# Individual Atom Qubit

*In recent years, scientists have come up with ways to isolate and manipulate individual quantum particles. But such techniques have been difficult to scale up, and the lack of a reliable way to manipulate large numbers of atoms remains a significant roadblock toward quantum computing. [25]*

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*Researchers from the Institute for Quantum Computing (IQC) at the University of Waterloo led the development of a new extensible wiring technique capable of controlling superconducting quantum bits, representing a significant step towards to the realization of a scalable quantum computer. [22]*

*Australian engineers have created a new quantum bit which remains in a stable superposition for 10 times longer than previously achieved, dramatically expanding the time during which calculations could be performed in a future silicon quantum computer. [21]*

*Harnessing solid-state quantum bits, or qubits, is a key step toward the mass production of electronic devices based on quantum information science and technology. However, realizing a robust qubit with a long lifetime is challenging, particularly in semiconductors comprising multiple types of atoms. [20]*

*Researchers from Delft, the University of Wisconsin and Ames Laboratory, led by Prof. Lieven Vandersypen of TU Delft's QuTech discovered that the stability of qubits could be maintained 100 times more effectively in silicon than in gallium arsenide. [19]*

*Researchers from MIT and MIT Lincoln Laboratory report an important step toward practical quantum computers, with a paper describing a prototype chip that can trap ions in an electric field and, with built-in optics, direct laser light toward each of them. [18]*

*An ion trap with four segmented blade electrodes used to trap a linear chain of atomic ions for quantum information processing. Each ion is addressed optically for individual control and readout using the high optical access of the trap. [17]*

*To date, researchers have realised qubits in the form of individual electrons (aktuell.ruhr-uni-bochum.de/pm2012/pm00090.html.en). However, this led to interferences and rendered the information carriers difficult to programme and read. The group has solved this problem by utilising electron holes as qubits, rather than electrons. [16]*

*Physicists from MIPT and the Russian Quantum Center have developed an easier method to create a universal quantum computer using multilevel quantum systems (qudits), each one of which is able to work with multiple "conventional" quantum elements – qubits. [15]*

*Precise atom implants in silicon provide a first step toward practical quantum computers. [14]*

*A method to produce significant amounts of semiconducting nanoparticles for light-emitting displays, sensors, solar panels and biomedical applications has gained momentum with a demonstration by researchers at the Department of Energy's Oak Ridge National Laboratory. [13]*

*A source of single photons that meets three important criteria for use in quantum-information systems has been unveiled in China by an international team of physicists. Based on a quantum dot, the device is an efficient source of photons that emerge as solo particles that are indistinguishable from each other. The researchers are now trying to use the source to create a quantum computer based on "boson sampling". [11]*

*With the help of a semiconductor quantum dot, physicists at the University of Basel have developed a new type of light source that emits single photons. For the first time, the researchers have managed to create a stream of identical photons. [10]*

*Optical photons would be ideal carriers to transfer quantum information over large distances. Researchers envisage a network where information is processed in certain nodes and transferred between them via photons. [9]*

*While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer using Quantum Information.*

*In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods.*

*The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the Wave-Particle Duality and the electron's spin also, building the Bridge between the Classical and Quantum Theories.*

*The Planck Distribution Law of the electromagnetic oscillators explains the electron/proton mass rate and the Weak and Strong Interactions by the diffraction patterns. The Weak Interaction changes the diffraction patterns by moving the electric charge from one side to the other side of the diffraction pattern, which violates the CP and Time reversal symmetry.*

*The diffraction patterns and the locality of the self-maintaining electromagnetic potential explains also the Quantum Entanglement, giving it as a natural part of the Relativistic Quantum Theory and making possible to build the Quantum Computer with the help of Quantum Information.*

## Contents

Author: George Rajna

## Preface

While physicists are continually looking for ways to unify the theory of relativity, which describes large-scale phenomena, with quantum theory, which describes small-scale phenomena, computer scientists are searching for technologies to build the quantum computer.

Australian engineers detect in real-time the quantum spin properties of a pair of atoms inside a silicon chip, and disclose new method to perform quantum logic operations between two atoms. [5]

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently – instead, a quantum state may be given for the system as a whole. [4]

I think that we have a simple bridge between the classical and quantum mechanics by understanding the Heisenberg Uncertainty Relations. It makes clear that the particles are not point like but have a dx and dp uncertainty.

## Scientists set traps for atoms with single-particle precision

Atoms, photons, and other quantum particles are often capricious and finicky by nature; very rarely at a standstill, they often collide with others of their kind. But if such particles can be individually corralled and controlled in large numbers, they may be harnessed as quantum bits, or qubits—tiny units of information whose state or orientation can be used to carry out calculations at rates significantly faster than today's semiconductor-based computer chips.

In recent years, scientists have come up with ways to isolate and manipulate individual quantum particles. But such techniques have been difficult to scale up, and the lack of a reliable way to manipulate large numbers of atoms remains a significant roadblock toward quantum computing.

Now, scientists from Harvard and MIT have found a way around this challenge. In a paper published today in the journal Science, the researchers report on a new method that enables them to use lasers as optical "tweezers" to pick individual atoms out from a cloud and hold them in place. As the atoms are "trapped," the scientists use a camera to create images of the atoms and their locations. Based on these images, they then manipulate the angle of the laser beams, to move individual atoms into any number of different configurations.

The team has so far created arrays of 50 atoms and manipulated them into various defect-free patterns, with single-atom control. Vladan Vuletic, one of the paper's authors and the Lester Wolfe Professor of Physics at MIT, likens the process to "building a small crystal of atoms, from the bottom, up."

"We have demonstrated a reconfigurable array of traps for single atoms, where we can prepare up to 50 individual atoms in separate traps deterministically, for future use in quantum information processing, quantum simulations, or precision measurements," says Vuletic, who is also a member of MIT's Research Laboratory of Electronics. "It's like Legos of atoms that you build up, and you can decide where you want each block to be."

The paper's other senior authors are lead author Manuel Endres and Markus Greiner and Mikhail Lukin of Harvard University.

### Staying neutral

The team designed its technique to manipulate neutral atoms, which carry no electrical charge. Most other quantum experiments have involved charged atoms, or ions, as their charge makes them more easily trappable. Scientists have also shown that ions, under certain conditions, can be made to perform quantum gates—logical operations between two quantum bits, similar to logic gates in classical circuits. However, because of their charged nature, ions repel each other and are difficult to assemble in dense arrays.

Neutral atoms, on the other hand, have no problem being in close proximity. The main obstacle to using neutral atoms as qubits has been that, unlike ions, they experience very weak forces and are not easily held in place.

"The trick is to trap them, and in particular, to trap many of them," Vuletic says. "People have been able to trap many neutral atoms, but not in a way that you could form a regular structure with them.

And for quantum computing, you need to be able to move specific atoms to specific locations, with individual control."

## Setting the trap

To trap individual neutral atoms, the researchers first used a laser to cool a cloud of rubidium atoms to ultracold, near-absolute-zero temperatures, slowing the atoms down from their usual, high-speed trajectories. They then directed a second laser beam through an instrument that splits the laser beam into many smaller beams, the number and angle of which depend on the radio frequency applied to the deflector.

The researchers focused the smaller laser beams through the cloud of ultracold atoms and found that each beam's focus—the point at which the beam's intensity was highest—attracted a single atom, essentially picking it out from the cloud and holding it in place.

"It's similar to charging up a comb by rubbing it against something woolen, and using it to pick up small pieces of paper," Vuletic says. "It's a similar process with atoms, which are attracted to regions of high intensity of the light field."

While the atoms are trapped, they emit light, which the scientists captured using a charge-coupled-device camera. By looking at their images, the researchers were able to discern which laser beams, or tweezers, were holding atoms and which were not. They could then change the radio frequency of each beam to "switch off" the tweezers without atoms, and rearrange those with atoms, to create arrays that were free of defects. The team ultimately created arrays of 50 atoms that were held in place for up to several seconds.

"The question is always, how many quantum operations can you perform in this time?" Vuletic says. "The typical timescale for neutral atoms is about 10 microseconds, so you could do about 100,000 operations in a second. We think for now this lifetime is fine."

