

Where discovery meets practice

IQ ST

INTEGRATED QUANTUM SCIENCE AND TECHNOLOGY

Center for Integrated Quantum Science and Technology IQ ST in Baden-Württemberg



Albert Einstein and Niels Bohr 1930. Photo: Paul Ehrenfest

“But I do not wish to be forced into abandoning strict causality without having defended it quite differently than I have so far. The idea that an electron exposed to a beam freely chooses the moment and direction in which it wants to move is unbearable to me. If that is the case, then I would rather be a cobbler or a casino employee than a physicist.”

“I cannot believe that the moon is in the sky only because a mouse is looking at it.”

Introduction

These two quotes by Albert Einstein not only express his well-known aversion to quantum theory, they also come from two quite different periods of his life. The first is from a letter dated 19 April 1924 to Max Born regarding the latter’s statistical interpretation of quantum mechanics. The second is from Einstein’s last lecture as part of a series of classes by the American physicist John Archibald Wheeler in 1954 at Princeton.

The realization that, in the quantum world, objects only exist when they are measured – and this is what is behind the moon/mouse analogy, is one that Einstein had arrived at in the course of a joint project with Nathan Rosen and Boris Podolski in 1935. Although the original intention of this had been to show that quantum mechanics is incomplete, today we know, thanks particularly to a publication by John Bell from 1964, that a feature of quantum mechanics is manifesting itself here. In the quantum world, there are correlations that, conventionally, do not exist.

For a long time, these quantum correlations – that occur when one observes the interaction between several quantum objects – were deemed oddities of the theory. Nowadays, however, we can use these as resources in order, for example, to transmit information more securely, develop new types of computer or construct highly accurate measuring equipment.

Thus quantum theory extends beyond the field of physics into other areas, e.g. mathematics, engineering, chemistry, and even biology. Let us look at a few examples which illustrate this. The field of cryptography uses number theory, which constitutes a subdiscipline of pure mathematics. Producing a quantum computer with new types of gates on the basis of the superposition principle from quantum mechanics requires the involvement of engineering. Customizing molecules and solid state systems for quantum information processing is a modern-day task for chemists. For a short time now, quantum mechanics has even been a research topic in biology, namely in connection with photosynthesis and its relevance for this process.

The individual branches of science can no longer solve these issues. A joint, integrated approach is necessary. Consequently, in the last few years, a distinct interdisciplinary science has developed which can be summarized under the heading of quantum science.

Both Ulm University and the University of Stuttgart together with the Max Planck Institute for Solid State Research (MPI FKF) have seized on this development and founded an interdisciplinary center

Introduction

to deal with these issues; this center extends beyond the boundaries of the institutions and locations. The Center for Integrated Quantum Science and Technology (IQST) is being funded by Ulm University, the University of Stuttgart and the Baden-Württemberg Ministry of Science, Research and the Arts (MWK BW). We are very grateful for this. Our thanks go in particular to Dr. Renate Fischer and Dr. Heribert Knorr from the MWK BW who have supported us hugely with the founding of IQST.

Ulm and Stuttgart, November 2015
Prof. Dr. Wolfgang P. Schleich
Institute of Quantum Physics,
IQST Board, Ulm University



At the heart of the University of Stuttgart are the engineering and natural sciences faculties, each of which has a successful tradition of research. For some years, quantum technology has been a key research focus in Stuttgart. Our forte is combining brilliant pure research in physics, which discovers new quantum physical principles, with the know-how from engineering, in order, from this, to develop forward-looking technologies. This strategic focus can already be seen in an award-winning team of scientists and in the Center for Applied Quantum Technologies ZAQuant, whose funding was approved by the federal and state governments in 2015.
New possibilities are opening up for students thanks to the interdisciplinary cooperation, and being a quantum engineer could soon become a reality.
IQST offers the opportunity of further expanding the leading role in quantum technologies and thus also of strengthening Baden-Württemberg as an industrial location.

University of Stuttgart, November 2015
Prof. Dr.-Ing. Wolfram Ressel
Rector, University of Stuttgart



At IQST, a number of highly respected scientists from the University of Stuttgart, Ulm University, and from the Max Planck Institute for Solid State Research in Stuttgart are working on research into new kinds of quantum phenomena. The aim is to discover things that were previously unknown, to understand the underlying mechanisms in order to subsequently use them in applications that are beneficial to society. The results already obtained in collaboration hitherto, concerning optical modulators, magnetic sensors, energetic effects in biosystems, and lots more, are extremely impressive and open up new territory for attractive areas of research in the future. Over and above this, they provide approaches for applying the findings, for example for secure data encryption technologies, for the analysis of complex epigenomic processes in living cells or for the targeted molecular design of innovative functional materials.
Ulm University will be making every effort to support IQST and doing everything to ensure that the network is able, also in the future, to maintain its leading interdisciplinary position in quantum research.

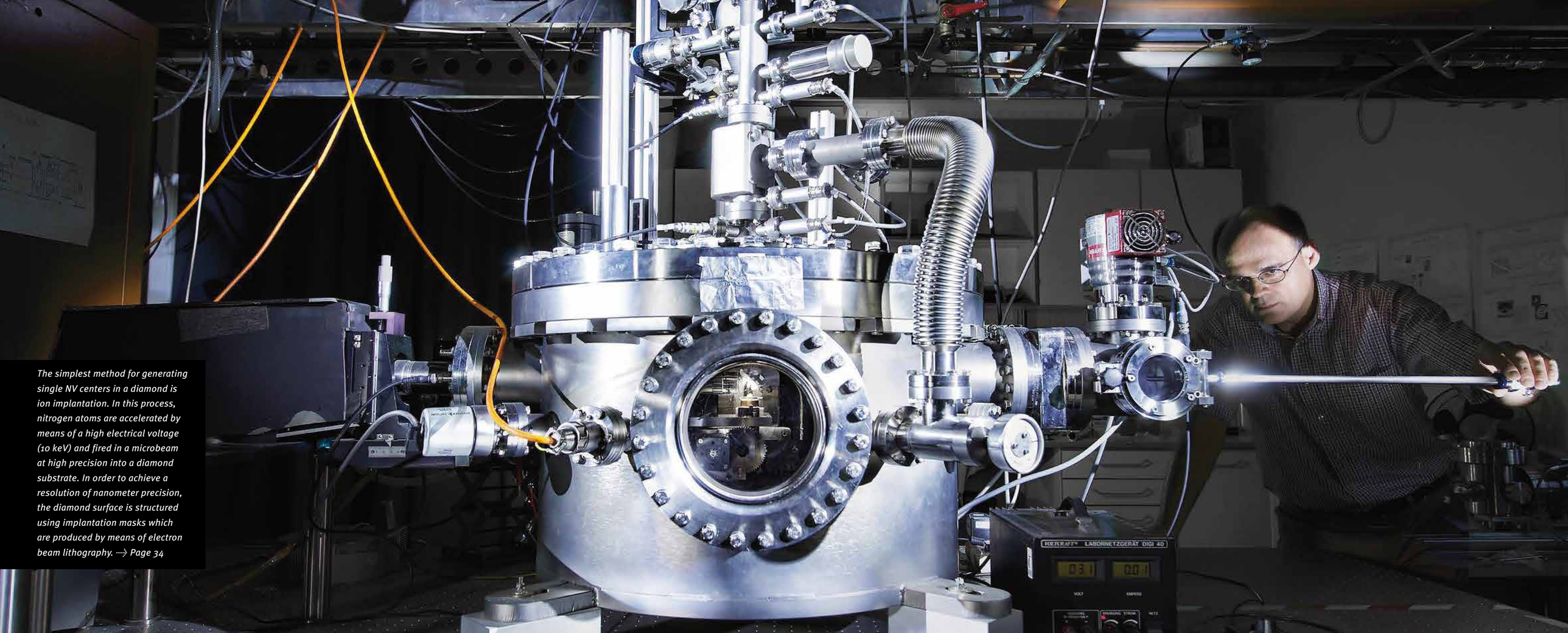
Ulm University, November 2015
Prof. Dr.-Ing. Michael Weber
President of Ulm University



Collective quantum phenomena in complex and nanostructured materials are key research topics at the Max Planck Institute for Solid State Research. At the IQST, the synergy between materials research and quantum technology is being significantly strengthened at a variety of levels. On the one hand, the targeted synthesis and modification of complex electronic materials, for example, is a hitherto still largely unexplored approach to research in quantum technology. On the other hand, sensors based on individual quantum systems are opening up new research prospects for understanding physical properties of solids on a nanoscopic scale. Together with our colleagues at the University of Stuttgart and Ulm University, we are investigating and making use of this potential, and look forward to intensifying this fruitful cooperation even further in the future.

Stuttgart, November 2015
Prof. Dr. Bernhard Keimer
Director, MPI for Solid State Research





The simplest method for generating single NV centers in a diamond is ion implantation. In this process, nitrogen atoms are accelerated by means of a high electrical voltage (10 keV) and fired in a microbeam at high precision into a diamond substrate. In order to achieve a resolution of nanometer precision, the diamond surface is structured using implantation masks which are produced by means of electron beam lithography. ⇢ *Page 34*

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Where discovery meets practice

At the Center for Quantum Science and Technology in Baden-Württemberg, new technological approaches are generated from abstract quantum physics. *Text: Dr. Christian J. Meier, Darmstadt*

Climate change, the overaging of society, declining data security: the major challenges facing mankind can only be solved with new technologies. Can quantum physics also make a contribution to this? That science whose effects people like to describe with the words "peculiar", "bizarre", or "spooky"? The surprising answer is: absolutely.

This is because, firstly, the ongoing miniaturization of technology is inevitably leading us into the world of extremely small particles, where the laws of quantum physics rule. Mastering them, therefore, is essential. In addition, quantum physics holds huge technological potential: extremely fast and energy-saving computers, tap-proof data transfer, maximum-precision sensors, or extremely low-loss energy technology.

In order, however, to overcome the hurdles to quantum technology, interdisciplinary efforts in pure research are needed. So that brilliant research results can make the leap to application, it is also necessary to have engineers who work closely together with quantum scientists.

Both of these things are provided by the Center for Integrated Quantum Science and Technology (IQST) at the University of Stuttgart, Ulm University, and at the Max Planck Institute for Solid State Research in Stuttgart. At IQST discoverers meet implementers. Physicists, chemists, biologists, and mathematicians research the world of quanta right across the board and in the process partly work hand in hand with engineers or cooperate directly with industry.

As an unique union of its kind in Germany, IQST supplies the critical mass to allow it to be perceived internationally as a center of competence for quantum science and technology.



Stuttgart



Ulm

Meeting global challenges with quantum physics

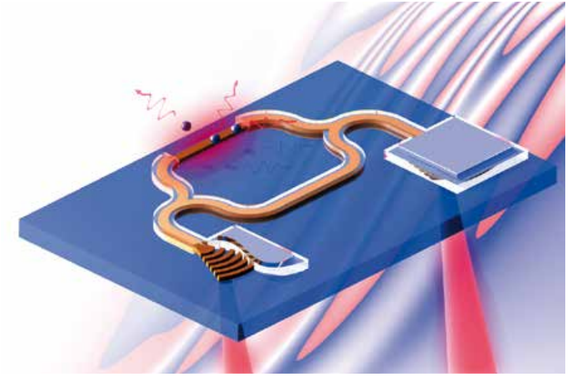
Increasing the performance of computers, data security in times of continuous digital surveillance and stimulus for renewable energy sources: mastering quanta can make key contributions to these challenges. Quantum technology is a key technology in a future that is increasingly difficult to get to grips with.

Miniaturization

The digital revolution has relied on ever decreasing sizes of electronic structures. Measured by the standards of the 1960s, today every smartphone contains a supercomputer. Since then, the number of electronic components on computer chips has been doubling every two years. Today, one finger nail-sized chip can accommodate billions of transistors, that is to say tiny electronic switches that in combination form logic circuits.

