantum dots whose spin degree of freedom represents the qubit. Typical materials for such quantum dots are GaAs, SiGe or carbon allotropes such as graphene or carbon nanotubes. The next decisive step for the possible breakthrough of this material class is the expansion to several qubits, which should all be separately addressable.

4.2.2 Photonic systems

In the quantum technologies, the photonic technologies can be measured to play a major role. Quantum states of the electromagnetic field are ideal carriers of information, since the interaction with the environment during propagation can be kept very low compared to other physical systems. Photonic technologies benefit from mature basic technology from industrial applications and the resulting ease of integration into existing systems. Photonics plays a pioneering role in quantum technologies and there are

many mature systems as a result. As an efficient carrier of information, electromagnetic fields play an important role in all application-oriented topics, not just in quantum communication. Quantum computing requires a connection between different units, and there are also proposals for purely optically based quantum computing. For quantum sensors, for example in gravitational detection, quantum states of the electromagnetic field are very well suited. There are also suggestions for the use of 'photonic hardware' in quantum simulation. Quantum states of the electromagnetic field also play a crucial role in reading out the results. Photonic quantum technologies are important in a wide variety of subject areas. For the technical implementation, photons are used both in the optical range and in the microwave range. It is to be expected that the significance of the tera-hertz and microwave range of the electromagnetic spectrum for quantum technology will increase significantly.

4.2.2.1 State of Research and Technology

Coherent effects, in which the relative phase of the electromagnetic field plays an important role, were first investigated in the interaction of atoms and molecules with high-frequency radiation and microwaves. After the invention of the laser, corresponding effects could also be observed in the visible part of the spectrum. From this, quantum optics developed with the observation of effects that can only be described with a quantized field theory

to. In connection with the advances made by qubits in the field of superconductivity, quantum optics techniques have again been transferred to the microwave range.
This interplay is a success story par excellence, which must now be continued.
Some of the techniques, such as direct detection of photons, have so far been limited to the visible and the near infrared. Other techniques, such as heterodyne detection of field vibrations, can be used across the spectrum.

On the light source side, two-level systems based on molecules, ions, atoms, color centers, and semiconductor quanta play an important role in the generation of single photons and entangled photon states.
Semiconductor quantum dots in photonic structures can generate photons very efficiently electrically or optically at the push of a button, and the wavelengths can be directly adapted to optical or telecommunication channels. Furthermore, nonlinear optical interactions can be used to generate quantum light.
In addition to photons, quantum light also plays a role, in which the quantum noise of the field amplitudes is asymmetrically distributed, the so-called squeezed light.

Photonic systems in the microwave range are very important in two respects. Firstly, microwave photons must be used for direct communication between individual superconducting quantum processors (Section 4.2.1.1) over short distances. For long-distance communication, frequency converters in the optical range must be developed. However, there is also the possibility that one day microwave radiation can be used directly for transmission. Secondly, photonic quantum computers can be realized that are fully compatible with superconducting quantum computers in terms of frequency range and material basis and thus allow integration on a chip. Quantum communication based on propagating quantum microwaves has already been successfully realized using an approach based on the quantum states of the continuous variables. Important milestones were the detection of path entanglement, the generation of squeezed states, the implementation of the shift operator as a fundamental requirement for quantum teleportation, and the development of a new method for state tomography.

4.2.2.2 Challenges and Goals

An important building block is the generation of special quantum states of light. The aim must be to develop sources that meet the following criteria: Efficient generation of different pure quantum states (single photons, Fock states, squeezed states, entangled states), generation in a single light mode, flexible choice of degrees of freedom (e.g. wavelength adjustment) , Possibility of mode multiplexing. The quantum states can be generated spontaneously, but must be announced and should be able to be linked to quantum memories. The choice of quantum states depends on the task to be accomplished. The non-linear interaction of the second or third order in crystals and optical fibers serves as a basis and must be so be developed to meet the above-mentioned high requirements. Ideally, the systems should be integrable and scalable. Systems in waveguide structures and resonators (chip-integrated, bulk, whisper galleries) are promising technologies that still have to be developed to meet the requirements. The systems can work on discrete or continuous Hilbert spaces.

Integrated photonic quantum systems are based on classic photonic integrated circuits (PICs). For these classic photonic components, there are already many years of experience with their integration, libraries of components that can be combined to form different system functionalities, and photonic design kits that extremely lower the access hurdles and thus allow many more researchers to design their desired PICs to realize. Novel quantum photonic components should also be integrated here.