Now, the team is investigating whether they can encourage neutral atoms to perform quantum gates—the most basic processing of information between two qubits.

While others have demonstrated this between two neutral atoms, they have not been able to retain quantum gates in systems involving large numbers of atoms. If Vuletic and his colleagues can successfully induce quantum gates in their systems of 50 atoms or more, they will have taken a significant step toward realizing quantum computing.

"People would also like to do other experiments aside from quantum computing, such as simulating condensed matter physics, with a predetermined number of atoms, and now with this technique it should be possible," Vuletic says. "It's very exciting." [25]

# Researcher explore balance between coherence and control with simple but complete platform for quantum processing

If you're building a quantum computer with the intention of making calculations not even imaginable with today's conventional technology, you're in for an arduous effort. Case in point: You're delving into new problems and situations associated with the foundational work of novel and complicated systems as well as cutting-edge technology.

Such is life for the scientists of the Martinis Group at UC Santa Barbara and Google, Inc., as they explore the exciting but also still somewhat counter-intuitive world of quantum computing. In a paper published in the journal Nature Physics, they and colleagues at Tulane University in New Orleans demonstrate a relatively simple yet complete platform for quantum processing, integrating the control of three superconducting qubits.

"We're probing the edge of our capability," said the paper's lead author, Pedram Roushan. There have been quite a few efforts to build and study individual parts of a quantum processor, he explained, but this particular project involves putting them all together in a basic building block that can be fully controlled and potentially scaled up into a functional quantum computer.

However, before a fully practicable quantum computer—with all its potential for vast, rapid and simultaneous calculations—can be made, various and sometimes unpredictable and spontaneous circumstances arise that have to be understood as the researchers pursue greater control and sophistication of their system.

"You're dealing with particles—qubits in this case—that are interacting with one another, and they're interacting with external fields," Roushan said. "This all leads to very complicated physics."

To help solve this particular many-body problem, he explained, their fully controllable quantum processing system had to be built from a single qubit up, in order to give the researchers opportunities to more clearly understand the states, behaviors and interactions that can occur.

By engineering the pulse sequences used to manipulate the spins of the photons in their system, the researchers created an artificial magnetic field affecting their closed loop of three qubits, causing the photons to interact strongly with not only each other, but also with the pseudo-magnetic field. Not a small feat.

"Naturally most systems where there is good control are photonic systems," said co-author Charles Neill. Unlike electrons, charge-less photons generally tend not to interact with each other nor with external magnetic fields, he explained. "In this article we show that we can get them to interact with each other very strongly, and interact with a magnetic field very strongly, which are the two things you need to do to get them to do interesting physics with photons," Neill said.

Another advantage of this synthetic condensed-matter system is the ability to drive it into its lowest-lying energy state—called the ground state—to probe its properties.

But with more control comes the potential for more decoherence. As the researchers strove for greater programmability and ability to influence and read the qubits, the more open their system was likely to be to error and loss of information.

"The more control we have over a quantum system, the more complex algorithms we would be able to run," said co-author Anthony Megrant. "However, every time we add a control line, we're also introducing a new source of decoherence." At the level of a single qubit, a tiny margin of error may be tolerated, the researchers explained, but even with a relatively small increase in the number of qubits, the potential for error multiplies exponentially.

"There are these corrections that are intrinsically quantum mechanical, and then they start to matter at the level of precision that we're getting at," Neill said.

To combat the potential for error while increasing their level of control, the team had to reconsider both the architecture of their circuit and the material that was being used in it. Instead of their traditionally single-level, planar layout, the researchers redesigned the circuit to allow control lines to "cross over" others via a self-supporting metallic "bridge." The dielectric—the insulating material between the conducting control wires—was itself found to be a major source of errors.

"All deposited dielectrics that we know of are very lossy," Megrant said, and so a more precisely fabricated and less defective substrate was brought in to minimize the likelihood of decoherence.

Progress is incremental but solid, according to the researchers, who continue to explore the true potential of their quantum system. Add to that delicate dance speed, which is essential for the kind of performance they want to see in a fully operational quantum computer. Slow speeds reduce control errors but make the system more vulnerable to coherence limits and defects imposed by the materials. Fast speeds avoid the influence of defects in the material but reduce the amount of control the operators have over the system, they said.

With this platform, however, scaling up will be a reality of the not-too-distant future, they said.

"If we can control these systems very precisely—maybe at the level of 30 qubits or so—we can get to the level of doing computations that no conventional computer can do," Roushan said. [24]

## Researchers nearly reach quantum limit with nanodrums

Extremely accurate measurements of microwave signals can potentially be used for data encryption based on quantum cryptography and other purposes.

Researchers at Aalto University and the University of Jyväskylä have developed a new method of measuring microwave signals extremely accurately. This method can be used for processing quantum information, for example, by efficiently transforming signals from microwave circuits to the optical regime.

### Important quantum limit

If you are trying to tune in a radio station but the tower is too far away, the signal gets distorted by noise. The noise results mostly from having to amplify the information carried by the signal in order to transfer it into an audible form. According to the laws of quantum mechanics, all amplifiers add noise. In the early 1980s, US physicist Carlton Caves proved theoretically that the Heisenberg uncertainty principle for such signals requires that at least half an energy quantum of noise must be added to the signal. In everyday life, this kind of noise does not matter, but researchers around the world have aimed to create amplifiers that would come close to Caves' limit.

'The quantum limit of amplifiers is essential for measuring delicate quantum signals, such as those generated in quantum computing or quantum mechanical measuring, because the added noise limits the size of signals that can be measured', explains Professor Mika Sillanpää.

## From quantum bits to flying qubits

So far, the solution for getting closest to the limit is an amplifier based on superconducting tunnel junctions developed in the 1980s, but this technology has its problems. Led by Sillanpää, the researchers from Aalto and the University of Jyväskylä combined a nanomechanical resonator – a vibrating nanodrum – with two superconducting circuits, i.e. cavities.

'As a result, we have made the most accurate microwave measurement with nanodrums so far', explains Caspar Ockeloen-Korppi from Aalto University, who conducted the actual measurement.

In addition to the microwave measurement, this device enables transforming quantum information from one frequency to another while simultaneously amplifying it.

'This would for example allow transferring information from superconducting quantum bits to the "flying qubits" in the visible light range and back', envision the creators of the theory for the device, Tero Heikkilä, Professor at the University of Jyväskylä, and Academy Research Fellow Francesco Massel. Therefore, the method has potential for data encryption based on quantum mechanics, i.e. quantum cryptography, as well as other applications. [23]

# New 3-D wiring technique brings scalable quantum computers closer to reality

Researchers from the Institute for Quantum Computing (IQC) at the University of Waterloo led the development of a new extensible wiring technique capable of controlling superconducting quantum bits, representing a significant step towards to the realization of a scalable quantum computer.

"The quantum socket is a wiring method that uses three-dimensional wires based on spring-loaded pins to address individual qubits," said Jeremy Béjanin, a PhD candidate with IQC and the Department of Physics and Astronomy at Waterloo. He and Thomas McConkey, PhD candidate from IQC and the Department of Electrical and Computer Engineering at Waterloo, are lead authors on the study that appears in the journal Physical Review Applied as an Editors' Suggestion and is featured in Physics. "The technique connects classical electronics with quantum circuits, and is extendable far beyond current limits, from one to possibly a few thousand qubits."

One promising implementation of a scalable quantum computing architecture uses a superconducting qubit, which is similar to the electronic circuits currently found in a classical computer, and is characterized by two states, 0 and 1. Quantum mechanics makes it possible to prepare the qubit in superposition states, meaning that the qubit can be in states 0 and 1 at the same time. To initialize the qubit in the 0 state, superconducting qubits are brought down to temperatures close to -273 degrees Celsius inside a cryostat, or dilution refrigerator.

To control and measure superconducting qubits, the researchers use microwave pulses. The pulses are typically sent from dedicated sources and pulse generators through a network of cables connecting the qubits in the cryostat's cold environment to the room-temperature electronics. The network of cables required to access the qubits inside the cryostat is a complex infrastructure and, until recently, has presented a barrier to scaling the quantum computing architecture.