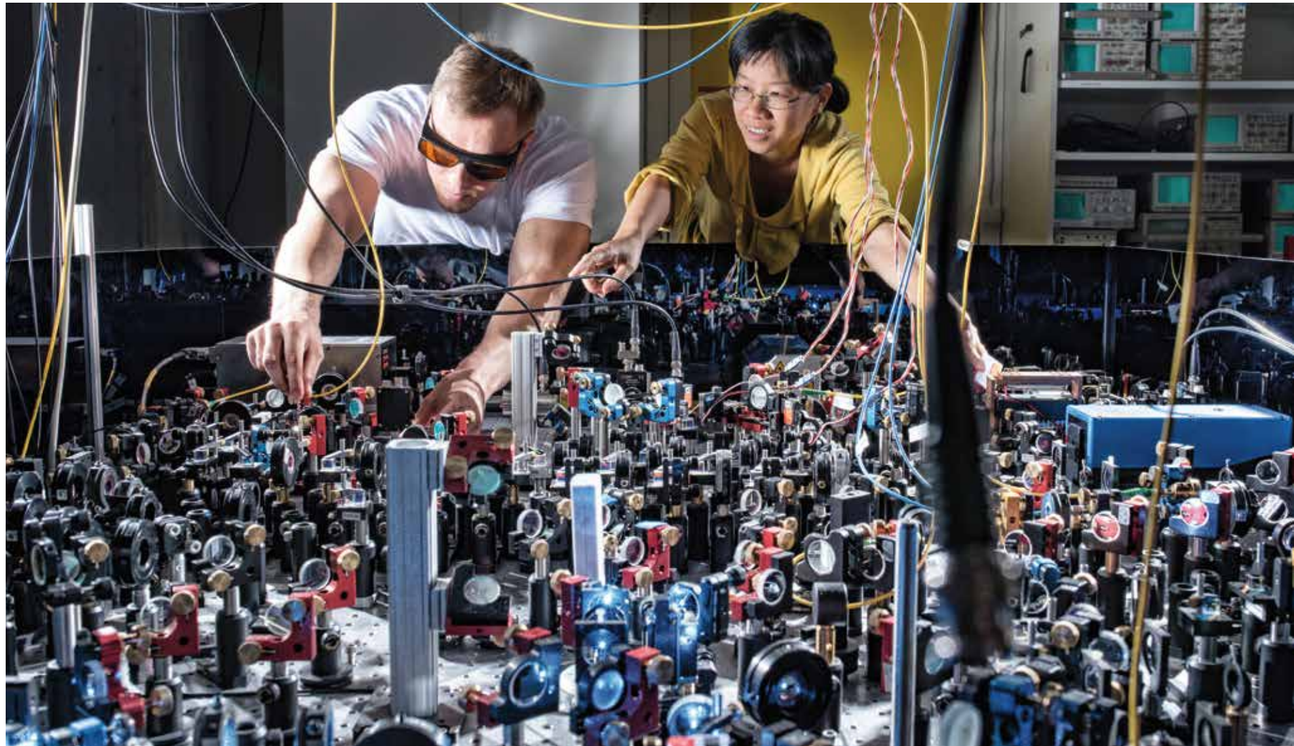
However, experts estimate that the shrinking will continue for a maximum of ten more years. Because current silicon technology will then meet its performance limits. Even now, in their laboratories, quantum physicists are going beyond the limits of the miniaturization possible with silicon technology. They monitor individual atoms, electrons or light particles. It doesn't get any smaller than this. Using these natural building blocks of matter, the functions of electronic components can be simulated, enabling further miniaturization of digital technology. The aim is to represent a bit by means of a single atom and, in data transfer, to transport a bit with a single photon.

In addition to this, the performance of computers can be considerably increased over and above the level possible today if the quantum properties of particles are made usable in a targeted way for computing processes – keyword: quantum computer.



A first prototype of an integrated Mach-Zehnder interferometer has been brought into being for the first time by the 5th Institute of Physics.

The picture shows the set-up for atomic spectroscopy of atomic gases at room temperature. The trick is to work out quantum effects at these comparatively high temperatures and make them usable. To be able to carry this out precisely, countless optical components are used. In the future, the plan is for the entire atomic spectroscopy laboratory to fit on one chip, i.e. all optical components, the laser source and light detectors and the atoms that are to undergo spectroscopy.



Data security

The NSA spying scandal has significantly increased sensitivity to IT security and data protection. The average computer user is wondering, just as much as the IT specialists, how secure data still is in the cloud. In addition, the requirements relating to encryption methods are becoming more intensive the more sensitive data is digitized. Health dossiers, land registrations, or confidential communications: all of this has to be securely encrypted not just until tomorrow but for decades to come.

Here, quantum physics can overcome the weaknesses of conventional encryption methods. The security of today's methods is based on extremely difficult mathematical problems which even a high-performance computer would take billions of years to crack. However, what today is still a tough nut may be a relatively easy task for a computer in 20 years' time. Encryption, therefore, has an expiry date.

What is known as quantum cryptography, however, guarantees security on the basis of natural laws. And these will still apply in 100 or 1,000 years' time. Because not all the properties of individual light particles can be copied, a message encrypted with these quantum objects cannot be intercepted without the sender and recipient realizing. Thus the eavesdropper will inevitably be noticed.

Data can also be protected with quantum computers. On the one hand, future quantum computers can, with the aid of the laws of quantum physics, crack what today are common encryption and digital signature techniques. This is because these are based on the fact that 300-figure numbers are very difficult to break down into prime numbers, that is to say numbers which can only be divided by themselves and 1. But this very task can be solved by a sufficiently capable quantum computer in next to no time. However, quantum physics also theoretically permits servers on which a customer can perform computing work without the Cloud service provider being able to tap input or output data.

Energy

Quantum computers will bring with them a wealth of new possibilities. They will be able to solve problems which would defeat even the biggest supercomputers today. These include the simulation of extremely complex problems in material development. One of these highly complex materials could hugely reduce our civilization's energy requirement while at the same time driving forward the widespread use of renewable energy sources: the high-temperature superconductor.

During the transport and storage of electrical energy, a large part of the latter is irrevocably lost. Unlike with conventional cables, superconductors have no electrical resistance. In some towns they are already being used to distribute electricity to households. However, the cables have to be cooled down to around –200 °C; at temperatures above this they lose their superconductive function. The aim of physicists is to develop superconductors that have lossless conduction at room temperature. This would permit a broad application of the technology.

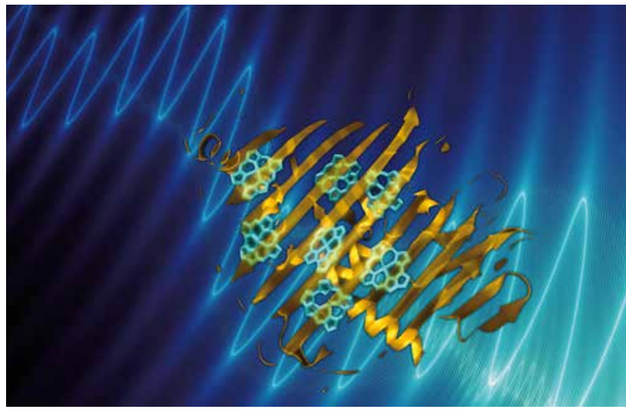
Alongside a lower-loss electricity grid, this would make the construction of maglev trains more attractive, because these then use less energy for cooling the magnets. Even electric drives for ships, whose diesel engines are today significant emitters of CO_2, are possible with high-temperature superconductors. Room-temperature superconductors would make them more attractive as well.

Renewable energies could also benefit from room-temperature superconductors by providing new types of energy stores. Superconductive coils allow electricity to circulate for long periods without losses. In the process, electrical energy is stored in a magnetic field. Superconductive batteries are very efficient and can be charged and discharged very quickly.

There are major obstacles to this major benefit, since high-temperature superconduction is an extremely complex phenomenon which physicists do not yet understand. With the aid of quantum computers, solid states can be simulated atom for atom so that a microscopic understanding becomes possible. The planned synthesis of room-temperature superconductors can be based on this.

Effects of quantum physics could also be used for more efficient solar cells. There are clear indications that during photosynthesis plants use certain quantum effects, in order to achieve exceptionally high efficiency. Currently, physicists at IQST are researching this topic. The

A photo-synthetic complex, composed of seven light-absorbing chromophores is studied by ultrafast laser pulses. This reveals the interplay of quantum coherent dynamics and vibrational motion of the surrounding protein that is essential for optimal function.



findings could be used to produce solar cells with significantly greater efficiency than is possible today.

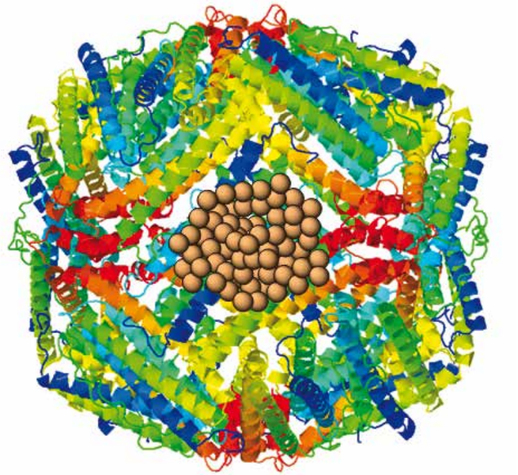
Measurement revolution

Single atoms, ions, or light particles are ideal sensors. This is because firstly they are by their nature identical, so do not need to be calibrated. Secondly, they respond extremely sensitively to physical stimuli, be these magnetic fields, electric fields, extremely small changes in gravity, the smallest variations in gravity or contact with single particles. Consequently, as sensors, they achieve extreme precision.

Skillful monitoring of their quantum properties permits even more: in conventional technology there is always residual noise which cannot be suppressed. But with the aid of quantum technology, exactly this is possible. The result is almost perfect precision. With quantum technology, the precision of today's sensors could be surpassed by several orders of magnitude.

There is a need for miniaturized sensors with high precision e.g. in medical research, in environmental sensor technology, in remote earth sensing, or space travel.

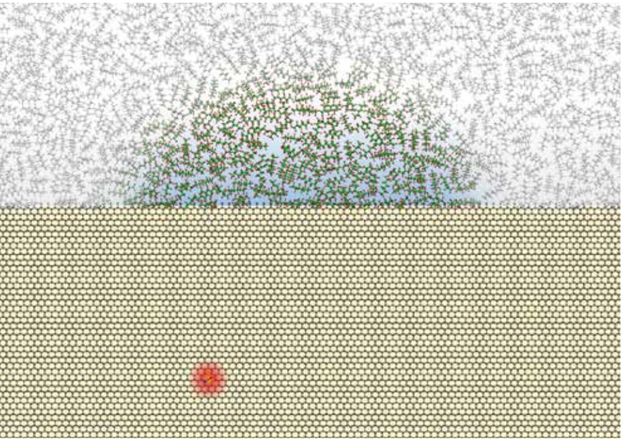
Tiny magnetic field sensors would allow the precise investigation of processes in the human body. In this way, a comprehensive picture of the mode of functioning of the brain and an understanding of diseases



Ferritin is a protein complex that serves as an iron store in the body. Every ferritin molecule can bind to up to 4,500 iron ions (spins) per molecule. Tiny diamond sensors are able to measure the very weak magnetic fields emanating from the ferritin proteins. In this way, the iron content in the blood can be directly determined.

IQST researchers Fedor Jelezko (Ulm University) and Jörg Wrachtrup (University of Stuttgart) have developed a first commercial "Diamond Quantum Device" with which magnetic and electric fields can be measured particularly precisely in the nano range. The benefit: the new sensor also works precisely at room temperature, is extremely small and, with high sensitivity and local resolution, permits views of the nanoworld never previously imagined.





Computer visualization of the nuclear spin detection experiment. With a single color center in the diamond (red dot) the nuclear spin magnetic field with a volume measuring a few nanometers (colored droplet, upper half of picture) can be detected. Until now, clinical MRI scanners only make objects visible that are larger than a few micrometers. Hence it would therefore be possible to observe biological molecules such as antibodies.

such as Alzheimer's or Parkinson's would be possible. Sensors which, thanks to entangled photons, detect single molecules, in principle enable miniaturized diagnostics, e.g. in the form of chip-sized analytical laboratories (Lab-on-a-Chip). For environmental analytics too, for example for detecting nanoparticles, such chemical sensors would also be very attractive.

Highly precise gravitational acceleration sensors, in turn, could make remote sensing significantly easier by locating oil or water reservoirs or subterranean rock layers.

On the basis of Heisenberg's uncertainty principle, frequency measurements can be accelerated, which could make signal processing more efficient. Maximum-precision miniaturized atomic clocks are also possible thanks to quantum technology. These permit, in principle, navigation systems which determine the position precisely to the millimeter, which could be used in driverless cars, for example.

Finally, in research, quantum sensors are used to measure gravitational waves or to test Einstein's theory of general relativity.

IQST as a beacon in this development

Quantum physics is becoming more and more relevant to technology and other fields of science. Often, however, there is a lack of institutions which fuse what were previously different worlds with one another. IQST is an attempt unique in Germany to create this interface.