Quantum states of light can be processed using circuits. The interaction is made possible by a nonlinear material. The necessary non-linearity can also be achieved by efficient coupling to another resonant (e.g. atomic) system. The interaction required for switching the quantum states (e.g. encoded in the phase) must be greatly increased by current systems (through the use of new measures materials, microstructuring, resonators). Quantum technological strategies also require the integration of more complex systems with several nonlinear elements and interferometers.

In order to connect different components in quantum technological systems, it is necessary to transfer quantum states and thereby adjust the degrees of freedom. Light can serve as a flexible transmitter of quantum information. At the same time, the degrees of freedom (wavelength, polarization, spatial mode) must be converted. con

Concrete examples are the connection of superconducting circuits and microwaves with optical links or the conversion of optical frequencies so that they are adapted to atomic transitions. Frequency conversions with non-linear processes can be used for this conversion. Here is high efficiency and flexibility are important. In order to achieve this, new types of systems must be developed that contain, for example, waveguide structures, new types of resonators or optomechanical interactions.

In addition to the basic conversion of light energy into electronic signals, more complex quantum receiver structures are also important for the detection of quantum states. All application-oriented topics benefit from quantum measurements at the limit allowed by quantum mechanics. In the optical field, this limit can often only be reached by combining optical and electronic elements. Optimum quantum receivers work with interferometric elements and optimized photon detectors or according to the heterodyne principle to measure the quadrature states of light. Such optimal quantum receivers should be developed as integrated elements that can measure or classify quantum states with high efficiency and speed. A development of waveguide or fiber-based systems with integrated high-efficiency photodiodes or superconducting detectors together with fast data acquisition and feedback serves as an example.

Possible key technologies in the field of photonic systems are:

- Improving efficiency and others Performance characteristics as well as the miniaturization and scalability of sources for quantum light: single photons, entangled photons, quantum squeezed field amplitudes and also coherent states,

- Components for fast electronic processing (FPGAs, data acquisition and preparation),
- high-precision optical components (coupling/2ÿ capture optics) and
- adaptive optics, computer-generated holograms.

There is also a need for research in Further development of the components for the Generation and detection of quantum light in the microwave range and their interaction in an overall system. Effective protocols for the preparation of remote quantum states and teleportation can then be implemented with these components. For this purpose, squeezed microwave states will be used as states of the continuous variables, which have already been successfully generated with parametric amplifiers based on Josephson junctions.

For the successful implementation of the protocols, the correlation times of dual-mode squeezed states as well as the squeezed-state shift operation need to be studied and optimized.

4.2.3 Atomic and Molecular Systems

The development of quantum mechanics as the basis of quantum technology has its origins in the struggle to understand atoms and molecules. In recent years, spectacular successes have been achieved in the field of quantum engineering with atoms and molecules, visible in 11 Nobel Prize winners in the last 20 years (Chu, Cohen Tannoudji, Phillips, Wieman, Cornell, Ketterle, Hall, Hänsch, Glauber, Haroche, Winelands).

4.2.3.1 State of Research and Technology

Today, atoms and molecules can be stored on a time scale of minutes to days in electromagnetic fields, controlled in all their degrees of freedom with laser and microwave fields, and generated in the form of quantum degenerate matter waves. in first th experiments could be shown how these advances can also be used for the complete quantum mechanical control of elementary chemical reactions.

Because they can be excellently isolated from their surroundings, atomic and molecular quantum systems exhibit an extremely high degree of coherence. Atomic quantum systems find application as a platform for quantum information processing, where stored atomic ions represent one of the most advanced, scalable systems on the way to a future quantum computer. Here, the longest coherence times of all systems to date of just under a minute were demonstrated, and the error in elementary logic operations is consistently lower than in all other systems. On top of that, microstructured surface traps provide one of the most scalable base platforms; all essential techniques necessary for scaling have already been successfully demonstrated in systems of a few ions, and elementary algorithms have been realized.

Atoms are used as frequency references in quantum sensors; Here, comparisons of different atomic clocks provide the most accurate measurements of natural constants in the form of frequency ratios and, thanks to their extreme precision with the help of relativistic effects, can be used in future for geodesy. In addition, clocks are the key components of satellite navigation. Optical frequency standards are realized on the basis of stored ions and neutral atoms in optical lattices.

Using the interference of matter waves, atomic interferometers can detect the tiniest accelerations and other inertial effects and are on the threshold of being used in space missions. For this purpose, chip-based nuclear traps were developed as a compact and robust basic technology. Atomic quantum systems are used in the quantum simulation of interacting many-particle systems; here you can do both implement a "bottom-up" approach (ions) as well as a "top-down" approach (e.g. cold gases in grids).