"All wire components in the quantum socket are specifically designed to operate at very low temperatures and perform well in the microwave range required to manipulate the qubits," said Matteo Mariantoni, a faculty member at IQC and the Department of Physics and Astronomy at Waterloo and senior author on the paper.

"We have been able to use it to control superconducting devices, which is one of the many critical steps necessary for the development of extensible quantum computing technologies."

The paper, Three-Dimensional Wiring for Extensible Quantum Computing: The Quantum Socket, is a collaborative effort of researchers at INGUN Prüfmittelbau GmbH, Germany, INGUN USA, and Google in the United States, plus the following researchers from IQC and Waterloo: Jeremy Béjanin, Thomas McConkey, John Rinehart, Carolyn Earnest, Corey Rae McRae, Daryoush Shiri, James Bateman, Yousef Rohanizadegan and Matteo Mariantoni. [22]

## Quantum computers: 10-fold boost in stability achieved

Australian engineers have created a new quantum bit which remains in a stable superposition for 10 times longer than previously achieved, dramatically expanding the time during which calculations could be performed in a future silicon quantum computer.

The new quantum bit, made up of the spin of a single atom in silicon and merged with an electromagnetic field - known as 'dressed qubit' - retains quantum information for much longer that an 'undressed' atom, opening up new avenues to build and operate the superpowerful quantum computers of the future.

The result by a team at Australia's University of New South Wales (UNSW), appears today in the online version of the international journal, Nature Nanotechnology.

"We have created a new quantum bit where the spin of a single electron is merged together with a strong electromagnetic field," said Arne Laucht, a Research Fellow at the School of Electrical Engineering & Telecommunications at UNSW, and lead author of the paper. "This quantum bit is more versatile and more long-lived than the electron alone, and will allow us to build more reliable quantum computers."

Building a quantum computer has been called the 'space race of the 21st century' - a difficult and ambitious challenge with the potential to deliver revolutionary tools for tackling otherwise impossible calculations, such as the design of complex drugs and advanced materials, or the rapid search of massive, unsorted databases.

Its speed and power lie in the fact that quantum systems can host multiple 'superpositions' of different initial states, which in a computer are treated as inputs which, in turn, all get processed at the same time.

"The greatest hurdle in using quantum objects for computing is to preserve their delicate superpositions long enough to allow us to perform useful calculations," said

Andrea Morello, leader of the research team and a Program Manager in the Centre for Quantum Computation & Communication Technology (CQC2T) at UNSW.

"Our decade-long research program had already established the most long-lived quantum bit in the solid state, by encoding quantum information in the spin of a single phosphorus atom inside a silicon chip, placed in a static magnetic field," he said.

What Laucht and colleagues did was push this further: "We have now implemented a new way to encode the information: we have subjected the atom to a very strong, continuously oscillating electromagnetic field at microwave frequencies, and thus we have 'redefined' the quantum bit as the orientation of the spin with respect to the microwave field."

The results are striking: since the electromagnetic field steadily oscillates at a very high frequency, any noise or disturbance at a different frequency results in a zero net effect. The researchers achieved an improvement by a factor of 10 in the time span during which a quantum superposition can be preserved.

Specifically, they measured a dephasing time of $T2^{*}=2.4$ milliseconds - a result that is 10-fold better than the standard qubit, allowing many more operations to be performed within the time span during which the delicate quantum information is safely preserved.

"This new 'dressed qubit' can be controlled in a variety of ways that would be impractical with an 'undressed qubit',", added Morello. "For example, it can be controlled by simply modulating the frequency of the microwave field, just like in an FM radio. The 'undressed qubit' instead requires turning the amplitude of the control fields on and off, like an AM radio.

"In some sense, this is why the dressed qubit is more immune to noise: the quantum information is controlled by the frequency, which is rock-solid, whereas the amplitude can be more easily affected by external noise".

Since the device is built upon standard silicon technology, this result paves the way to the construction of powerful and reliable quantum processors based upon the same fabrication process already used for today's computers.

The UNSW team leads the world in developing quantum computing in silicon, and Morello's team is part of the consortium of UNSW researchers who have struck a A$70 million deal between UNSW, the researchers, business and the Australian government to develop a prototype silicon quantum integrated circuit - the first step in building the world's first quantum computer in silicon.

A functional quantum computer would allow massive increases in speed and efficiency for certain computing tasks - even when compared with today's fastest silicon-based 'classical' computers. In a number of key areas - such as searching large databases, solving complicated sets of equations, and modelling atomic systems such as biological molecules and drugs - they would far surpass today's computers.They would also be enormously useful in the finance and healthcare industries, and for government, security and defence organisations.

Quantum computers could identify and develop new medicines by greatly accelerating the computer-aided design of pharmaceutical compounds (and minimising lengthy trial and error testing), and develop new, lighter and stronger materials spanning consumer electronics to aircraft. They would also make possible new types of computational applications and solutions that are beyond our ability to foresee. [21]

## Exceptionally robust quantum states found in industrially important semiconductor

Harnessing solid-state quantum bits, or qubits, is a key step toward the mass production of electronic devices based on quantum information science and technology. However, realizing a robust qubit with a long lifetime is challenging, particularly in semiconductors comprising multiple types of atoms.

The close collaboration between experiments in Prof. David Awschalom's group and theory and simulations in Prof. Giulia Galli's group, both in the Institute for Molecular Engineering, has enabled a crucial step toward solid-state qubits in industrially important semiconductors. In a paper, published Sept. 29 in Nature Communications, the two groups showed that electron qubits bound to atom-like defects in a commercial silicon carbide wafer can exhibit the longest electronic coherence times ever measured in a natural crystal.

"Quantum coherence underlies all quantum information technologies, such as quantum communication and quantum sensing. However, the coherence time in materials is eventually limited by the magnetic noise produced by the fluctuating nuclear spins in a crystal," said Hosung Seo, an IME postdoctoral researcher and the paper's lead author.

Defects in silicon carbide have recently attracted attention as potential candidates for solid-state qubits. Due to its extensive use in the optoelectronics and power electronics industries, silicon carbide also has a strong potential for mass production.

However, spin qubits in silicon carbide have been expected to have inherently short coherence times because of the high concentration of magnetic nuclei in the crystals. Counterintuitively, the electron coherence time in silicon carbide reaches 1.3 milliseconds—the longest time measured in a naturally isotopic crystal.

Based on the tight integration of theory and experiment, the two IME groups identified the key mechanisms behind the remarkably robust spin coherence in silicon carbide. They found that the binary nature of its crystal plays a central role in suppressing the magnetic noise produced by the nuclear spin fluctuation.

"Our work has important implications beyond silicon carbide. The essential physics and the dynamics responsible for the coherence found in silicon carbide, a binary crystal, may allow qubits in ternary and quaternary crystals to have even longer spin coherence times," said Abram Falk, now a researcher at IBM's T.J. Watson Research Center and the paper's primary experimental author.

Seo and Falk also emphasized that interesting host crystals with useful functionalities are normally found in binary or ternary crystals such as carbides, nitrides and oxides. The results suggest that developing defect spin qubits in complex polyatomic crystals would be a promising route to realize novel, multifunctional, quantum systems. [20]

## More stable qubits in perfectly normal silicon

The power of future quantum computers stems from the use of qubits, or quantum bits, which do not have to be either 0 or 1, but can also be 0 and 1 at the same time. It is not yet clear on which technology these qubits in quantum computers will be based, but qubits based on electron spins are looking more and more promising. It was thought that these could only be produced in the expensive semiconductor material gallium arsenide, but researchers have now discovered that the more common material silicon, the basic material of modern computer chips, is even better. Researchers from Delft, the University of Wisconsin and Ames Laboratory, led by Prof. Lieven Vandersypen of TU Delft's QuTech discovered that the stability of qubits could be maintained 100 times more effectively in silicon than in gallium arsenide.

They publishing their research in PNAS this week.