Quantum physics is not a narrowly restricted discipline; rather, it influences broad areas of the natural sciences and, in future, of technology. Whether physicists are concerned with atoms, lasers, solid state materials, nanomaterials, or measuring technology, the laws of quantum physics always play a key role. But for chemists and biologists, too, the world of quanta is becoming more and more important. For example, there is increasing evidence that the efficiency of photosynthesis is thanks to quantum coherence. Other life processes which are probably based on quantum effects are one's sense of smell or magnetoreception for direction-finding among birds. Thus completely new functional principles are opening up for biology, by means of which biological systems right through to cell receptors, the goal of most modern drugs, can be better understood.

Technicians and engineers are becoming increasingly interested in quantum physics. Glass fiber cables, for example, are using fewer and fewer photons to transport a bit. The more telecommunications approaches its goal of transporting a bit on only a single photon, the fewer bits ought to be lost during the transfer. This is similar to the requirements already being encountered by quantum physicists in their experiments with single photons. The overlap between the world of discoverers and that of those implementing the knowledge will therefore increase in the future.

Quantum technology can therefore only be developed as part of broad interdisciplinary efforts. IQST covers a key area of this breadth. Here, physicists, chemists, biologists, mathematicians and engineers work together in close physical proximity. The experimental work is supervised by theoretical experts. Brilliant researchers – some of whom are world-famous representatives from their subject – are researching several of the most promising branches of quantum physics. They are devoting themselves both to individual quantum objects such as atoms or light particles, but also to complex systems such as sensors made from carbon nanotubes or graphene and also to solids such as high-temperature superconductors.

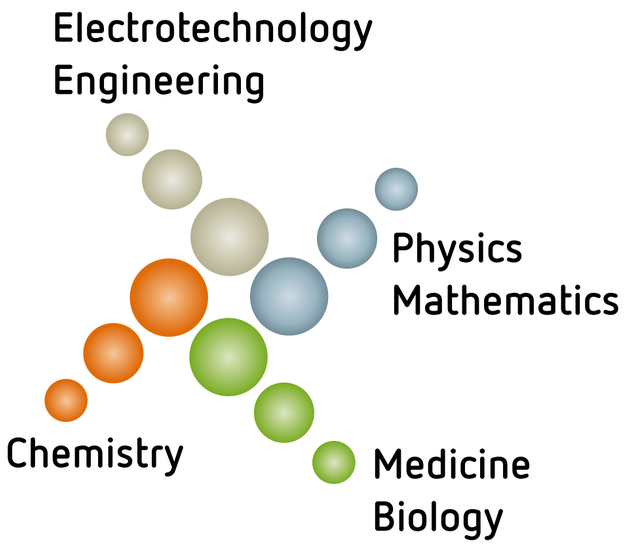
In Stuttgart and Ulm, discovery and implementation converge in order to new ideas into practice more easily. The aim is to bridge the often bemoaned "Valley of Death", i.e. to prevent key pure research results that are of interest for technology from lying idle or being developed into business models in other countries, for example, in the USA or Asia. IQST's members' many contacts with industry are among its assets. In some cases, quantum technological equipment is already at the prototype stage and is being tested by industry.

Hence IQST is a unique union in Germany, which is enjoying an ever higher profile in the professional world not only thanks to researchers who are very well connected and famous internationally, but also

because of its structure which encompasses the entire field of quantum science and technology. In the near future, IQST may grow into a beacon of its specialist area that is visible worldwide.

What also singles out the research at IQST is, on the one hand, its pure researchers' great spirit of discovery and courage to try things out. They play with single atoms or photons and light particles. In the process, they generate outward forms of matter that have never before been observed. Or they try to produce new materials with previously unseen electrical properties, or test new types of quantum optical components.

On the other hand, at the same time the researchers always have the application in mind. For example, they try to observe technically interesting quantum effects at room temperature or to transfer them into technically integratable components. They research materials in which the highly sensitive qubits (quantum bits) are protected from disruptive environmental influences, and develop methods for operating quantum computers as efficiently as possible. In this way, the chance increases that these concepts, which were previously of more of an academic nature, will find industrial application.



At IQST, the different branches are merged together and the interdisciplinary activities intensified.

Quantum physics governs the world of matter not just at the level of atoms, electrons or photons. In other words, not only the microcosm obeys its rules.

So far, researchers have not yet found any size limit for which matter would only obey the laws of conventional physics. A superconducting cable several kilometers in length can be described as a connected quantum system, as Bernhard Keimer, physicist and IQST member from the Max Planck Institute for Solid State Physics in Stuttgart emphasizes. More electrons are involved in this system than there are grains of sand on the earth, says Keimer, a number with more than 20 decimal places.

IQST covers a large part of the range of quantum systems – from single particles such as atoms or photons, through to complex systems such as graphene, semiconductor components or, indeed, superconductors. Below are some examples of research fields relating to systems of differing complexity.

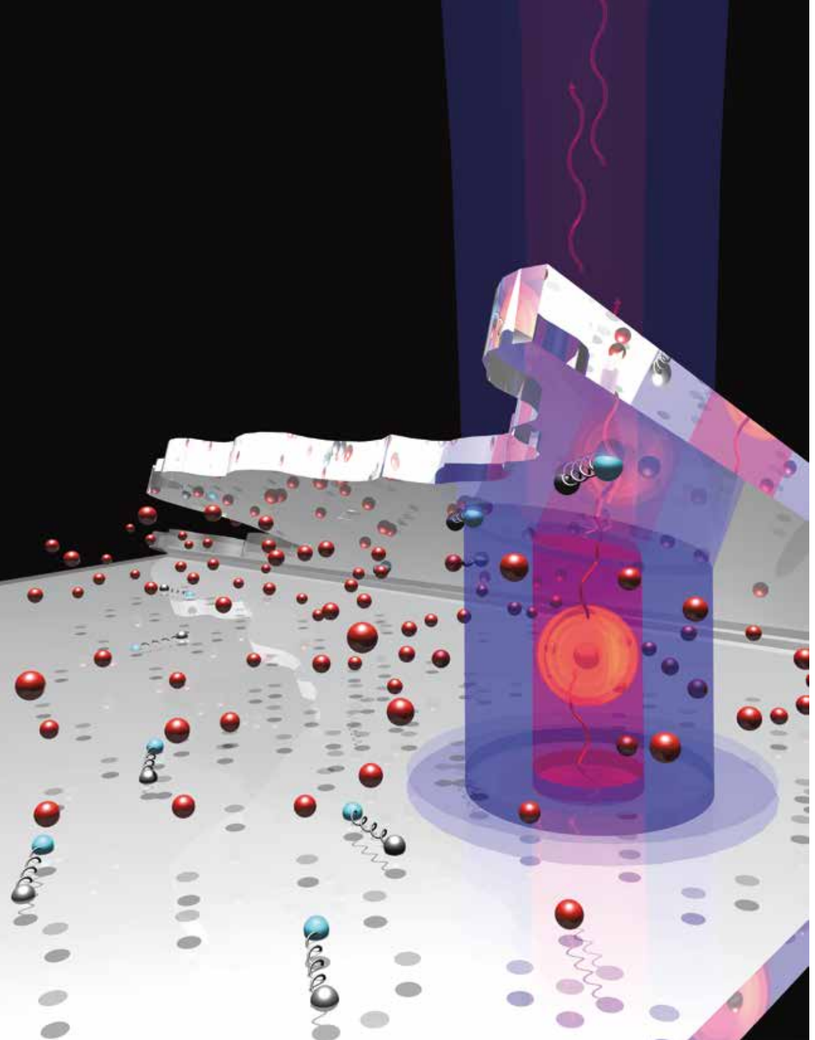
Rydberg atoms: quantum technology's whizz-kid.

A veritable horn of plenty for the discoverers at IQST is atoms in which one electron is situated 10,000 times further away from the atomic nucleus than the remaining electrons. In this "Rydberg state" (named after the Swedish physicist Johannes Robert Rydberg , 1854-1919), the electron responds very sensitively to external influences. An image of this is that of spheres hanging on springs. Electrons in orbit close to the atomic nucleus experience a strong pull from the latter; they are hanging as if they were on a rigid spring which, despite being pulled hard, can barely be deflected. The electron in the Rydberg state is held to the atom only weakly. It is hanging, so to speak, on a soft spring and responds even to being pulled gently.

By these means, a single photon can be detected. For their relevant work on this, Serge Haroche and David Wineland received the Nobel Prize for Physics in 2012. Research into Rydberg atoms holds, in the future too, the potential for spectacular results. In Stuttgart, Tilman Pfau's team (5th Institute of Physics) is devoting itself to the study of Rydberg atoms.

In what is a first worldwide, the team has demonstrated, at the same time as a group from the Max Planck Institute for Quantum Optics in Garching, that a single photon can substantially weaken a light current. Thus it has created an optical transistor. Such components could one day form the basic element of optical computers, that is to say computers that work with light instead of electrical currents and consequently could be simultaneously more efficient and energy-saving.

The problem here for a long time was that photons barely interact with one another, which means that one photon cannot slow down the other. Rydberg atoms enable and strengthen the interaction between the photon and the beam of light. They do this so efficiently that a



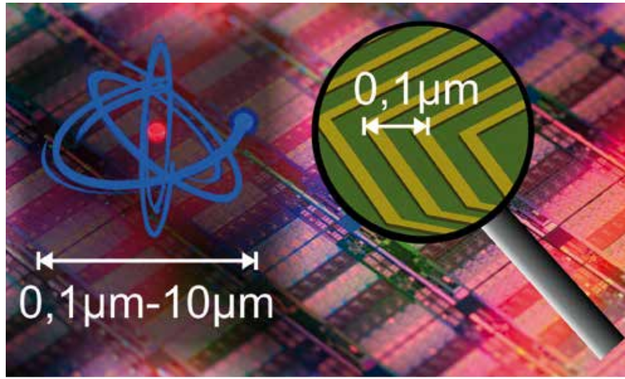
In order to be able to carry out effective spectroscopy of atomic gases, they are introduced into a glass cell at very low pressure. If one of these atoms (small red spheres) is excited in the vicinity of the glass wall of this spectroscopy cell through laser light into a Rydberg state, this reacts very sensitively to vibrations in the molecule (small turquoise-colored and grey spheres with spring) in the glass. The Rydberg atoms therefore behave like a sensor for temperature-dependent processes in the glass.

single switching photon makes a gas cloud opaque for more than 30 photons.

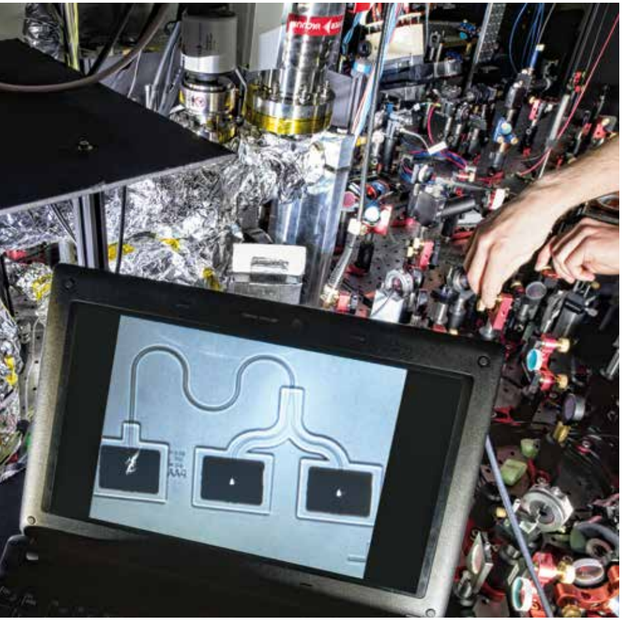
Single photons are also required for quantum cryptography. Conventional light sources such as LEDs or lasers, however, emit portions of several photons. Rydberg atoms act like revolving doors for photons and can therefore make a line of single photons from groups of photons. Tilman Pfau's team is working on making this effect usable for technology by carrying it out at room temperature in a special glass fiber. The physicists have already been able to show that Rydberg atoms "locked into" fibers retain the properties of free Rydberg atoms, so can be used for the revolving door effect.

The sensitivity of Rydberg atoms means they are ideally suited as sensors for magnetic fields or electric fields. Tilman Pfau's team has developed small vapor cells measuring a few centimeters in which single atoms can be excited at room temperature into Rydberg atoms. In collaboration with IQST's neighboring institute, the Institute for Large Area Microelectronics (IGM), the intention is now to develop the cell further. Using industry-oriented manufacturing technology, the intention is to integrate the sensor electronics into the cell. Here IGM always has in mind the future suitability for mass production.