In quantum communication, atomic systems can serve as quantum repeaters and storage elements. First successes were achieved in the miniaturization, control and integration of systems for the manipulation and storage of atoms and ions. Important steps to overcome the limitations of classical phy sik by means of non-classical states undertaken, and novel detection concepts and methods for spectroscopy based on quantum logic were also developed. Quantum logic algorithms make it possible to combine the advantages of different species in so-called "hybrid systems". An example of this is quantum logic spectroscopy, in which a spectroscopy atom is prepared and read out by a logic atom that can be easily controlled.

Altogether, atoms and molecules represent the most broadly based and at the same time one of the most advanced quantum hardware for quantum computers, quantum simulations and sensors and, when coupled to photons, are also used for communication sentence.

4.2.3.2 Challenges and Goals

Due to the almost perfect quantum properties of atomic and molecular quantum systems, they are able to test the quality of the fields they control like maybe no other quantum system. This applies in particular to the use as quantum bits and the realization of quantum gates with high quality as well as sensor technology and frequency metrology. An important challenge for the field is therefore the availability of corresponding control fields with extreme stability and accuracy. At the same time, with regard to the scalability and portability of sensors, it must be ensured that they are compact and low-maintenance.

With regard to the scaling of atomic and molecular quantum systems, the development of scalable sources of quantum matter (e.g. atom chips and microstructured ion traps for quantum information processing) is of paramount importance. This requires solutions that allow large numbers of atoms to be manipulated in a very small space without compromising the outstanding properties of these quantum systems. Among other things, this requires significant efforts in microfabrication as well as surface and material analysis. Ultimately, for scaling the atoms to be controlled, it will be necessary to integrate electronic as well as passive and active optical components directly into the trap structures. Miniaturized, permanently evacuated vacuum chambers with the appropriate specifications must be developed for this. For this purpose, it is necessary in Germany, for example in the context of spin-offs, to build up generally available manufacturing capacities and to bundle existing know-how. In Germany there is a great deal of potential in a European comparison, but there is also a significant need; For example, corresponding capacities are being systematically built up in the USA.

Another challenge is not to compromise on the specific performance data when miniaturizing, integrating and scaling atomic and molecular quantum systems and sources of quantum matter. Key steps and techniques of such systems have been demonstrated in independent experiments and now need to be brought together and scaled to advance in all four pillars of quantum technology.

In parallel, novel concepts for the production and detection of non-classical correlations and entanglement are required for use in all four pillars. This should result in a reduction in the complexity of applications, an increase in the quality o generated correlations and optimal use, for example in the sensor system.

A great potential for novel applications lies in the combination of atomic and molecular quantum systems with the other forms of quantum hardware. For example, due to their long coherence times, atoms are excellent storage devices for quantum states, while solid-state systems are ideal as fast “processing platforms” due to their high speeds, and photons are suitable for transporting quantum states.

The development of corresponding quantum interfaces should play a prominent role; Due to the miniaturization associated with progressive integration, there are considerable synergies, especially in combination with the goal of scaling. Such “hybrid” quantum systems could combine the best of different worlds into one integrated package.

In the long term, networks of quantum systems can be built up in this way, opening up completely new perspectives in sensor technology, for example. Global fiber optic networks with corresponding classical and quantum-based repeaters would enable global quantum key transmission as well as time and frequency transmission at the highest level with the same infrastructure.

Clock comparisons over such a network would be an important prerequisite, for example, for redefinitions of the SI second and the global height system based on clocks (relativistic geodesy), for tests of fundamental physics (theories of relativity), and for a search for physics beyond the standard model (darker matter and dark energy) with quantum optical systems.

QUTEGA

5. Key Technologies

5.1 Quantum compatible data acquisition, fast electronics and cryogenics

Temperatures in the millikelvin range are required for superconducting quantum systems. An easy-to-use "push-button" cooling system based on the dry mixing cooler developed at the Walther-Meißner-Institute has been commercially available for several years and needs to be further developed in a targeted mann There is a need for development with regard to the microwave components compatible with this temperature range (eg attenuators, circulators, beam splitters, low-noise amplifiers). With increasing complexity, in addition to improving the general performance data, the reduction in size and costs are particularly important. Multiplexers to reduce the necessary data lines are also becoming increasingly important. There is an important need for development in the field of quantum-limited microwave amplifiers with the widest possible bandwidth. Parametric amplifiers based on Josephson junctions represent a successful approach here. High-performance HEMT technologies, which are designed for operation at cryogenic temperatures and exhibit excellent noise characteristics in operation down to below 1 Kelvin, also have a great deal for corresponding amplifiers Potential.