## Fragile

Because qubits can be both 1 and 0 simultaneously, a quantum computer will be able to tackle computing problems that are out of reach of the current supercomputers. The main issue for researchers is that this superposition is very fragile. 'Two numbers are very important for qubits,' explains research leader Lieven Vandersypen. 'The length of time the superposition can be maintained before it spontaneously reverts to 1 or 0 is critical for an effectively functioning quantum computer. In gallium arsenide, this is about 10 nanoseconds, but in silicon we have achieved a factor of 100 longer. Using smart technologies we were able to stretch this to 0.4 milliseconds. Although a coherence time of 0.4 milliseconds may not sound very long, for a computer it is nearly an eternity. Moreover, the gate fidelity in silicon is 10-100 times better. The gate fidelity is the measure of whether an operation you perform on a qubit will actually work.'

## Silicon

The researchers used 'standard' silicon, an extremely cheap material of which there is an almost infinite supply: it is the main ingredient of sand. Earlier research by the University of New South Wales in Australia demonstrated that isotopically purified silicon-28 can produce even better results. "Silicon naturally contains three isotopes, including the common form Si-28, and the less common form with atomic number 29. The latter form has been proven to degrade the coherence and gate fidelity considerably. Researchers believe that replacing gallium arsenide with silicon will be extremely important for the design of the quantum computer. The required technology for fabricating nanostructures in silicon has already reached an advanced stage in chip technology, and now, as the researchers hoped, silicon also proves to be a better qubit material.

## Scaling up

Researchers of TU Delft are collaborating intensively with other researchers, among others from Intel Corporation, who joined a partnership with QuTech last year.

The greatest challenge for quantum technologists now is to scale up the various qubits for use in circuits of multiple interplaying qubits. 'At least hundreds of qubits - and preferably many more - will need to work together to make a working quantum computer,' says Vandersypen. [19]

# Toward practical quantum computers: Built-in optics could enable chips that use trapped ions as quantum bits

Researchers from MIT and MIT Lincoln Laboratory report an important step toward practical quantum computers, with a paper describing a prototype chip that can trap ions in an electric field and, with built-in optics, direct laser light toward each of them.

Quantum computers are largely hypothetical devices that could perform some calculations much more rapidly than conventional computers can. Instead of the bits of classical computation, which can represent 0 or 1, quantum computers consist of quantum bits, or qubits, which can, in some sense, represent 0 and 1 simultaneously.

Although quantum systems with as many as 12 qubits have been demonstrated in the lab, building quantum computers complex enough to perform useful computations will require miniaturizing qubit technology, much the way the miniaturization of transistors enabled modern computers.

Trapped ions are probably the most widely studied qubit technology, but they've historically required a large and complex hardware apparatus. In today's Nature Nanotechnology, researchers from MIT and MIT Lincoln Laboratory report an important step toward practical quantum computers, with a paper describing a prototype chip that can trap ions in an electric field and, with built-in optics, direct laser light toward each of them.

"If you look at the traditional assembly, it's a barrel that has a vacuum inside it, and inside that is this cage that's trapping the ions. Then there's basically an entire laboratory of external optics that are guiding the laser beams to the assembly of ions," says Rajeev Ram, an MIT professor of electrical engineering and one of the senior authors on the paper. "Our vision is to take that external laboratory and miniaturize much of it onto a chip."

## Caged in

The Quantum Information and Integrated Nanosystems group at Lincoln Laboratory was one of several research groups already working to develop simpler, smaller ion traps known as surface traps. A standard ion trap looks like a tiny cage, whose bars are electrodes that produce an electric field. Ions line up in the center of the cage, parallel to the bars. A surface trap, by contrast, is a chip with electrodes embedded in its surface. The ions hover 50 micrometers above the electrodes.

Cage traps are intrinsically limited in size, but surface traps could, in principle, be extended indefinitely. With current technology, they would still have to be held in a vacuum chamber, but they would allow many more qubits to be crammed inside.

"We believe that surface traps are a key technology to enable these systems to scale to the very large number of ions that will be required for large-scale quantum computing," says Jeremy Sage, who together with John Chiaverini leads Lincoln Laboratory's trapped-ion quantum-information-processing project. "These cage traps work very well, but they really only work for maybe 10 to 20 ions, and they basically max out around there."

Performing a quantum computation, however, requires precisely controlling the energy state of every qubit independently, and trapped-ion qubits are controlled with laser beams. In a surface trap, the ions are only about 5 micrometers apart. Hitting a single ion with an external laser, without affecting its neighbors, is incredibly difficult; only a few groups had previously attempted it, and their techniques weren't practical for large-scale systems.

### Getting onboard

That's where Ram's group comes in. Ram and Karan Mehta, an MIT graduate student in electrical engineering and first author on the new paper, designed and built a suite of on-chip optical components that can channel laser light toward individual ions. Sage, Chiaverini, and their Lincoln Lab colleagues Colin Bruzewicz and Robert McConnell retooled their surface trap to accommodate the integrated optics without compromising its performance. Together, both groups designed and executed the experiments to test the new system.

"Typically, for surface electrode traps, the laser beam is coming from an optical table and entering this system, so there's always this concern about the beam vibrating or moving," Ram says. "With photonic integration, you're not concerned about beam-pointing stability, because it's all on the same chip that the electrodes are on. So now everything is registered against each other, and it's stable."

The researchers' new chip is built on a quartz substrate. On top of the quartz is a network of silicon nitride "waveguides," which route laser light across the chip.

Above the waveguides is a layer of glass, and on top of that are the niobium electrodes. Beneath the holes in the electrodes, the waveguides break into a series of sequential ridges, a "diffraction grating" precisely engineered to direct light up through the holes and concentrate it into a beam narrow enough that it will target a single ion, 50 micrometers above the surface of the chip.

### Prospects

With the prototype chip, the researchers were evaluating the performance of the diffraction gratings and the ion traps, but there was no mechanism for varying the amount of light delivered to each ion. In ongoing work, the researchers are investigating the addition of light modulators to the diffraction gratings, so that different qubits can simultaneously receive light of different, time-varying intensities. That would make programming the qubits more efficient, which is vital in a practical quantum information system, since the number of quantum operations the system can perform is limited by the "coherence time" of the qubits. [18]

## Programmable ions set the stage for general-purpose quantum computers

An ion trap with four segmented blade electrodes used to trap a linear chain of atomic ions for quantum information processing. Each ion is addressed optically for individual control and readout using the high optical access of the trap.

Quantum computers promise speedy solutions to some difficult problems, but building large-scale, general-purpose quantum devices is a problem fraught with technical challenges.

To date, many research groups have created small but functional quantum computers. By combining a handful of atoms, electrons or superconducting junctions, researchers now regularly demonstrate quantum effects and run simple quantum algorithms—small programs dedicated to solving particular problems.

But these laboratory devices are often hard-wired to run one program or limited to fixed patterns of interactions between the quantum constituents. Making a quantum computer that can run arbitrary algorithms requires the right kind of physical system and a suite of programming tools. Atomic ions, confined by fields from nearby electrodes, are among the most promising platforms for meeting these needs.

In a paper published as the cover story in Nature on August 4, researchers working with Christopher Monroe, a Fellow of the Joint Quantum Institute and the Joint Center for Quantum Information and Computer Science at the University of Maryland, introduced the first fully programmable and reconfigurable quantum computer module. The new device, dubbed a module because of its potential to connect with copies of itself, takes advantage of the unique properties offered by trapped ions to run any algorithm on five quantum bits, or qubits—the fundamental unit of information in a quantum computer.

"For any computer to be useful, the user should not be required to know what's inside," Monroe says. "Very few people care what their iPhone is actually doing at the physical level. Our experiment brings high-quality quantum bits up to a higher level of functionality by allowing them to be programmed and reconfigured in software."

The new module builds on decades of research into trapping and controlling ions. It uses standard techniques but also introduces novel methods for control and measurement. This includes manipulating many ions at once using an array of tightly-focused laser beams, as well as dedicated detection channels that watch for the glow of each ion.