Particularly fascinating physics is also possible with Rydberg atoms. In the process, the Stuttgart physicists are discovering new exotic

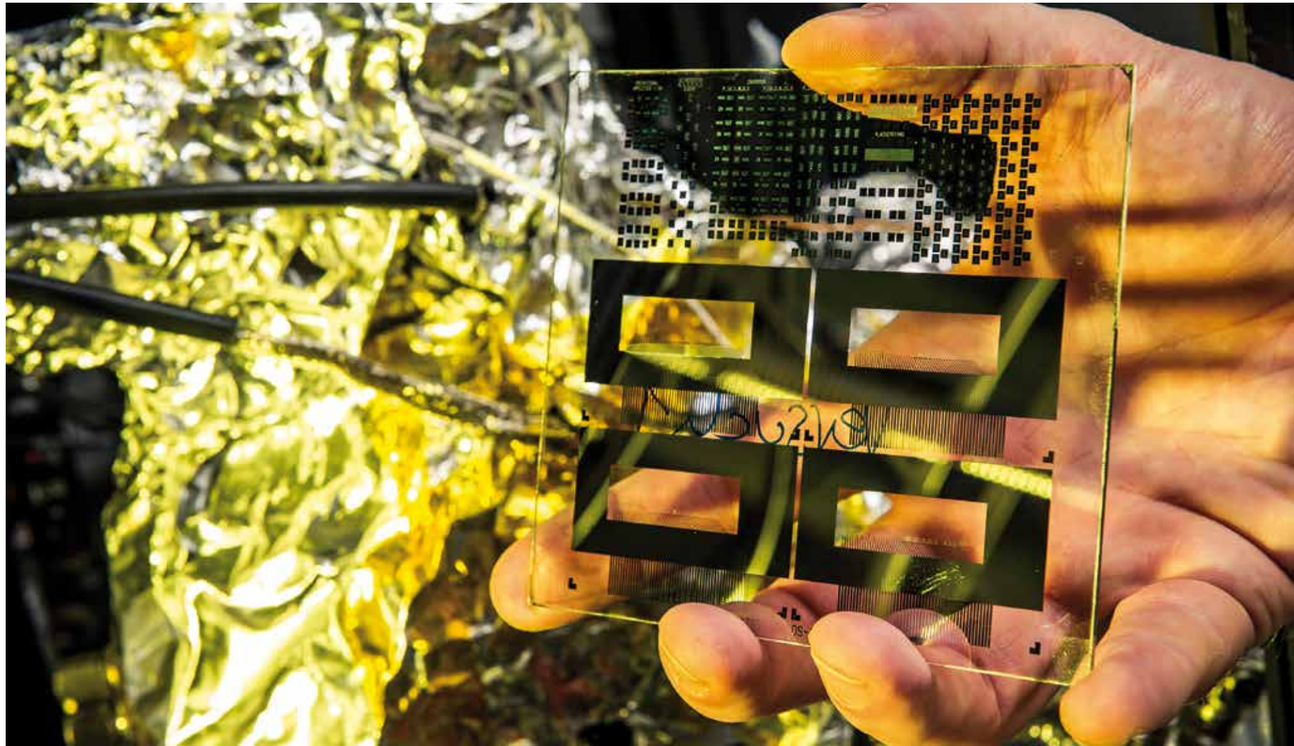


Big instead of small: whilst modern computer processors are getting smaller and smaller, the Stuttgart researchers are using giant atoms for quantum information processing. What are known as Rydberg atoms are up to 100 times bigger than the traces on modern processor chips. They can be specifically excited individually with a laser beam and hence be used as a single photon source. (Background photo: Intel)



forms of matter. For example, two Rydberg atoms can bond to an unusual molecule. With the Rydberg molecule not only are the two atomic nuclei situated much further apart from each other than with a conventional molecule but the bonding mechanism also fundamentally differs from the types of bonding known from chemistry. IQST is therefore broadening the chemical playing field.

In a similar way to how, in microelectronics, there are wires for electric current, there are conductive paths for photons. In microscopically small glass rods, the light can expand at almost the speed of light and is thus much faster than an electric current. For electricity, there are already many integrated components such as switches, storage components, etc. For light, components must first be developed, above all if one wishes to utilize the quantum mechanical properties of the light. To this end, one takes light particles which initially do not interact with each other and introduces them into an optically active medium, e.g. a gas composed of rubidium atoms. By this means, the light field can be manipulated. If one combines both techniques, an interface is generated between the intangible world of photons and the tangible world of electronics. In a first trial, it has now thus been possible to produce a microscopically small interface in an optical network.



The fact that Rydberg atoms, although in a gaseous state, can freeze for a very brief moment to a glass is something that was likewise demonstrated by the Stuttgart IQST researchers. This exotic state of a gaseous glass was produced at room temperature, which was previously deemed impossible in professional circles.

Quantum mechanical wave function of a giant Rydberg molecule which, owing to its shape, is also termed a trilobite state. A Rydberg molecule is a combination of a Rydberg atom and a non-excited, i.e. "normal", atom. It achieves the size of a microorganism. The researchers are currently working on a microscope with which one can directly observe this molecule.



Frozen gas from Rydberg atoms

Pfau's team is planning another novel achievement in the form of the imaging of a single Rydberg atom by means of a microscope. The atoms are a few hundred nanometers in size, which means that essentially they should be visible under a light microscope. But because the atomic cloud in which the Rydberg atom is located is highly light-absorbent, the task is like taking photographs in the fog. Although there are special microscopy techniques that can do this, these are difficult to implement in the context of the complex Stuttgart experiment. If the IQST researchers are successful, the atom orbitals familiar to us from school physics and reminiscent of dumbbells and donuts will be available as photographs. A fascinating thought.

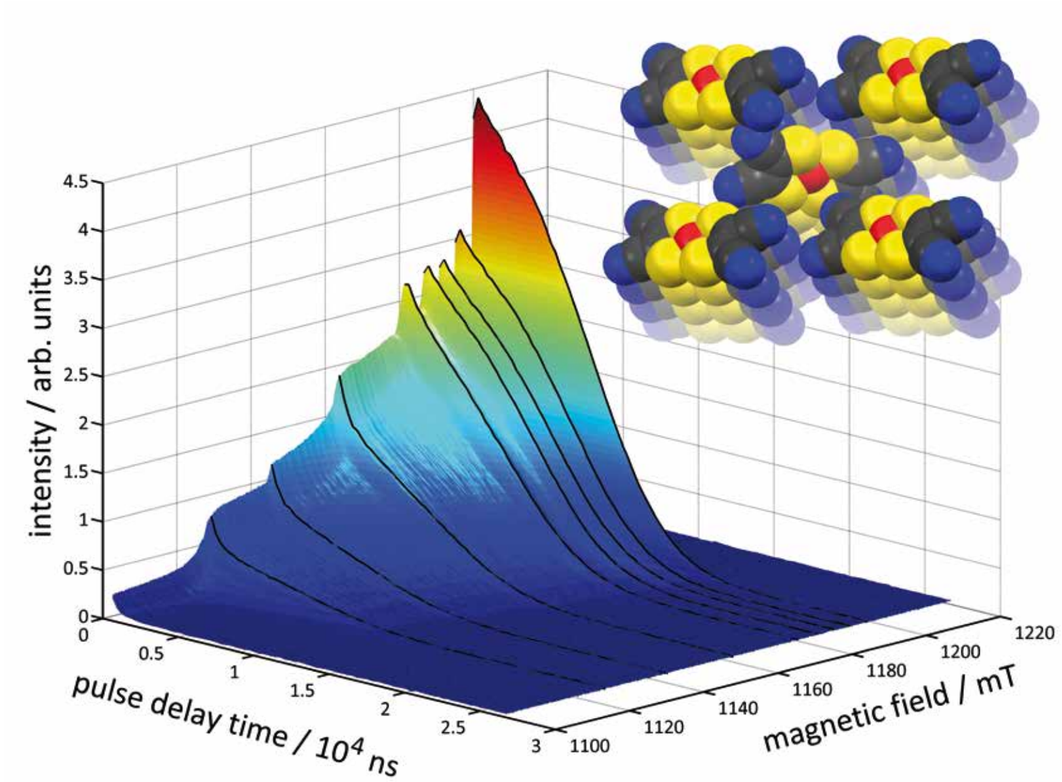


Experimental set-up for the microscope intended to make the Rydberg atoms visible. This would be the first time an atom were visible under an optical microscope.

Quantum engineering from chemistry's construction kit

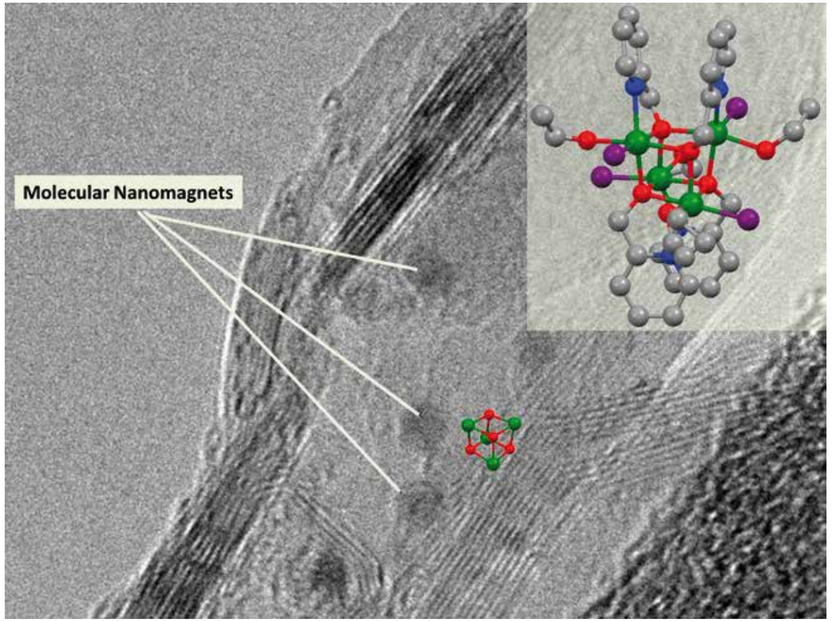
IQST researcher Prof. Joris van Slageren embodies the interdisciplinary nature of quantum sciences. Trained as a chemist with postdoctoral experience in physics, he is entering new territory at the Institute of Physical Chemistry at the University of Stuttgart by combining chemistry and quantum physics.

He is developing molecular quantum bits, that is to say molecules which can have two different magnetic orientations at the same time. Such a state of superposition is as though a compass needle were pointing north and south simultaneously. In conventional physics, no such parallel existence of possibilities exists. "We are hoping to thereby bring about logic operations which cannot be achieved with conventional methods," says Van Slageren. The team of IQST researchers consisting of chemists, physicists, and physical engineers is trying to bring into being new types of qubits from metal complexes. In the process, precise attention is being paid to ensuring that the remaining atoms in the molecule that have specifically been incorporated do not interfere with the superposition state. The advantage of such qubits is their scalability. When developing quantum computers, insufficient scalability is a major stumbling block. In current systems, expanding from a few to hundreds or thousands of qubits involves unjustifiable effort and expense. "By means of self-assembly, hundreds of qubits can be arranged regularly on a surface," states Van Slageren. Here every molecule is positioned on a site precisely determined in advance. The regularity is absolutely essential for the device so that the writing and reading head can find the qubits perfectly. Secondly, it makes it possible to control the interaction between the qubits by means of ligands (Lat. ligare = "to bind/tie"). These are groups of molecules hanging onto the metal complex which produce a potentially switchable connection between the qubits. By this means, an important resource can also be produced for quantum computing: what is referred to as entanglement between qubits.



So that useful computations can be performed with qubits, their superposition states must have long coherence times (see glossary). The image shows the structure of a potential qubit (top right) and a three-dimensional representation of the coherence decay curves and their magnetic field dependence. The image shows that the coherence time is very long, independent of the orientation of the molecule.

At the Institute for Semiconductor Engineering at the University of Stuttgart, Prof. Jörg Schulze is researching new types of semiconductor devices with a special focus on spintronic applications. In spintronics the electron spin, an additional property of electrons, is used for signal transmission. The spin is, alongside the electrical charge, an additional property of electrons intended to be used for signal transmission. It is a kind of twisting which makes particles into tiny magnetic compass needles. The advantage is that, during the operation of spintronic devices, less heat is generated. The heat released is increasingly becoming a limiting problem when it comes to increasing the performance of conventional computer chips further. Together with Joris van Slageren, Jörg Schulze is working on new approaches for combining molecular quantum bits with silicon technology. “We see terrific possibilities for controlling and reading the molecular quantum bits with our technologies,” says Prof. Schulze.
Linking molecular quantum systems with electrically conductive carbon nanomaterials opens up a further new dimension in electronics, namely molecular nano-spintronics. In the transition from microelectronics to nanoelectronics, many regard CNTs (short for carbon nanotubes) or the “magic material” graphene as being silicon’s successor. This is because in these materials, electrons move very fast. The conductivity of the hybrid system can be switched on and off through targeted control of the orientation of the molecular magnetization. A further idea is to use the carbon nanomaterial for the switchable coupling of quantum bits. From the chemistry construction kit, therefore, new types of components for a quantum computer could emerge which facilitate its realization.