For atomic and molecular quantum systems, on the other hand, cooling units are needed that work at 4K, but have the greatest possible cooling capacity due to the optical access with very low vibration amplitudes.

The analysis of all quantum systems requires fast, hardware-programmed signal processing systems that work in real time (on the basis of field programmable gate arrays, FPGA), e.g. for state tomography and the implementation of quantum feedback. Low-noise and agile current, voltage and frequency sources integrated in real-time environments are required for the control of most quantum systems. It would be desirable to have common software and hardware platforms for the to develop control and evaluation of experiments.

5.2 Lasers, Detectors, Sources and Interfaces

Sources and detectors for single photons are central components for the realization of quantum communication systems. They are key components both for long-distance communication (several 10 km), which typically takes place via glass fibers in the optical/infrared range (e.g. telecom band), and for short-distance communication, e.g. between individual quantum processors. However, both superconducting and atomic and molecular qubits have energy scales in the milli-electronvolt range; therefore, such communication and control over short distances will often take place in the microwave range.
The development of efficient sources and detectors for quantum light (detection efficiency, quality, repetition rates, dead time, clock jitter, controllability, integrability and scalability) is of central importance for both frequency ranges. They represent central technology components, eg for the realization of quantum repeaters. They are also available for implementation in the microwave range interesting metrological applications indispensable.

The development of integrated systems (photonic integration), in which sources and detectors for quantum light (optical and microwave range) are integrated on a chip and connected by photonic waveguides, appears due to the good state of research in basic research in this area at the present time promising and urgently necessary.

It requires increased efforts in the area of technology development, since without the development of basic technologies it will hardly be possible to transfer concepts that have already been demonstrated in basic research into technical applications.
The combination of semiconductor and superconductor technologies is particularly interesting for the development of integrated photon sources and detectors. Technological developments of this kind are an important prerequisite for the long-term realization of quantum repeaters, modular multi-node quantum networks, communication systems for quantum processors, photonic quantum computers or metrological concepts such as quantum lighting or quantum radar Silicon, SiNx, InP, and GaAs as waveguides as well as heterointegration in 2D or 3D. These technologies allow the phase-stable integration of different optical and electronic functionalities and can also be scaled to medium and large quantities.

For applications in sensor technology and for atomic and molecular quantum systems, integrated, field-compatible and modularized laser sources are required that do not compromise the possibilities offered by these quantum systems through their spectral properties. For spectral ranges that do not belong to the standard telecommunications range (e.g. the ultraviolet spectral range), the development of com-

components that have been available for some time with standard telecommunications wavelengths (fiber-based modulators, couplers, etc.). These components also include frequency converters, which combine different frequency ranges of electromagnetic radiation with one another and in which the quantum properties of the converted radiation are preserved as far as possible. Such converters are required in particular for hybrid systems. The conversion between optical and microwave frequencies is a particularly challenging example.

For many quantum sensors such as optical clocks, future long-base atom interferometers and gravitational-wave detectors, the thermal noise of mirror layers and substrates is already a major limitation. New materials and approaches to reduce this noise and other disruptive influences such as vibrations must be investigated and made available for applications.

Fiber optic networks will play an important role in a number of quantum technology applications. Therefore, special components for the joint use of fiber optic networks for eg quantum key transmission and time and frequency transmission must be developed and the necessary fiber optic infrastructure must be made permanently available.

5.3 Materials, components and quantum technological devices

Material growth and the manufacture of components are key technologies on the way to a solid-state-based quantum computer. This applies to all solid-based approaches, be they topological, superconducting or nanoscopic systems.

Another important key area is the electrical characterization of the components. Particularly suitable measuring devices are used for this purpose ments are necessary that make it possible to keep environmental influences (e.g. electro-smog) away from the components to the extent required.

In the field of topological quantum computing , material development represents one of the major challenges. In the course of the development of topological materials , a few systems have emerged that could be particularly suitable for implementing topological quantum computing concepts in combination with superconductors .