"These are the kinds of discoveries that the NSF Physics Frontiers Centers program is intended to enable," says Jean Cottam Allen, a program director in the National Science Foundation's physics division. "This work is at the frontier of quantum computing, and it's helping to lay a foundation and bring practical quantum computing closer to being a reality."

The team tested their module on small instances of three problems that quantum computers are known to solve quickly. Having the flexibility to test the module on a variety of problems is a major step forward, says Shantanu Debnath, a graduate student at JQI and the paper's lead author. "By directly connecting any pair of qubits, we can reconfigure the system to implement any algorithm," Debnath says. "While it's just five qubits, we know how to apply the same technique to much larger collections."

At the module's heart, though, is something that's not even quantum: A database stores the best shapes for the laser pulses that drive quantum logic gates, the building blocks of quantum algorithms. Those shapes are calculated ahead of time using a regular computer, and the module uses software to translate an algorithm into the pulses in the database.

## Putting the pieces together

Every quantum algorithm consists of three basic ingredients. First, the qubits are prepared in a particular state; second, they undergo a sequence of quantum logic gates; and last, a quantum measurement extracts the algorithm's output.

The module performs these tasks using different colors of laser light. One color prepares the ions using a technique called optical pumping, in which each qubit is illuminated until it sits in the proper quantum energy state. The same laser helps read out the quantum state of each atomic ion at the end of the process. In between, a separate laser strikes the ions to drive quantum logic gates.

These gates are like the switches and transistors that power ordinary computers. Here, lasers push on the ions and couple their internal qubit information to their motion, allowing any two ions in the module to interact via their strong electrical repulsion. Two ions from across the chain notice each other through this electrical interaction, just as raising and releasing one ball in a Newton's cradle transfers energy to the other side.

The re-configurability of the laser beams is a key advantage, Debnath says. "By reducing an algorithm into a series of laser pulses that push on the appropriate ions, we can reconfigure the wiring between these qubits from the outside," he says. "It becomes a software problem, and no other quantum computing architecture has this flexibility."

To test the module, the team ran three different quantum algorithms, including a demonstration of a Quantum Fourier Transform (QFT), which finds how often a given mathematical function repeats. It is a key piece in Shor's quantum factoring algorithm, which would break some of the most widely-used security standards on the internet if run on a big enough quantum computer.

Two of the algorithms ran successfully more than 90% of the time, while the QFT topped out at a 70% success rate. The team says that this is due to residual errors in the pulse-shaped gates as well as systematic errors that accumulate over the course of the computation, neither of which appear fundamentally insurmountable.

They note that the QFT algorithm requires all possible two-qubit gates and should be among the most complicated quantum calculations.

The team believes that eventually more qubits—perhaps as many as 100—could be added to their quantum computer module. It is also possible to link separate modules together, either by physically moving the ions or by using photons to carry information between them.

Although the module has only five qubits, its flexibility allows for programming quantum algorithms that have never been run before, Debnath says. The researchers are now looking to run algorithms on a module with more qubits, including the demonstration of quantum error correction routines as part of a project funded by the Intelligence Advanced Research Projects Activity. [17]

## Realizing quantum bits

A research team from Germany, France and Switzerland has realised quantum bits, short qubits, in a new form. One day, they might become the information units of quantum computers.

To date, researchers have realised qubits in the form of individual electrons (aktuell.ruhr-uni-bochum.de/pm2012/pm00090.html.en). However, this led to interferences and rendered the information carriers difficult to programme and read. The group has solved this problem by utilising electron holes as qubits, rather than electrons.

A report has been published in the journal Nature Materials by a team of researchers from Ruhr-Universität Bochum, the University of Basel, and Lyon University; among its contributors were the two Bochum-based researchers Prof Dr Andreas Wieck and Dr Arne Ludwig from the Chair of Applied Solid State Physics. The project was headed by the Swiss researcher Prof Dr Richard Warburton.

### Electrons as qubits

In order to realise qubits in the form of electrons, an electron is locked in a tiny semiconductor volume, the so-called quantum dot. The spin turns the electron into a small permanent magnet. Researchers are able to manipulate the spin via an external magnetic field and initiate precession. The direction of the spin is used to code information.

The problem: the nuclear spins of the surrounding atoms also generate magnetic fields, which distort the external magnetic field in a random, unpredictable manner. This, in turn, interferes with programming and reading qubits. Consequently, the team searched for another method. The solution: rather than locking individual electrons in the quantum dot, the team removed specific electrons. Thus, positively charged vacancies were generated in the electron structure, so-called electron holes.

### Advantages of electron holes

Electron holes have a spin, too. Researchers can manipulate it via the magnetic field in order to code information. As the holes are positively charged, they are decoupled from the nuclei of the surrounding atoms, which are likewise positively charged. This is why they are virtually immune against the interfering forces of the nuclear spin.

"This is important if we one day want to manufacture reproducible components that are based on quantum bits," explains Andreas Wieck. However, this method is only applicable at low temperatures, as the holes are more likely to be disturbed by warmth than the electrons.

At Ruhr-Universität, researchers are able to generate quantum dots of outstanding quality. The experiment could be conducted thanks to a structural design developed by Arne Ludwig in Basel and subsequently realised at the RUB Department headed by Andreas Wieck. It enabled the researcher to apply not just individual electrons to quantum dots, but also electron holes. Sascha René Valentin, PhD student from Bochum, utilised the technique for the purpose of the current study. [16]

## Russian physicists discover a new approach for building quantum computers

Physicists from MIPT and the Russian Quantum Center have developed an easier method to create a universal quantum computer using multilevel quantum systems (qudits), each one of which is able to work with multiple "conventional" quantum elements – qubits.

Professor Vladimir Man'ko, Aleksey Fedorov and Evgeny Kiktenko have published the results of their studies of multilevel quantum systems in a series of papers in Physical Review A, Physics Letters A, and also Quantum Measurements and Quantum Metrology.

"In our studies, we demonstrated that correlations similar to those used for quantum information technologies in composite quantum systems also occur in non-composite systems – systems which we suppose may be easier to work with in certain cases. In our latest paper we proposed a method of using entanglement between internal degrees of freedom of a single eight-level system to implement the protocol of quantum teleportation, which was previously implemented experimentally for a system of three two-level systems," says Vladimir Man'ko.

Quantum computers, which promise to bring about a revolution in computer technology, could be built from elementary processing elements called quantum bits – qubits. While elements of classical computers (bits) can only be in two states (logic zero and logic one), qubits are based on quantum objects that can be in a coherent superposition of two states, which means that they can encode the intermediate states between logic zero and one. When a qubit is measured, the outcome is either a zero or a one with a certain probability (determined by the laws of quantum mechanics).

In a quantum computer, the initial condition of a particular problem is written in the initial state of the qubit system, then the qubits enter into a special interaction (determined by the specific problem). Finally, the user reads the answer to the problem by measuring the final states of the quantum bits.

Quantum computers will be able to solve certain problems that are currently far beyond the reach of even the most powerful classical supercomputers. In cryptography, for example, the time required for a conventional computer to break the RSA algorithm, which is based on the prime factorization of large numbers, would be comparable to the age of the universe. A quantum computer, on the other hand, could solve the problem in a matter of minutes.

However, there is a significant obstacle standing in the way of a quantum revolution – the instability of quantum states. Quantum objects that are used to create qubits – ions, electrons, Josephson junctions etc. can only maintain a certain quantum state for a very short time. However, calculations not only require that qubits maintain their state, but also that they interact with one another. Physicists all over the world are trying to extend the lifespan of qubits. Superconducting qubits used to "survive" only for a few nanoseconds, but now they can be kept for milliseconds before decoherence – which is closer to the time required for calculations.

In a system with dozens or hundreds of qubits, however, the problem is fundamentally more complex.

Man'ko, Fedorov, and Kiktenko began to look at the problem from the other way around – rather than try to maintain the stability of a large qubit system, they tried to increase the dimensions of the systems required for calculations. They are investigating the possibility of using qudits rather than qubits for calculations. Qudits are quantum objects in which the number of possible states (levels) is greater than two (their number is denoted by the letter D). There are qutrits, which have three states; ququarts, which have four states, etc. Algorithms are now actively being studied in which the use of qudits could prove to be more beneficial than using qubits.