Using transmission electron microscopy, molecules can be made visible. The image shows cube-shaped molecular nanomagnets which were introduced into the interior of carbon nanotubes, and the complete molecular structure in the top right.

Entangled photons seek out single molecules

Limits to the sensitivity of sensors previously regarded as rigid can be overcome with the aid of quantum physics. In this way, researchers from IQST want to construct extremely fine artificial noses.

The entanglement of states is not only of crucial importance for quantum information technology, it can also increase the sensitivity of sensors beyond the limits long deemed insuperable. What is referred to as shot noise is one of these limits. This is noticeable, for example, on digital images taken in semi-darkness. Individual pixels vary at random in color and brightness, unrelated to the actual motif. The cause of this (in addition to the noise of the electronics of the image sensor) is random fluctuations in the number of photons reaching the sensor.

Physicists have managed to show that this noise can be suppressed with the aid of entangled photons. This is because entangled photons are no longer independent of each other, which is why their fluctuations are also connected and can therefore mutually neutralize each other. They showed in a complex experimental set-up that the image quality can thus be improved.

Entangled photons can also be used to improve other types of sensors. At IQST, Peter Michler from the Institute of Semiconductor Optics and Functional Interfaces at the University of Stuttgart is working on this together with his colleague Boris Mizaikoff from the Institute of Analytical and Bioanalytical Chemistry from Ulm University. The new sensor chip is intended to detect single molecules with the aid of what is known as interferometry. One of two light signals interacts with the molecule and is thus slowed down a little. The resulting transit-time difference has the effect that the light signals become stronger or weaker when superimposed on one another. In order to find a single molecule, a very small transit-time difference must be measured, which is barely possible with traditional light. By using entangled photons, one can go below the natural shot noise limit for conventional light, which ultimately permits the detection of smaller transit-time differences.

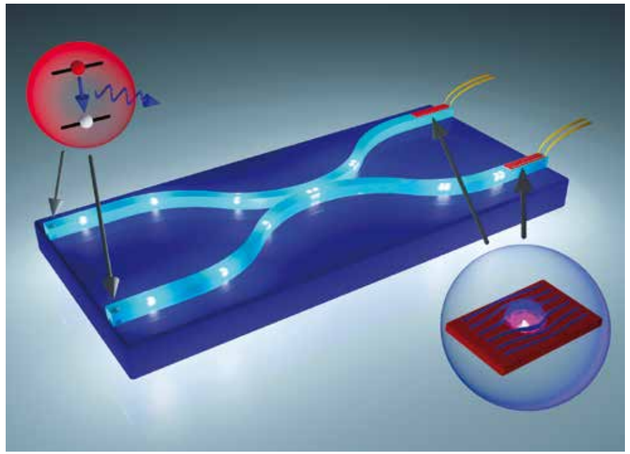
With their expertise in the area of semiconductor optics, Michler's team is developing the light source for generating entangled photons on a semiconductor chip.

Miniaturization and practical applicability of this highly sensitive sensor technology is therefore taking center stage. The challenges are big ones. The IQST researchers are trying to integrate, on a chip, sources for individual photons on the basis of quantum dots. In order to generate two entangled photons, two absolutely identical photons must be generated and superimposed on the chip. "This requires the production of virtually identical quantum dots on the chip which are synchronized to the same emission wavelength with the aid of electric fields, for example," says Michler, explaining the difficulty. Figuratively speaking, it is about integrating artificial atoms on the chip.

The technology could also contribute towards the impending revolution in metrology, because it can in principle be used for a wide variety of interferometric measurements, e.g. for distance measurements. The researchers are attempting to entangle more than two photons on chips, because as the number of entangled photons increases, the precision of the sensor technology increases.

Single photon sources integrated on chips could also be of great benefit to quantum cryptography.

The research by Michler's team shows particularly impressively how at IQST different skills, in this case semiconductor physics and quantum optics, flow into each other and create the potential for innovative technologies.



Schematic representation of a semi-conductor chip for the entanglement of pairs of photons. The intention is, through the entanglement, for the noise unavoidable with conventional chips to be suppressed (see text). On the left-hand edge of the picture the photons are emitted from what are known as quantum dots and transported away by wave guides. The entanglement occurs in the center of the chip where the wave guides touch each other. Superconducting single photon detectors (right-hand edge of picture) subsequently detect the photons.

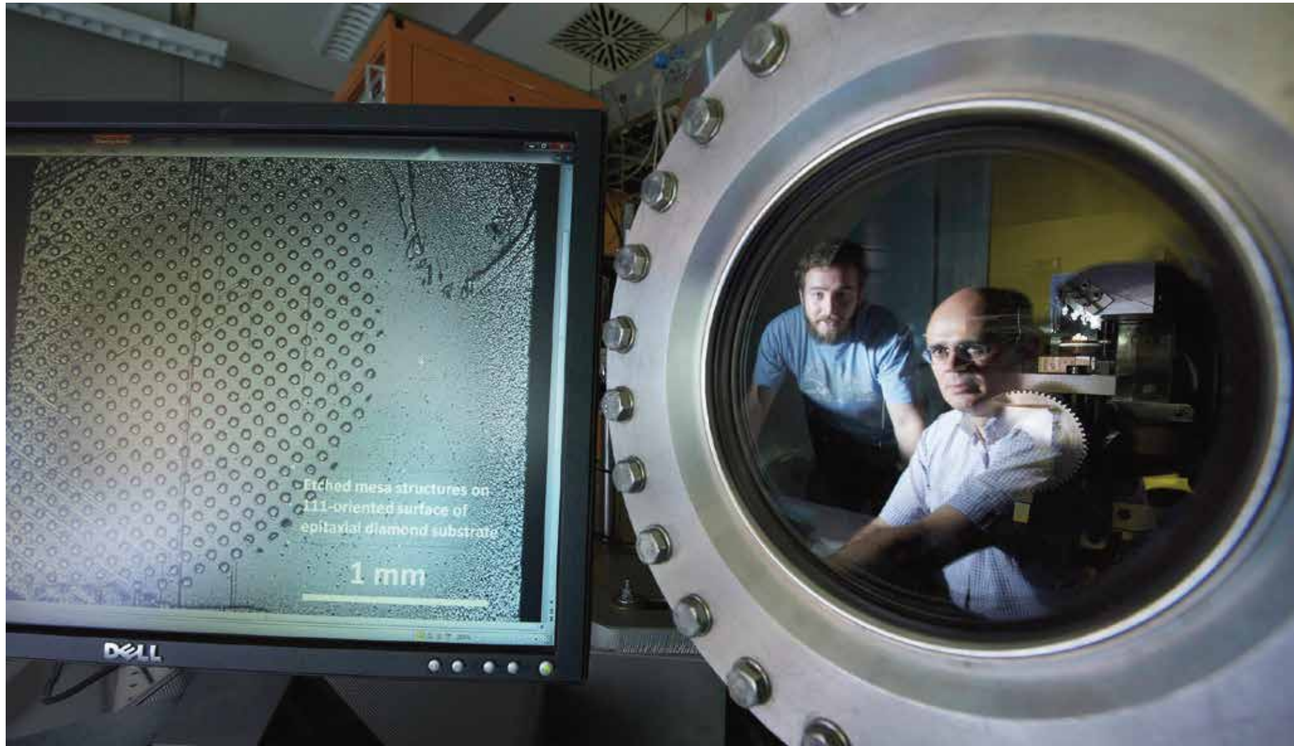
Diamonds at the heart of the quantum computer

Researchers across the world are trying out several possibilities for building a quantum computer. IQST researchers led by Jörg Wrachtrup from Stuttgart are pioneers in one of the most promising approaches. They have already developed important basic components of a quantum computer.

The development of a practical quantum computer also requires a mixture of courageous pure research, which tries out new ideas, and an application-related approach, which even at early stages of technological development is already thinking about the subsequent applicability. IQST combines both aspects. Here too, experimental and theoretical physicists are working together.

A high-performance quantum computer which can be used for everyday problems or to solve research tasks does not yet exist. In such a computer, thousands of qubits would have to work together. Alongside the difficulty of scaling, there is another substantial problem, namely what is referred to as decoherence. This is a consequence of disruptive environmental influences. Even a small interaction of the qubits with the environment, for example with invading photons, can disrupt a computing operation in a quantum computer. Researchers are developing ever more effective correction techniques for errors resulting from decoherence. However, good screening from the environment is the best protection against decoherence. Researchers usually protect their qubits through a vacuum or extremely low temperatures near to absolute zero (–273 °C). Admittedly, such requirements are an obstacle to routine use of the quantum computer.

Embedding qubits in diamonds promises low-noise functioning quantum computers under normal conditions. The extremely hard material acts, so to speak, as a screen for the qubits. In other materials, at room temperature, there are a number of crystal oscillations. With the diamond, on the other hand, these oscillations require more energy to become excited as they possess a higher frequency. Consequently, the interior of a diamond is very still at room temperature, explains IQST researcher Jörg Wrachtrup. In the crystal lattice of the jewel, only a hotter environment brings about chaos from vibrations.



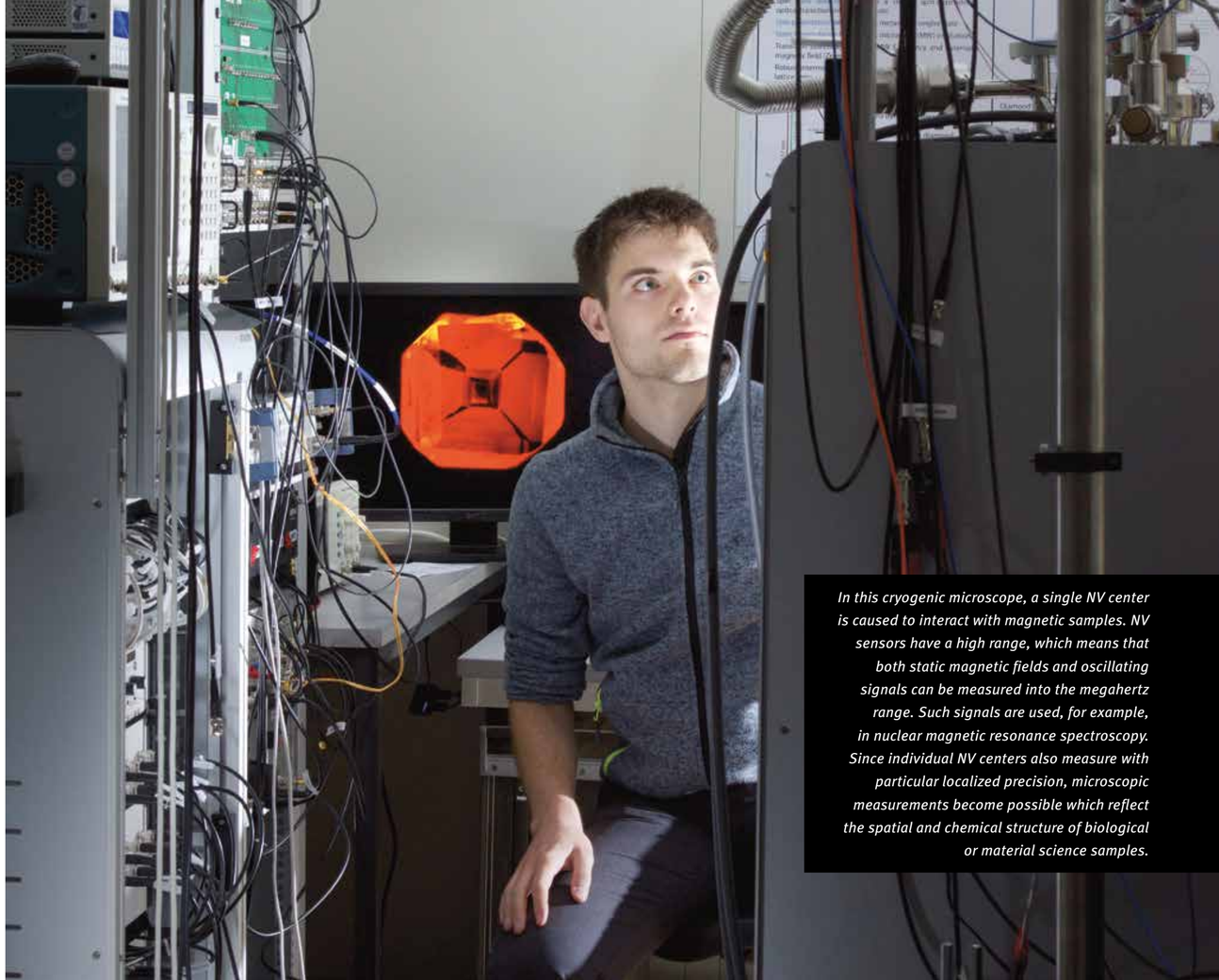
One of the biggest challenges in the construction of a quantum computer is positioning the NV (nitrogen-vacancy) centers with nanometer precision. IQST researchers have developed a high level of expertise in this. With the aid of a nano-structured implantation mask, they direct nitrogen ions accurately to their intended site in the diamond crystal. A zoom view of a diamond surface that has been structured in such a way and is ready for implantation can be viewed on the screen (left). The implantation islands can be addressed individually, generating areas with a defined distance and surface proximity of the NV centers.