Scalable structures for capturing and manipulating individual atoms and molecules have been produced using microstructuring methods for several years and show great potential for the use of these systems in sensor technology, quantum simulation and quantum computers. With regard to scaling, efforts should be made to develop capacities for the production of such microstructures that meet the requirements of these quantum systems in terms of materials and geometry and that are reproducible and generally available (to all users). Here synergies between neutral atom traps and ion traps can be used. And it also makes sense to promote the connection of other elements, such as superconducting elements.

For the production of quantum technological components and systems
Competences in micro- and nanoelectronics and photonics are required to implement the results of basic research in the field of
To be able to convert quantum technologies into marketable devices:

- Micro and nanoelectronic components
- Photonic and opto-electronic components
  ment
- Micromechanical components (MEMS)
- Construction and connection technology, in particular for cryogenic operation and under vacuum

- epitaxy and processing of silicon, compound semiconductors, diamond and superconducting layer systems

- Deterministic and nanometer-precise implantation of individual doping ions in ultra-pure crystals such as diamond, silicon, etc. to create photonic components and quantum memory components

In the area of research and for subsequent applications, there is a priority need in the areas of quantum communication and quantum computing, for example, for small series of functional single photon sources that emit identical photons on demand. A The miniaturized atomic clocks already available in the USA1 are a very good example of the successful implementation of basic research results in a marketable product .

5.4 Quantum Measurements

For the long-range connection of atomic and molecular quantum systems and for the use of these quantum systems as frequency converters between different spectral ranges, the development of integrated detection techniques is of great importance, for example integrated and miniaturized fiber optic detection elements in ion traps, detectors of higher efficiency and number of channels with simultaneously high spatial resolution . In addition, new quantum algorithms must be used for sensitive and efficient readout of hybrid systems based, for example, on non-classical states.

1 http://www.microsemi.com/products/timing synchronization-systems/embedded-timingsolutions/ components/sa-45s-chip-scale-atomic-clock

6. Standardization

The certification of quantum systems on the hardware side and of quantum protocols on the software side is of particular importance. Theoretical modeling plays a decisive role here, both for safety proofs and with regard to the compatibility of individual subsystems. Standardization is a sovereign task.
Standards make it possible to calibrate and certify other devices or systems by comparison. For more complex systems, the definition and standardization of interfaces is crucial. This applies to both hardware and software interfaces ware area. There is already an active working group on the subject of standardization in the field of quantum key distribution for cryptography, which is coordinated by the European Technologies Standards Institute (ETSI). ETSI wrote a statement on this topic in 2015: ETSI White Paper No. 8: 'Quantum Safe Cryptography and Security – An . introduction, benefits, enablers and challenges' 1 Similar activities are also required in other a

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http://www.etsi.org/images/files/ETSIWhitePa1 pers/QuantumSafeWhitepaper.pdf

QUTEGA

7. Structure of the National ,,,,,,Initiative

Quantum technologies are developing new ones Methods and applications for information processing and communication as well as for highly sensitive and highly accurate
Sensor technology in metrology and standard disation. In addition, they represent important foundations for improvements and refinements in numerous fields of technology, for example in chemistry, biology or nanotechnology and in sensor technology in general. They are indispensable in the ongoing miniaturization of nanoelectronics and show how quantum phenomena can be used in a variety of ways. Germany contributed to the creation

development of these interdisciplinary technologies have already made important contributions to research. With internationally renowned scientists at universities and non-university research institutes, Germany has an excellent starting point for the future. It is important to use this. In contrast to more and more European and non-European countries, there is still insufficient industrial implementation of quantum technologies in Germany. The expertise on the individual aspects of quantum technologies is widely spread across the most diverse specialist areas.

At many different locations throughout Germany, research on quantum technologies is carried out at an internationally visible level. This geographic diversity can certainly be seen as a strength of the German research landscape. For example, this results in easier access to a student elite, most of whom are stationary at the beginning of their careers. At the same time, however, there is a clear deficit in coordination: synergy effects are often not sufficiently used. With the help of an improvement in structures, closer networking and a bundling of competencies should be sought.

7.1 Research Funding Instruments

In the following, we recommend measures that we consider expedient and necessary to efficiently promote quantum technologies and bring them to industrial application. Those responsible will have to decide elsewhere by whom and by which institutions these proposals can be implemented.

In order to achieve the goal of establishing and applying quantum technology, not only should research projects be funded, but incentives should also be created for structural improvements that lead to more efficient utilization of research capacities.