"A qudit with four or five levels is able to function as a system of two "ordinary" qubits, and eight levels is enough to imitate a three-qubit system. At first, we saw this as a mathematical equivalence allowing us to obtain new entropic correlations. For example, we obtained the value of mutual information (the measure of correlation) between virtual qubits isolated in a state space of a single four-level system," says Fedorov.

He and his colleagues demonstrated that on one qudit with five levels, created using an artificial atom, it is possible to perform full quantum computations—in particular, the realization of the Deutsch algorithm. This algorithm is designed to test the values of a large number of binary variables.

It can be called the fake coin algorithm: imagine that you have a number of coins, some of which are fake – they have the same image on the obverse and reverse sides. To find these coins using the "classical method", you have to look at both sides. With the Deutsch algorithm, you "merge" the obverse and reverse sides of the coin and you can then see a fake coin by only looking at one side.

The idea of using multilevel systems to emulate multi-qubit processors was proposed earlier in the work of Russian physicists from the Kazan Physical-Technical Institute. To run a two-qubit Deutsch algorithm, for example, they proposed using a nuclear spin of 3/2 with four different states. In recent years, however, experimental progress in creating qudits in superconducting circuits has shown that they have a number of advantages.

However, superconducting circuits require five levels: the last level performs an ancillary role to allow for a complete set of all possible quantum operations.

"We are making significant progress, because in certain physical implementations, it is easier to control multilevel qudits than a system of the corresponding number of qubits, and this means that we are one step closer to creating a full-fledged quantum computer. Multilevel elements offer advantages in other quantum technologies too, such as quantum cryptography," says Fedorov. [15]

## Precise atom implants in silicon provide a first step toward practical quantum computers

Sandia National Laboratories has taken a first step toward creating a practical quantum computer, able to handle huge numbers of computations instantaneously.

Here's the recipe:

A "donor" atom propelled by an ion beam is inserted very precisely in microseconds into an industry-standard silicon substrate.

The donor atom—in this case, antimony (Sb) —carries one more electron (five) than a silicon atom (four). Because electrons pair up, the odd Sb electron remains free.

Instruments monitor the free electron to determine if, under pressure from an electromagnetic field, it faces up or down, a property called "spin." Electrons in this role, called qubits, signal "yes" or "no" from the subatomic scale, and so act as the information bearers of a quantum computer.

The ability to precisely place a donor atom in silicon means that it should be possible to insert a second donor atom just far enough away, in the "Goldilocks" zone where communication is neither lost through distance nor muffled by too-close proximity. Sandia will try to do this later this year, said lead researcher Meenakshi Singh, a postdoctoral fellow. Qubits "talking" to each other are the basis of quantum computing circuits.

The successful Sandia first step, reported in Applied Physics Letters, makes use of electromagnetic forces provided by a neighboring quantum dot pre-embedded in the silicon. The quantum dot—itself a tiny sea of electrons—contains a variety of energy levels and operates like a transistor to block or pass the qubit.

If an available dot energy level is compatible with the electron, the transistor gate is effectively open and the electron jumps into the dot. If not, the qubit stays put. That action is reported back to the surface by a photodiode sensor sensitive to current flows rather than photon movement. Because of the multiple "gates" in the quantum dot, many qubits at different energy levels could pass through the transistor, or be denied passage, theoretically making possible an extremely wide array of information processing.

"Our method is promising because, since it reads the electron's spin rather than its electrical charge, its information is not swallowed by background static and instead remains coherent for a relatively long time," Singh said. "Also, we use silicon as our basic material, for which commercial fabrication technologies are already developed, rather than employing superconducting components that can be expensive."

A third unique quality of the Sandia method is the precise and rapid placement of donor atoms exactly where they should be, placed in microseconds within nanometers of their target, instead of a buckshot approach that places qubits only where they statistically average to Goldilocks distances.

While components of this experiment have been demonstrated before, this is the first time all have worked together on a single chip, with researchers knowing accurately the vertical and horizontal placement of each qubit, instead of mere statistical approximations.

Sandia researcher and paper author Mike Lilly expects "the Sandia technique will allow fabrication of more complicated multi-qubit structures and do so at higher yield than existing donor implant approaches."

Components of the successful silicon device were fabricated in Sandia's Microsystems and Engineering Sciences Application (MESA) facility. The donor atoms were placed at Sandia's Ion Beam Laboratory. Experiment measurements were made at the Sandia/Los Alamos Center for Integrated Nanotechnologies, a user facility supported by DOE's Office of Basic Energy Sciences.

The method in its entirety is straightforward but requires a range of technical expertise and machinery, Singh said. "We used ion beams, silicon fabrication facilities, low-temperature measurements and simulations. It's hard to find a non-commercial place outside of a national lab that can do all of this." [14]

## Team demonstrates large-scale technique to produce quantum dots

A method to produce significant amounts of semiconducting nanoparticles for light-emitting displays, sensors, solar panels and biomedical applications has gained momentum with a demonstration by researchers at the Department of Energy's Oak Ridge National Laboratory.

While zinc sulfide nanoparticles - a type of quantum dot that is a semiconductor - have many potential applications, high cost and limited availability have been obstacles to their widespread use. That could change, however, because of a scalable ORNL technique outlined in a paper published in Applied Microbiology and Biotechnology.

Unlike conventional inorganic approaches that use expensive precursors, toxic chemicals, high temperatures and high pressures, a team led by ORNL's Ji-Won Moon used bacteria fed by inexpensive sugar at a temperature of 150 degrees Fahrenheit in 25- and 250-gallon reactors. Ultimately, the team produced about three-fourths of a pound of zinc sulfide nanoparticles - without process optimization, leaving room for even higher yields.

The ORNL biomanufacturing technique is based on a platform technology that can also produce nanometer-size semiconducting materials as well as magnetic, photovoltaic, catalytic and phosphor materials. Unlike most biological synthesis technologies that occur inside the cell, ORNL's biomanufactured quantum dot synthesis occurs outside of the cells. As a result, the nanomaterials are produced as loose particles that are easy to separate through simple washing and centrifuging.

The results are encouraging, according to Moon, who also noted that the ORNL approach reduces production costs by approximately 90 percent compared to other methods.

"Since biomanufacturing can control the quantum dot diameter, it is possible to produce a wide range of specifically tuned semiconducting nanomaterials, making them attractive for a variety of applications that include electronics, displays, solar cells, computer memory, energy storage, printed electronics and bio-imaging," Moon said.

Successful biomanufacturing of light-emitting or semiconducting nanoparticles requires the ability to control material synthesis at the nanometer scale with sufficiently high reliability, reproducibility and yield to be cost effective. With the ORNL approach, Moon said that goal has been achieved.

Researchers envision their quantum dots being used initially in buffer layers of photovoltaic cells and other thin film-based devices that can benefit from their electro-optical properties as light-emitting materials. [13]

## Superfast light source made from artificial atom

All light sources work by absorbing energy – for example, from an electric current – and emit energy as light. But the energy can also be lost as heat and it is therefore important that the light sources emit the light as quickly as possible, before the energy is lost as heat. Superfast light sources can be used, for example, in laser lights, LED lights and in single-photon light sources for quantum technology. New research results from the Niels Bohr Institute show that light sources can be made much faster by using a principle that was predicted theoretically in 1954. The results are published in the scientific journal, Physical Review Letters.

Researchers at the Niels Bohr Institute are working with quantum dots, which are a kind of artificial atom that can be incorporated into optical chips. In a quantum dot, an electron can be excited (i.e. jump up), for example, by shining a light on it with a laser and the electron leaves a 'hole'. The stronger the interaction between light and matter, the faster the electron decays back into the hole and the faster the light is emitted.

But the interaction between light and matter is naturally very weak and it makes the light sources very slow to emit light and this can reduce energy efficiency.

Already in 1954, the physicist Robert Dicke predicted that the interaction between light and matter could be increased by having a number of atoms that 'share' the excited state in a quantum superposition.