The physicist is a world leader when it comes to using what are known as NV centers in the diamond as qubits. “NV” stands for nitrogen-vacancy. This is an irregularity in the diamond lattice otherwise built uniformly from carbon atoms. Here two neighboring carbon atoms are replaced by one nitrogen atom and one empty lattice site (vacancy). This system behaves like an atom which is captured in a grid and is therefore isolated from its environment. It possesses an electron spin which remains long enough in a defined spin state to be able to use it for calculation in the quantum computer. Jörg Wrachtrup was one of the first scientists to recognize the potential of the NV center for the quantum computer.

Wrachtrup’s team have succeeded in bringing into being an essential component of a quantum computer in a diamond: what is known as a quantum register. This is understood to mean a storage and computation unit consisting of several qubits entangled with one another. The atomic nuclei of two carbon atoms and a nitrogen atom served as qubits. The researchers controlled this trio of qubits by means of an NV center. The NV center is a suitable “mouthpiece” for control commands, because its spin responds quickly to external radio frequency pulses and passes on the information to the qubits of the register.

Every calculation by a computer consists of several individual steps: “logic operations” is what the researchers call these. The Stuttgart IQST researchers have implemented a certain logic operation (known as a CNOT gate) in their small diamond quantum computer. “All of this works at room temperature,” says Jörg Wrachtrup proudly. Admittedly, even the diamond is not completely free from vibrations, which is why the quantum register is subject to interference now and again and therefore “miscalculates”. Wrachtrup’s team has, however, succeeded in developing a method for remedying such errors. It is based on correction techniques as are used in conventional telecommunications technology. Here three bits carry one information unit. They are constantly compared. Should one be incorrect, then in a kind of “majority decision” the value of the two others is assumed to be valid.

Now the IQST researchers want to increase the number of cooperating qubits. The hurdle here is introducing the NV centers into the diamond at regular intervals of less than 20 nanometers. “That is a challenge for nanotechnology,” says Wrachtrup. “We are at the limits of what is feasible.” For the task, the researchers use metal masks with tiny holes through which they hurl nitrogen atoms at diamonds.



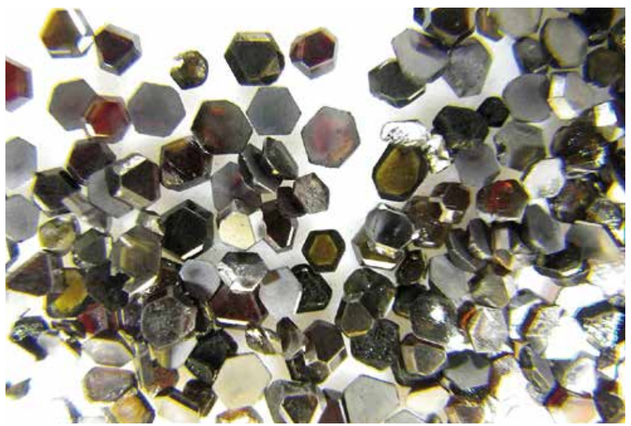
In this cryogenic microscope, a single NV center is caused to interact with magnetic samples. NV sensors have a high range, which means that both static magnetic fields and oscillating signals can be measured into the megahertz range. Such signals are used, for example, in nuclear magnetic resonance spectroscopy. Since individual NV centers also measure with particular localized precision, microscopic measurements become possible which reflect the spatial and chemical structure of biological or material science samples.

Lubricating oil for quantum computers

Quantum computers will not inherently compute at maximum speed. IQST researchers are developing methods intended to accelerate the computing operation and a language designed to enable a fluid exchange of information with these computers of the future.

Since an NV center is barely larger than a single atom and, in addition, is extremely sensitive to electric and magnetic fields, it can in principle be used as a magnetic field sensor with a previously unattained resolution in the nanometer range. Jörg Wrachtrup's team is researching areas of application for this new sensor, which range from the detection of individual spins to imaging methods with a microscopic resolution. Also conceivable are nanoparticles from diamond which can be injected into patients' bodies, in order to collect, with hitherto unknown precision, data for diagnostic purposes. The NV centers in the diamond can also be used as highly sensitive pressure sensors. Since diamonds are very temperature-resistant, the sensors could also be used in a waste gas stream or, in automotive development, in the cylinder. The company Bosch now wants to develop a compact version of a prototype from Wrachtrup's laboratory.

IQST researcher Fedor Jelezko from Ulm University is using the diamond sensors for pure research. His team wants to thereby decode the structure of complex biomolecules. "This is also possible at room temperature," says Jelezko, naming an advantage over other methods where the molecules are analyzed at extremely low temperatures. "We want to use the system for analyses of natural processes," adds Jelezko. Here, one should also be asking the question of whether photosynthesis owes its efficiency to quantum mechanical superposition. A question whose theory the IQST scientists Susana Huelga and Martin Plenio are looking at.



With tiny, millimeter-sized diamonds, magnetic and electric fields can be detected with nanometer precision.

The feature of quantum computers that stands out most is that, owing to quantum mechanical superposition, they can simultaneously test possibilities for solving difficult problems and, as a result, arrive at the result considerably more quickly than traditional computers which, for example during a database search, have to check entries individually. But a quantum computer will have to be cleverly programmed in order to be able to develop its suitability for simultaneous computing. Both the problem to be solved and the result shall be coded in a quantum computer in the form of a complex quantum mechanical state of its qubits – similar to how in a modern computer both input and output are represented in the form of sequences of "0" and "1". The computing operation therefore corresponds to transition from one quantum state to the other.

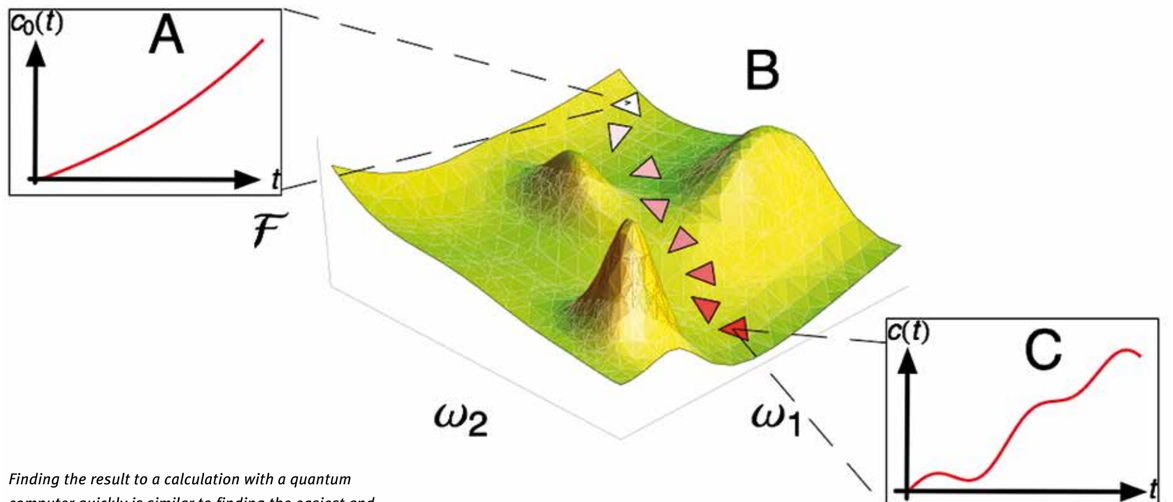
IQST researchers Tommaso Calarco and Simone Montangero from Ulm University are researching how the optimum transition from the initial state to the end state can be determined. In other words, they investigate by which means a quantum computer can go from start to finish most quickly. This is no trivial task, which Calarco explains as follows: "An unpracticed waiter will carry a tray full of glasses of champagne to the table by walking at a steady pace, because if he speeds up too much, the glasses will tip over. An expert, however, will skillfully hold the tray at an angle when he sets off and then position it horizontally again when he is walking along. In this way, he skillfully evens out the forces acting on the glasses. He will arrive at his guest's table significantly quicker."

The waiter, he explains, learns from experience how he has to move the tray. The optimum computation method for the quantum computer can also hardly be calculated. Calarco and Montangero have developed a method for how the optimum path can still be found quickly. This works in a similar way to a waiter who finds out by means of trial and error how the tray should best be tilted.

Within IQST, Fedor Jelezko has already used the method to achieve a robust system for controlling the quantum system in the diamond.

Engineers are also interested in the IQST researchers' methods, because complex technical problems often result in a level of computing work that in practice can hardly be achieved: if, for example, cranes are supposed to take their loads more quickly from A to B without the hanging load starting to swing.

The team under physicist Martin Plenio from Ulm University is also developing a language, so to speak, that enables fluid communication with quantum computers. "As the number of qubits increases, the number of variables describing the quantum computer increases to the unmeasurable," says Plenio. Even at 14 entangled qubits – the current world record – one would, if using the conventional route,



Finding the result to a calculation with a quantum computer quickly is similar to finding the easiest and fastest route through a mountain landscape. Tommaso Calarco, Simone Montangero and colleagues are developing methods which facilitate this optimum path for a wide variety of specific problems.

have to measure for 300 days in order to know the state of this quantum register in its entirety. "With our algorithms, this reading of the data can take place within a quarter of an hour," states Plenio. The team working under Rainer Blatt from Innsbruck University, which holds the world record, is currently trying out this methodology.

Other IQST researchers concerned with practical quantum computing are the theoretical physicists around Hans-Peter Büchler from the University of Stuttgart. They are following an approach which Microsoft's research department also regards as very promising: the topological quantum computer. Here, it is not the properties of single particles that are to serve as qubits, but collective phenomena of a large number of particles. When cooled, electrons, for example, arrange themselves in certain patterns. That's why we have the expression topological, which stems from the Greek topos = location, place. "Such phenomena are not local," explains Büchler, i.e. they are not restricted to a point or small area. Consequently, says the physicist, they are also difficult to destroy.

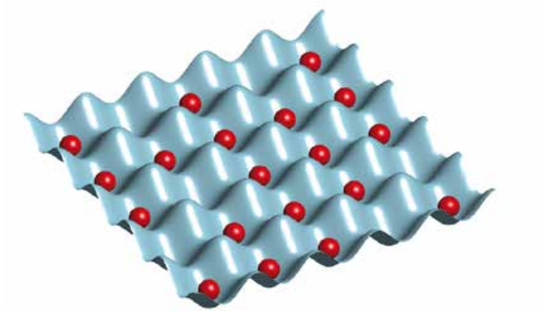
One example is what are known as anyons (exotic quasiparticles). They occur in two-dimensional electron systems and behave like particles, although they actually arise from the interplay of the many electrons, like a water wave arises from the cooperation of very many water molecules. In a three-dimensional space-time (two space dimensions + the dimension of time), the anyons are in orbits reminiscent of braided hair. These orbits, known as "braids", are to be used similarly to a qubit as a carrier of quantum information. One can imagine the greater stability of such an orbit compared with a qubit achieved with a particle as follows. In order to disrupt a braid, one has to cut it apart at one point and join it together again. This is more difficult than kicking a ball (particle) against a wall.

This type of robustness is designed to protect topological qubits from decoherence. This research is, however, in its infancy.

Atomic ballet

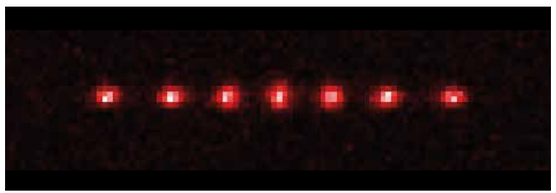
IQST researchers are developing one of the most promising applications of quantum physics: quantum simulators. With their help, models of highly complex materials can be created which, so far, are too much even for supercomputers.