7.1.1 Research and development funding

Research in the various fields can be funded in a compact and focused manner under priority topics. The research required includes the further development of the underlying theories. In particular, the creation of collaborative research should support the integration of industry at the interfaces to engineering, chemistry and biology. The platforms created in this way also become spin-offs support in the longer term. This also includes a climate that is friendly to spin-offs. The necessary closer networking of industry and scientific institutions can be achieved through mutually used sabbaticals for scientists and developers.

Funding of consortia: The organization of the development of quantum technologies within the framework of consortia, which can be geographically local or distributed, is considered to be particularly efficient. In these consortiums, representatives from science and Industry work together on the realization of specific market-relevant projects. This ensures close and result-oriented coordination. In the case of basic topics, consortia will be necessary in which no industry is actively involved. The application-related topics should allow different degrees of industrial participation, which take into account the very different stages of development in quantum research. The appraisal of the funding applications by an international panel would be welcome. The participation of international experts is very suitable as long as no confidential information from the companies involved in the consortium has to be disclosed in the process. Therefore this type of peer review recommended especially for consortia that deal with basic research topics and thus have little or no industrial participation.

Creation of centers for quantum technologies: Existing research activities, often distributed across different subject areas, can be pooled and supported by funding centers. In any case, initiatives for such centers should initially start as industry or application-related consortia in order to eventually develop into centers if they are successful. Joint events and the expansion of joint infrastructure enable improved cooperation. Such

Centers make particular sense, for example, when capital-intensive cross-sectional technologies need to be implemented that should be available to all quantum researchers. The use of jointly developed technologies will lead to an increase in spin-offs, which should be consciously promoted. A good example of this are institutions such as the Center for NanoScience (CeNS) in Munich. Such centers reach the industry more easily when the research groups involved come together. This not only improves the job prospects of the graduates, but also facilitates the acceptance of the technology by the industry.

Sabbaticals for industry and research: A flexible, limited exchange of specialists brings advantages for both sides: A significant improvement in the exchange of skills and the consideration and interests of industry in research are achieved. Sab baticals promote permeability that can be used in both directions. Industry representatives can temporarily move to research institutions and scientists to industrial companies.

7.1.2 Structural Measures

Education: Quantum technologies are currently being used in schools and in subjects overarching university education is only insufficiently addressed. This lets it down back to the fact that these are relatively young technologies. So far, the engineers in the relevant industries have been involved very little familiar with quantum technologies. In order to promote industrial application, quantum technologies should therefore increasingly be included in the university education of engineers in the future.

Structural changes at universities: In recent years, there has been a significant weakening of mid-level academic positions. In order to ensure continuity in research work, however, this mid-level position is indispensable. Through frequently and within staff changing over short periods of time is currently in danger of losing experience, which is essential for the comprehensive investigation of scientific topics and for the development of ideas. The creation of posts in the academic mid-level faculty will therefore make a decisive difference. In addition, new professorships with the appropriate orientation should be created to strengthen quantum technologies.

Establishment of a coordination office: A coordination office promotes coordination between the researchers involved in the national initiative. It also serves as a contact point for federal and state governments, state and private funding institutions, but above all for industry. an essential Another task will be the assessment of the consequences of technology, which should be started as early as possible. The work of the coordination office is supported by the QUTEGA committee.

7.1.3 Public Relations and Educational Efforts

Quantum physics is currently perceived by the public more as a scientific curiosity. This also applies to large circles in business. Especially the ones with that The concepts and potential for applications associated with the term "second quantum revolution" (ie, for example, the superposition principle and the peculiarities of the quantum measurement process) are largely unknown. From the point of view of the QUTEGA initiative, a special and joint educational effort at the beginning of the program seems extremely important in order to familiarize both the technically interested and the general public with this topic. Concretely, these efforts should try to integrate quantum physics more than before into the school curriculum, design and operate an attractive traveling exhibition or provide suitable web content, to name just the most important points.

7.2 Recommendations

The main focus of the national initiative of the BMBF should be on project funding:

- The greatest broad impact is achieved by **supporting consortia .** This form of support should therefore be given the greatest weight. Initially, funding could only be carried out in this way.

- The establishment of **centers** with the participation of scientific institutions and industrial partners makes sense when the underlying idea is particularly convincing in terms of content and the path to application is clearly mapped out. In particular, these centers can arise from previously funded consortia, so that they only appear in a later funding phase.

- A small portion of the funding available is to be used for **public relations work, workshops and sabbaticals .**

The research topics for public Tenders should be based on the headings of the subsections:

- **Quantum computing**
- **Quantum sensors**
- **Quantum communication**
- **Comprehensive theoretical models** •**Key technologies for quantum systems**

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