### Quantum speed up

Demonstrating this effect has been challinging so far because the atoms either come so close together that they bump into each other or they are so far apart that the quantum speed up does not work. Researchers at the Niels Bohr Institute have now finally demonstrated the effect experimentally, but in an entirely different physical system than Dicke had in mind. They have shown this so-called superradiance for photons emitted from a single quantum dot.

"We have developed a quantum dot so that it behaves as if it was comprised of five quantum dots, which means that the light is five times stronger. This is due to the attraction between the electron and the hole. But what is special is that the quantum dot still only emits a single photon at a time. It is an outstanding single-photon source," says Søren Stobbe, who is an associate professor in the Quantum Photonic research group at the Niels Bohr Institute at the University of Copenhagen and led the project. The experiment was carried out in collaboration with Professor David Ritchie's research group at the University of Cambridge, who have made the quantum dots.

Petru Tighineanu, a postdoc in the Quantum Photonics research group at the Niels Bohr Institute, has carried out the experiments and he explains the effect as such, that the atoms are very small and light is very 'big' because of its long wavelength, so the light almost cannot 'see' the atoms – like a lorry that is driving on a road and does not notice a small pebble. But if many pebbles become a larger stone, the lorry will be able to register it and then the interaction becomes much more dramatic. In the same way, light interacts much more strongly with the quantum dot if the quantum dot contains the special superradiant quantum state, which makes it look much bigger.

### Increasing the light-matter interaction

"The increased light-matter interaction makes the quantum dots more robust in regards to the disturbances that are found in all materials, for example, acoustic oscillations. It helps to make the photons more uniform and is important for how large you can build future quantum computers," says Søren Stobbe.

He adds that it is actually the temperature, which is only a few degrees above absolute zero, that limits how fast the light emissions can remain in their current experiments. In the long term, they will study the quantum dots at even lower temperatures, where the effects could be very dramatic. [12]

## Single-photon source is efficient and indistinguishable

Devices that emit one – and only one – photon on demand play a central role in light-based quantum-information systems. Each photon must also be emitted in the same quantum state, which makes each photon indistinguishable from all the others. This is important because the quantum state of the photon is used to carry a quantum bit (qubit) of information.

Quantum dots are tiny pieces of semiconductor that show great promise as single-photon sources. When a laser pulse is fired at a quantum dot, an electron is excited between two distinct energy levels. The excited state then decays to create a single photon with a very specific energy. However, this process can involve other electron excitations that result in the emission of photons with a wide range of energies – photons that are therefore not indistinguishable.

## Exciting dots

This problem can be solved by exciting the quantum dot with a pulse of light at the same energy as the emitted photon. This is called resonance fluorescence, and has been used to create devices that are very good at producing indistinguishable single photons. However, this process is inefficient, and only produces a photon about 6% of the time.

Now, Chaoyang Lu, Jian-Wei Pan and colleagues at the University of Science and Technology of China have joined forces with researchers in Denmark, Germany and the UK to create a resonance-fluorescence-based source that emits a photon 66% of the time when it is prompted by a laser pulse. Of these photons, 99.1% are solo and 98.5% are in indistinguishable quantum states – with both figures of merit being suitable for applications in quantum-information systems.

Lu told physicsworld.com that nearly all of the laser pulses that strike the source produce a photon, but about 34% of these photons are unable to escape the device. The device was operated at a laser-pulse frequency of 81 MHz and a pulse power of 24 nW, which is a much lower power requirement than other quantum-dot-based sources.

## Quantum sandwich

The factor-of-ten improvement in efficiency was achieved by sandwiching a quantum dot in the centre of a "micropillar" created by stacking 40 disc-like layers (see figure). Each layer is a "distributed Bragg reflector", which is a pair of mirrors that together have a thickness of one quarter the wavelength of the emitted photons.

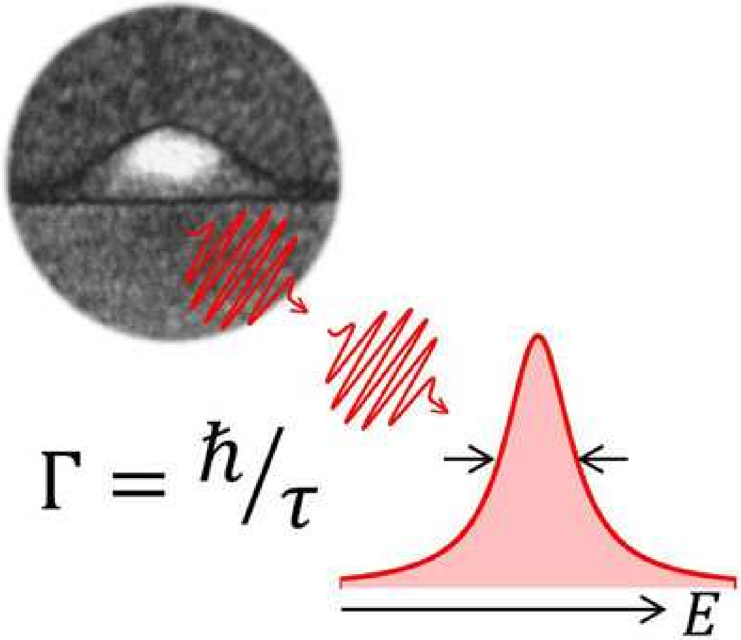
The micropillar is about 2.5 µm in diameter and about 10 µm tall, and it allowed the team to harness the "Purcell effect", whereby the rate of fluorescence is increased significantly when the emitter is placed in a resonant cavity.

Lu says that the team is already thinking about how the photon sources could be used to perform boson sampling (see "'Boson sampling' offers shortcut to quantum computing"). This involves a network of beam splitters that converts one set of photons arriving at a number of parallel input ports into a second set leaving via a number of parallel outputs. The "result" of the computation is the probability that a certain input configuration will lead to a certain output. This result cannot be easily calculated using a conventional computer, and this has led some physicists to suggest that boson sampling could be used to solve practical problems that would take classical computers vast amounts of time to solve.

Other possible applications for the source are the quantum teleportation of three properties of a quantum system – the current record is two properties and is held by Lu and Pan – or quantum cryptography.

The research is described in Physical Review Letters. [11]

## Semiconductor quantum dots as ideal single-photon source




A single-photon source never emits two or more photons at the same time. Single photons are important in the field of quantum information technology where, for example, they are used in quantum computers. Alongside the brightness and robustness of the light source, the indistinguishability of the photons is especially crucial. In particular, this means that all photons must be the same color. Creating such a source of identical single photons has proven very difficult in the past.

However, quantum dots made of semiconductor materials are offering new hope. A quantum dot is a collection of a few hundred thousand atoms that can form itself into a semiconductor under certain conditions. Single electrons can be captured in these quantum dots and locked into a very small area. An individual photon is emitted when an engineered quantum state collapses.

### Noise in the semiconductor

A team of scientists led by Dr. Andreas Kuhlmann and Prof. Richard J. Warburton from the University of Basel have already shown in past publications that the indistinguishability of the photons is reduced by the fluctuating nuclear spin of the quantum dot atoms. For the first time ever, the scientists have managed to control the nuclear spin to such an extent that even photons sent out at very large intervals are the same color.

Quantum cryptography and quantum communication are two potential areas of application for single-photon sources. These technologies could make it possible to perform calculations that are far beyond the capabilities of today's computers. [10]

## How to Win at Bridge Using Quantum Physics

Contract bridge is the chess of card games. You might know it as some stuffy old game your grandparents play, but it requires major brainpower, and preferably an obsession with rules and strategy. So how to make it even geekier? Throw in some quantum mechanics to try to gain a competitive advantage. The idea here is to use the quantum magic of entangled photons–which are essentially twins, sharing every property–to transmit two bits of information to your bridge partner for the price of one. Understanding how to do this is not an easy task, but it will help elucidate some basic building blocks of quantum information theory. It's also kind of fun to consider whether or not such tactics could ever be allowed in professional sports. [6]

## Quantum Information

In quantum mechanics, quantum information is physical information that is held in the "state" of a quantum system. The most popular unit of quantum information is the qubit, a two-level quantum system. However, unlike classical digital states (which are discrete), a two-state quantum system can actually be in a superposition of the two states at any given time.