At the University of Stuttgart, researchers at the institute of the unfortunately recently deceased IQST Co-founder Alejandro Muramatsu routinely simulates systems consisting of several particles on the computer, working together with experimental IQST researchers. One of these is Johannes Hecker Denschlag from Ulm University. His team has mastered the art of arranging atoms regularly, like a troop of soldiers, and manipulating them. The Ulm researchers catch the atoms in a lattice of intersecting laser beams like eggs in an egg box. "We can play with the atoms," says Hecker Denschlag. The researchers control the interactions between the atoms; they can, for example, switch them between attractive and repellent. Or they generate, at the touch of a button, pairs of atoms, i.e. simulated molecules. "Worldwide, there are only a few groups of researchers that have mastered this," states Hecker Denschlag.



With their control of the atomic ensembles, the researchers can also simulate solids. "We are working on simulating graphene, for example, and then analyze this artificial graphene under conditions which one cannot achieve with real graphene," explains Hecker Denschlag. Büchler's theoretical team from the University of Stuttgart supplements this research with computer models of graphene which, for example, work out what the conductivity of the magic material is dependent upon.

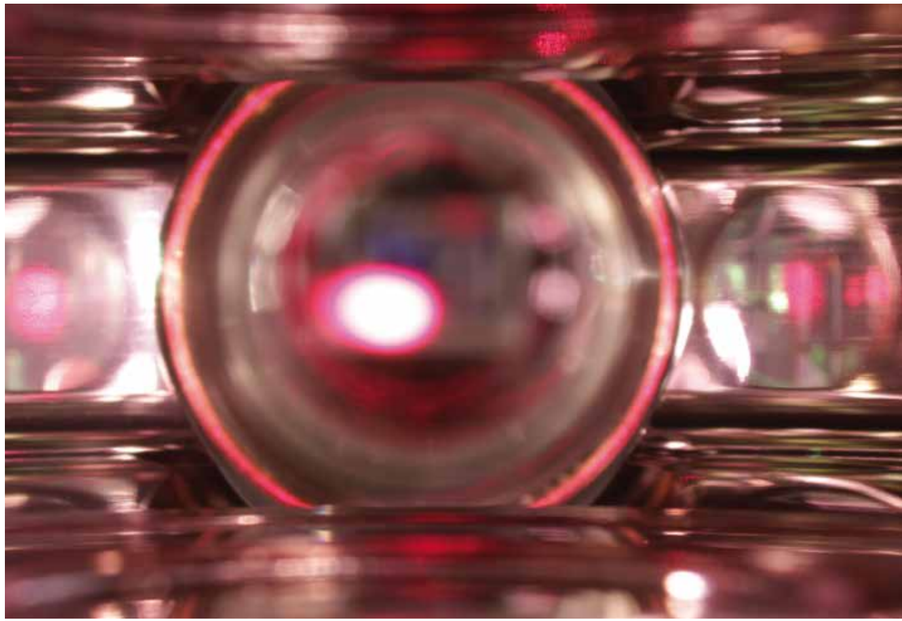
Currently, the IQST researchers working with Hecker Denschlag are unlocking a totally new field from scratch. They are adding individual ions to the atomic ensembles. In this way, for example, targeted contaminants of solids, what are known as dopants, that have a high technological relevance can be investigated.



Far left: Uncharged (neutral) atoms, captured in what is known as an optical lattice. It is created from intersecting laser beams and holds atoms securely like an egg box holds eggs. This results in a regular arrangement of atoms, similar to that in a crystal. Such artificial crystals serve as model systems for investigating issues in solid state physics.

Left: Chain of seven barium ions in a linear Paul trap. An electrical AC field holds the electrically charged ions secure. The distance between the ions is approx. 30-40 micrometers (thousandths of a millimeter). The ions are cooled with the aid of laser light to just 0.5 thousandths of a degree above absolute zero (–273 °C).

Right: View inside the vacuum equipment. Visible in the center is a luminescent cloud of ultra-cold lithium atoms which is being prepared for the graphene experiments.



Control over a sea of electrons

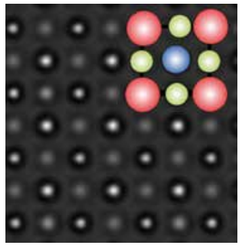
Superconductors, which conduct electricity without any losses at normal temperatures, are the dream of IQST researcher Bernhard Keimer. However, before the required materials can be developed, the highly complex behavior of the electrons in superconductors has to be understood.

Quantum simulators, as are being made a reality by Hecker Denschlag's team, are deemed in professional circles to be one of the most promising applications of quantum physics. This is because they could facilitate understanding of high-temperature superconductors. Most experts are convinced that, once the high-temperature superconductor (HTSC for short) has been understood, solids can be constructed that conduct electricity at room temperature without loss.

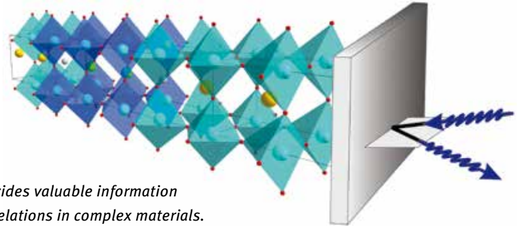
This is also the goal which IQST researcher Bernhard Keimer from the Max Planck Institute for Solid State Research in Stuttgart is committed to. A global network of superconductors, whose interior electrons form a single connected quantum system is definitely realistic, the physicist believes. This dimension shows how highly complex such a quantum system can be: more electrons than there are grains of sand on all the beaches of the earth are acting within it. "Yet it is possible to grasp this complexity," says Keimer. Keimer's team is trying to do this using several approaches. One of these is, in cooperation with chemists, to synthesize new materials which possess a similar structure to known HTSC, e.g. copper oxide compounds. These materials are then characterized by the team. Subsequently, theoretical quantum scientists try to understand the data with the aid of numerical computer models. This can, in turn, provide valuable pointers for the synthesis of new materials. Experiment and theory thus feed each other lines and, in the best case, come closer and closer to a recipe for the room-temperature superconductor.

"We are still a long way from designing new high-temperature superconductors with customized properties," concedes Keimer. But the long-term goal is to "produce something that can also be sold".

Thus Keimer has outlined the motivation of many IQST scientists. They combine their spirit of discovery, their passion for trying things out, with the aim of making the newly discovered effects usable for technology. Those with practical roles at IQST are keen to pick up the ideas. Thus from pure research new things can emerge which can contribute to the solution of global challenges and enrich people's everyday lives.



Atomic structure of a $LaNiO_3$ (lanthanum nickel oxide) heterostructure, which was produced in Stuttgart and characterized in Ulm using electron microscopy (Kinyanjui et al., Applied Physics Letters 104, 221909 (2014). red = lanthanum, blue = nickel, green = oxygen



The scattering of photons provides valuable information about electronic quantum correlations in complex materials.

Setup for optical experiments on quantum materials.



IQST in figures

The collaboration of the University of Stuttgart, Ulm University and the Max Planck Institute for Solid State Research in Stuttgart is exemplary for Baden-Württemberg and, thanks to the use of the infrastructure at both sites, is opening up new visions. Diverse partnerships with leading international research institutions in Europe and worldwide are strengthening the importance of this research network.

18 participating institutes at the University of Stuttgart, Ulm University and the Max Planck Institute for Solid State Research (Stuttgart)

22 professors (fellows)

750,000 euros of funding per year for 5 years (1/3 each from Ulm University and the University of Stuttgart, 1/3 from the Federal State of Baden-Württemberg)

At the locations of Stuttgart and Ulm there is a particularly high density of expertise and outstanding up-and-coming scientists, something which is evidenced by numerous science prizes and highly remunerative funding programs:

4 Leibniz prizes (German Research Foundation)

2 Max-Planck prizes (Max Planck Society)

15 ERC Grants (European Research Council)

3 ERC Synergy Grants (European Research Council)

2 Humboldt professors (Alexander von Humboldt Foundation)

4 scientists in the group are among the scientists most quoted worldwide. (The World's most influential scientific minds, Thomson Reuters).

Future developments at IQST

Several major EU projects and a priority program of the German Research Foundation are being coordinated at the IQST. The aim is to increase networking with European industry in order to drive forward knowledge transfer from research to industry.

The IQST has set itself the goal of tackling the challenges of the second quantum revolution, i.e. the exploitation of the entanglement of many-particle systems, by means of interdisciplinary cooperation that extends beyond the bounds of the universities and extramural institutions. Particularly important is the implementation of the new quantum technologies in products that are useful to society.

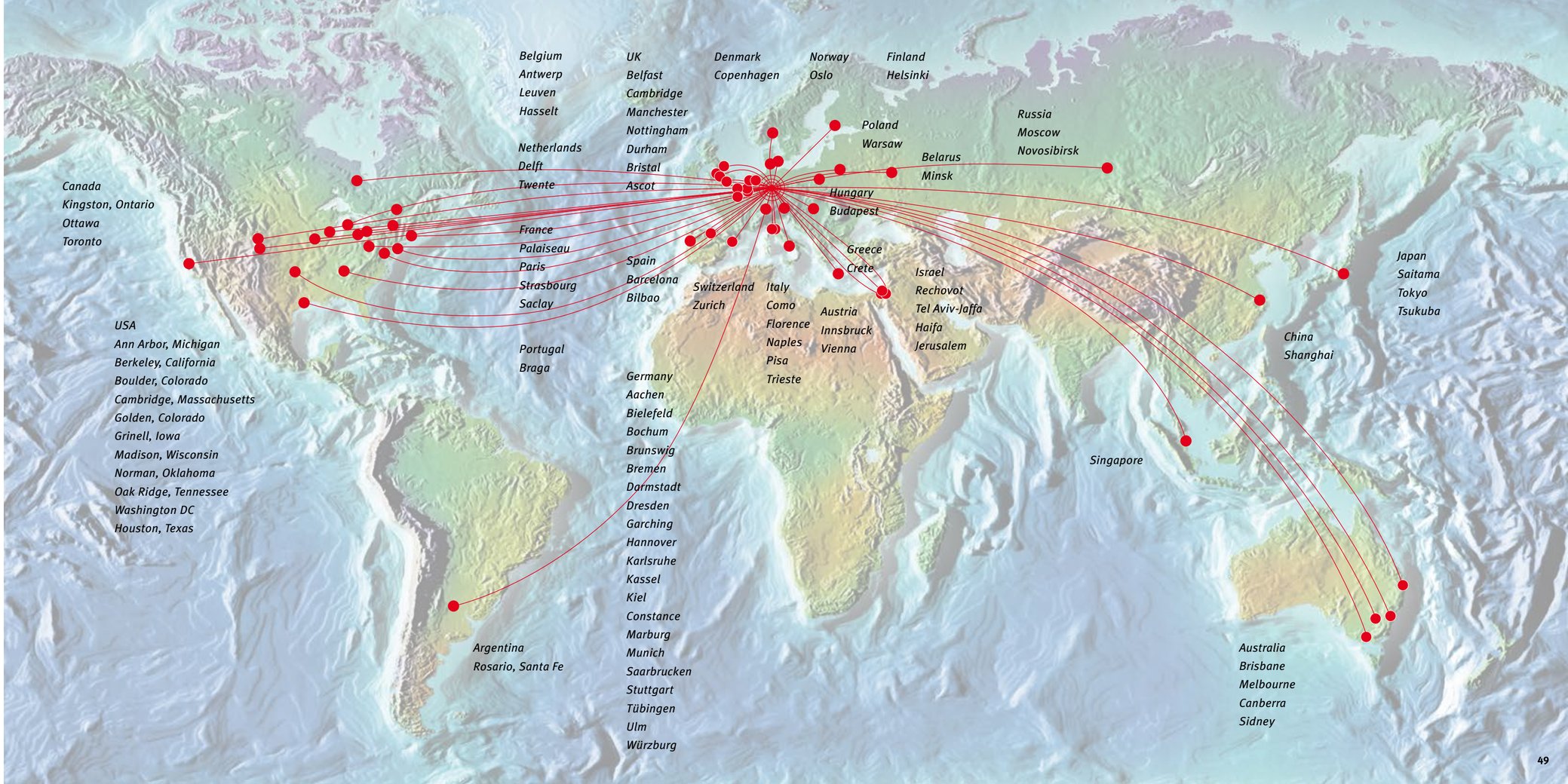
In the regional Allianz für Quanteninnovationen [Alliance for Quantum Innovations], which is coordinated by IQST researchers Fedor Jelezko (Ulm University) and Jörg Wrachtrup (University of Stuttgart), technology transfer in the context of cooperation projects with industry is crucially important. In addition, at both IQST locations, substantial new buildings with ultra-modern laboratories and infrastructures are under construction, funded by the Federal State of Baden-Württemberg and the German federal government: on the Ulm University campus a separate research building is being provided for the newly founded Zentrum für Quantenbiowissenschaften (ZQB) [Center for Quantum Biosciences], and in Stuttgart the Zentrum für Angewandte Quantentechnologien (ZAQuant) [Center for Applied Quantum Technologies] is getting an extensive new building, in which, among other things, the knowledge acquired in Ulm in the field of biology and medicine are to be implemented in prototypes.

The long-term growth of the Center is being driven forward within the scope of additional coordinated research programs and networks. To this end, within the IQST network, intensive preparations are underway to create the required overall conditions.

A further stated aim of the Center is to drive forward the internationalization of the IQST. This is to be facilitated by setting up a worldwide Graduate School, with the Center in Stuttgart and Ulm and a dynamic exchange of guest researchers, e.g. with the Hebrew University (Israel), the University of British Columbia (Canada) and the University of Tokyo (Japan). The Graduate School will be all-embracing, addressing the basic principles of quantum sciences and technologies but also having links to industry. The sustainable promotion of international scientific exchange in the IQST is additionally being reinforced through the expansion of the visiting and guest professor program. All measures also serve to assist with the preparation for the excellence initiative in 2017.

IQST connected worldwide

Cooperation activities with a number of leading research institutes around the globe flow into the projects coordinated and processed at IQST. The world map shows how wide the network is.
All members of the center have intensive international ties and maintain partnerships worldwide in their research areas.



IQST minds

Executive Board



Prof. Dr. Tommaso Calarco, Speaker IQST
Ulm University
Institute for Complex Quantum Systems
... is developing monitoring techniques for many-body problems and wishes, by this means, to make quantum technologies more efficient.



Prof. Dr. Tilman Pfau, Speaker IQST
University of Stuttgart
5th Institute of Physics
... is researching the interaction of atoms in ultracold quantum gases, in order to generate new states of matter under controlled conditions.

Prof. Dr. Wolfgang Schleich
Ulm University
Institute of Quantum Physics
... is concerned with questions of quantum mechanics and quantum optics where they overlap with gravitation and number theory.



Prof. Dr. Fedor Jelezko
Ulm University
Institute of Quantum Optics
... is researching the application of diamond quantum sensors which, as highly sensitive quantum microscopes, can make the structures and functions of individual biomolecules visible.





Prof. Dr. Jörg Wrachtrup
University of Stuttgart
3rd Institute of Physics
... is researching with diamonds and trying to use their special properties and flaws for quantum information processing.



Prof. Dr. Bernhard Keimer
Max Planck Institute for Solid State Research, Stuttgart
... is exploring the technical application potential of materials which, owing to the quantum nature of their particles, exhibit exceptional magnetic properties.

Fellows



Prof. Dr. Joachim Ankerhold
Ulm University
Institute for Complex Quantum Systems
... is researching quantum dynamics at interfaces between solid state physics and quantum optics or chemistry and in the area of crossover with classical physics.



Prof. Dr.-Ing. Norbert Frühauf
University of Stuttgart
Institute for Large Area Microelectronics
... is developing thin-film transistors with which, in the future, screens can be built from self-luminous organic substances, so-called OLEDs.

Prof. Dr.-Ing. Manfred Berroth
University of Stuttgart
Institute of Electrical and Optical Communication Engineering
... is developing very fast and high-resolution digital-to-analog converters for the interface between computer and glass fiber for a faster Internet.



Prof. Dr. Harald Giessen
University of Stuttgart
4th Institute of Physics
... focuses on the combination of micro- and nano-optics in order to realize solid state quantum systems which can be easily interfaced with classical optical information channels, which utilizes methods of plasmonics, metamaterials and high-resolution 3D printing.





Prof. Dr. Hans-Peter Büchler
University of Stuttgart
Institute of Theoretical Physics III
... is on the trail of exotic states in the quantum world and their description in the context of many-body quantum theory.



Prof. Dr. Johannes Hecker Denschlag
Ulm University
Institute of Quantum Matter
... is on the trail of elementary quantum chemical processes in the molecular bond and is trying to derive new methods from this.

Fellows



Prof. Dr. Susana F. Huelga
Ulm University
Institute of Theoretical Physics
… is researching open quantum systems for applications in quantum technologies.

Prof. Dr. Ute Kaiser
Ulm University
Central Facility for Materials Science
Electron Microscopy
… is conducting research in the area of atomic and molecular imaging of defect centers in diamond quantum sensors and in biological molecules with the aid of aberration-corrected, low-voltage electron microscopy.



Prof. Dr. Alexander Kubanek
Ulm University
Institute of Quantum Optics
… is developing non-conventional light sources for applications in quantum information processing and in sensor technology.



Prof. Dr. Jens Michaelis
Ulm University
Institute of Biophysics
… is researching the movement and dynamics of individual proteins for a mechanistic understanding of important molecular biological processes.



Prof. Dr. Peter Michler
University of Stuttgart, Institute of Semiconductor Optics and Functional Interfaces
… is researching semiconductor nanostructures in order to explore their potential for new types of light sources, e.g. single photon sources and sources for entangled photons.



Prof. Dr. Simone Montangero
Ulm University
Institute for Complex Quantum Systems
… applies high-performance numerical methods to study many-body systems and engineer novel quantum technologies.



Prof. Dr. Alejandro Muramatsu † 2015
University of Stuttgart
Institute of Theoretical Physics III
… is calculating the complex world of many-body systems for new quantum materials.



Prof. Dr. Martin Plenio
Ulm University
Institute of Theoretical Physics
… is researching quantum information and quantum technologies as well as their consequences and applications in biology and medicine.



Prof. Dr. Jörg Schulze
University of Stuttgart
Institute for Semiconductor Engineering
… is bringing the quantum world, with its new materials, effects, and concepts, into silicon-dominated microelectronics.



Prof. Dr. Joris van Slageren
University of Stuttgart
Institute of Physical Chemistry
… is researching molecular nanomagnets, in particular their use as molecular quantum bits.



Prof. Dr. Karsten Urban
Ulm University
Institute for Numerical Mathematics
… is concerned with the numerical solving and simulation of partial differential equations, with scientific calculation, and is also conducting research in the area of reduced basic methods.

Glossary

“I think I can safely say that nobody understands quantum mechanics.”
Richard Feynman, Nobel prize 1965

Atom orbital
Electrons do not move on fixed paths around the nucleus. There is a certain probability that they are positioned in defined areas around the atomic nucleus. The cloud-shaped formation of an atomic orbital illustrates the probabilities for each possible position. The orbitals are determined precisely by the wave function of the electron.

Bit
Smallest possible information unit. It is mostly represented by the two values “0” and “1”.

Photon
Light consists of myriads of massless particles which are also called photons. Each photon has a particular color which is determined by the wavelength. Although they have no mass, photons can, when they encounter matter, cause it to move through their impulse. Photons are therefore revealed as a wave or as particles depending on the situation. Photons never collide with other photons. They do not see each other. Isolating or generating a single photon is an experimental challenge.

Quantum cryptography
The use of quantum physics effects for innovative encryption techniques. In this way, thanks to superposition a link can be set up between sender and recipient in which any eavesdropping operation is inevitably noticed.

Quantum computer
A computer that processes quantum information. Thanks to superposition and entanglement, it can test lots of possibilities for solving a problem at the same time and thereby arrive at the result faster than a conventional computer. Admittedly, this does not work for all types of computation. The quantum computer will therefore probably not be used as a universal computer (as today’s computers are).

Quantum dot
A tiny piece of semiconductor (a few nanometers in diameter), which is surrounded by a shell made from another semiconductor material, comparable to a cherry stone and the fruit flesh surrounding it. The inner semiconductor forms, in a similar way to an atom, discrete energy levels for electrons. Consequently, quantum dots are also regarded as “artificial atoms”. In quantum technology, they are to be used as miniaturized sources for single photons as are of interest, for example, for quantum cryptography.

Quantum information
Information which is stored in a quantum physical system. Such information cannot be described with the laws of conventional information theory. It forms the basis of applications such as the quantum computer or quantum cryptography. The unit of quantum information is the qubit.

Quantum coherence
A relationship between the parts of a quantum system. Without quantum coherence, for example, the qubits in a quantum computer cannot perform any calculations. Quantum coherence is comparable with the interference capability of beams of light: only if the phases of two light sources have a permanent and constant (over time) relationship with one another can the two waves be constructively or destructively superimposed.

Coherence time
The length of time for which the quantum coherence is maintained. Only within the coherence time are calculations possible on a quantum computer. Individual computation steps should therefore only last for tiny fractions of what already is mostly a short coherence time, so that more complex tasks become solvable. The coherence time varies for different types of qubits between a few millionths of a second through to several seconds.

Qubit
Smallest storage unit for quantum information. It is brought about through two-state quantum systems, e.g. two polarization directions of photons. Unlike the conventional bit, which can either assume the value 0 or the value 1, a qubit can store “mixtures” of the values 0 and 1, for example 70% “0” and 30% “1”. It can therefore assume an infinite number of values. This capacity for parallel processing of two diametrical information units forms the basis for the potential capacity of quantum computers.

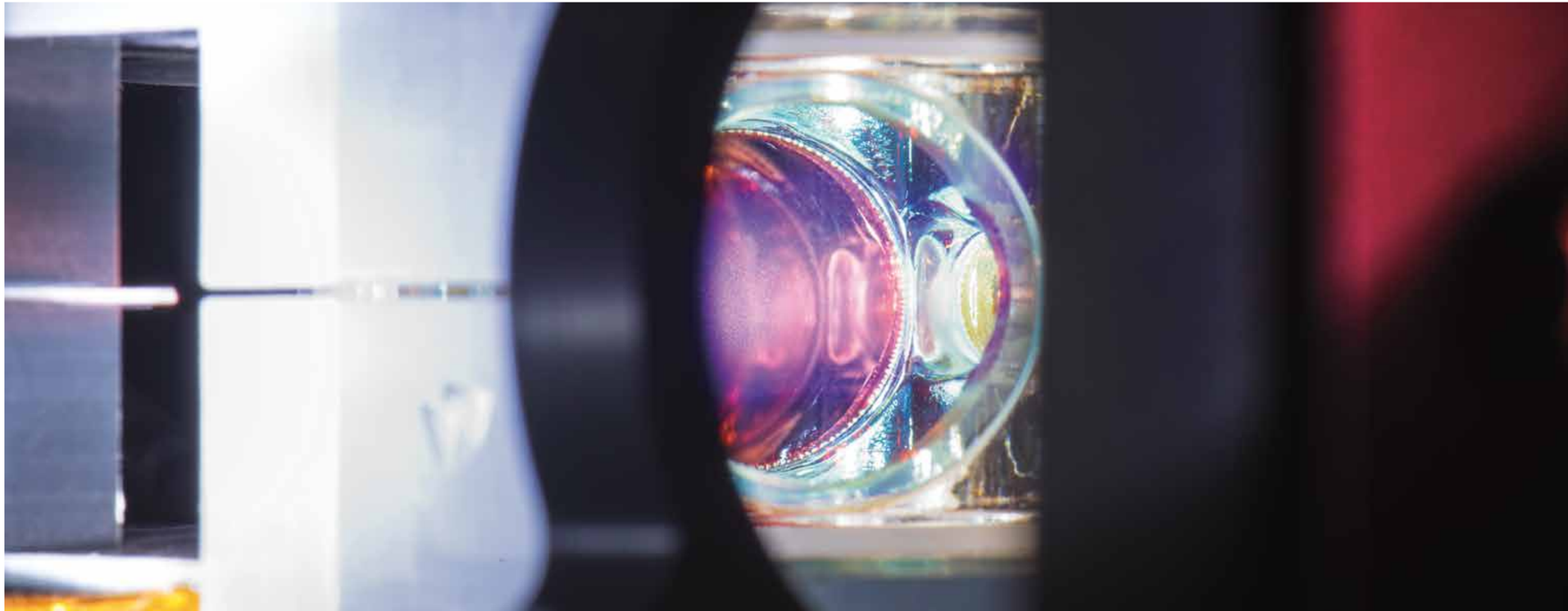
Spin
The English expression for “turn” or “twist”. What is meant is a type of precession of particles. The spin can act as a carrier of quantum information.

Superposition
A particle or some other quantum system, e.g. the electrons in a superconductor, exists simultaneously in all its possible physical states. Only the measurement of a variable, e.g. the position, singles

out a particular state out of all those possible. The selection here is purely random.

Superconduction
If electrons move through a conductor, they are slowed down by friction effects. If one cools special materials to very low temperatures, electrons move in pairs through the system without friction.

Entanglement
According to the rules of quantum physics, particles can be so closely connected to each other that the measurement of one instantly influences the state of the other, even if the distance between the two particles is very large. This effect has already been proven for photons situated 150 km away from one another.



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