Quantum information differs from classical information in several respects, among which we note the following:

However, despite this, the amount of information that can be retrieved in a single qubit is equal to one bit. It is in the processing of information (quantum computation) that a difference occurs.

The ability to manipulate quantum information enables us to perform tasks that would be unachievable in a classical context, such as unconditionally secure transmission of information. Quantum information processing is the most general field that is concerned with quantum information. There are certain tasks which classical computers cannot perform "efficiently" (that is, in polynomial time) according to any known algorithm. However, a quantum computer can compute the answer to some of these problems in polynomial time; one well-known example of this is Shor's factoring algorithm. Other algorithms can speed up a task less dramatically - for example, Grover's search algorithm which gives a quadratic speed-up over the best possible classical algorithm.

Quantum information, and changes in quantum information, can be quantitatively measured by using an analogue of Shannon entropy. Given a statistical ensemble of quantum mechanical systems with the density matrix S, it is given by.

Many of the same entropy measures in classical information theory can also be generalized to the quantum case, such as the conditional quantum entropy. [7]

## Heralded Qubit Transfer

Optical photons would be ideal carriers to transfer quantum information over large distances. Researchers envisage a network where information is processed in certain nodes and transferred between them via photons. However, inherent losses in long-distance networks mean that the information transfer is subject to probabilistic errors, making it hard to know whether the transfer of a qubit of information has been successful. Now Gerhard Rempe and colleagues from the Max Planck Institute for Quantum Optics in Germany have developed a new protocol that solves this problem through a strategy that “heralds” the accurate transfer of quantum information at a network node.

The method developed by the researchers involves transferring a photonic qubit to an atomic qubit trapped inside an optical cavity. The photon-atom quantum information transfer is initiated via a quantum “logic-gate” operation, performed by reflecting the photon from the atom-cavity system, which creates an entangled atom-photon state. The detection of the reflected photon then collapses the atom into a definite state. This state can be one of two possibilities, depending on the photonic state detected: Either the atom is in the initial qubit state encoded in the photon and the transfer process is complete, or the atom is in a rotated version of this state. The authors were able to show that the roles of the atom and photon could be reversed. Their method could thus be used as a quantum memory that stores (photon-to-atom state transfer) and recreates (atom-to-photon state transfer) a single-photon polarization qubit. [9]

## Quantum Teleportation

Quantum teleportation is a process by which quantum information (e.g. the exact state of an atom or photon) can be transmitted (exactly, in principle) from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location. Because it depends on classical communication, which can proceed no faster than the speed of light, it cannot be used for superluminal transport or communication of classical bits. It also cannot be used to make copies of a system, as this violates the no-cloning theorem. Although the name is inspired by the teleportation commonly used in fiction, current technology provides no possibility of anything resembling the fictional form of teleportation. While it is possible to teleport one or more qubits of information between two (entangled) atoms, this has not yet been achieved between molecules or anything larger. One may think of teleportation either as a kind of transportation, or as a kind of communication; it provides a way of transporting a qubit from one location to another, without having to move a physical particle along with it.

The seminal paper first expounding the idea was published by C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres and W. K. Wootters in 1993. Since then, quantum teleportation has been realized in various physical systems. Presently, the record distance for quantum teleportation is 143 km (89 mi) with photons, and 21 m with material systems. In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

## Quantum Computing

A team of electrical engineers at UNSW Australia has observed the unique quantum behavior of a pair of spins in silicon and designed a new method to use them for "2-bit" quantum logic operations.

These milestones bring researchers a step closer to building a quantum computer, which promises dramatic data processing improvements.

Quantum bits, or qubits, are the building blocks of quantum computers. While many ways to create a qubits exist, the Australian team has focused on the use of single atoms of phosphorus, embedded inside a silicon chip similar to those used in normal computers.

The first author on the experimental work, PhD student Juan Pablo Dehollain, recalls the first time he realized what he was looking at.

"We clearly saw these two distinct quantum states, but they behaved very differently from what we were used to with a single atom. We had a real 'Eureka!' moment when we realized what was happening – we were seeing in real time the `entangled' quantum states of a pair of atoms." [5]

## Quantum Entanglement

Measurements of physical properties such as position, momentum, spin, polarization, etc. performed on entangled particles are found to be appropriately correlated. For example, if a pair of particles is generated in such a way that their total spin is known to be zero, and one particle is found to have clockwise spin on a certain axis, then the spin of the other particle, measured on the same axis, will be found to be counterclockwise. Because of the nature of quantum measurement, however, this behavior gives rise to effects that can appear paradoxical: any measurement of a property of a particle can be seen as acting on that particle (e.g. by collapsing a number of superimposed states); and in the case of entangled particles, such action must be on the entangled system as a whole. It thus appears that one particle of an entangled pair "knows" what measurement has been performed on the other, and with what outcome, even though there is no known means for such information to be communicated between the particles, which at the time of measurement may be separated by arbitrarily large distances. [4]

## The Bridge

The accelerating electrons explain not only the Maxwell Equations and the Special Relativity, but the Heisenberg Uncertainty Relation, the wave particle duality and the electron's spin also, building the bridge between the Classical and Quantum Theories. [1]

### Accelerating charges

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field. In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion.
The same thing happens on the atomic scale giving a dp impulse difference and a dx way difference between the different part of the not point like particles.

### Relativistic effect

Another bridge between the classical and quantum mechanics in the realm of relativity is that the charge distribution is lowering in the reference frame of the accelerating charges linearly: $ds/dt = at$ (time coordinate), but in the reference frame of the current it is parabolic: $s = a/2\ t^2$ (geometric coordinate).

## Heisenberg Uncertainty Relation

In the atomic scale the Heisenberg uncertainty relation gives the same result, since the moving electron in the atom accelerating in the electric field of the proton, causing a charge distribution on delta x position difference and with a delta p momentum difference such a way that they product is about the half Planck reduced constant. For the proton this delta x much less in the nucleon, than in the orbit of the electron in the atom, the delta p is much higher because of the greater proton mass.

This means that the electron and proton are not point like particles, but has a real charge distribution.

## Wave – Particle Duality

The accelerating electrons explains the wave – particle duality of the electrons and photons, since the elementary charges are distributed on delta x position with delta p impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electrons electromagnetic field with the same distribution of wavelengths.

## Atomic model

The constantly accelerating electron in the Hydrogen atom is moving on the equipotential line of the proton and it's kinetic and potential energy will be constant. Its energy will change only when it is changing its way to another equipotential line with another value of potential energy or getting free with enough kinetic energy. This means that the Rutherford-Bohr atomic model is right and only that changing acceleration of the electric charge causes radiation, not the steady acceleration. The steady acceleration of the charges only creates a centric parabolic steady electric field around the charge, the magnetic field. This gives the magnetic moment of the atoms, summing up the proton and electron magnetic moments caused by their circular motions and spins.

## The Relativistic Bridge

Commonly accepted idea that the relativistic effect on the particle physics it is the fermions' spin - another unresolved problem in the classical concepts. If the electric charges can move only with accelerated motions in the self maintaining electromagnetic field, once upon a time they would reach the velocity of the electromagnetic field. The resolution of this problem is the spinning particle, constantly accelerating and not reaching the velocity of light because the acceleration is radial. One origin of the Quantum Physics is the Planck Distribution Law of the electromagnetic oscillators, giving equal intensity for 2 different wavelengths on any temperature. Any of these two wavelengths will give equal intensity diffraction patterns, building different asymmetric constructions, for example proton - electron structures (atoms), molecules, etc. Since the particles are centers of diffraction patterns they also have particle – wave duality as the electromagnetic waves have. [2]

## The weak interaction

The weak interaction transforms an electric charge in the diffraction pattern from one side to the other side, causing an electric dipole momentum change, which violates the CP and time reversal symmetry. The Electroweak Interaction shows that the Weak Interaction is basically electromagnetic in nature. The arrow of time shows the entropy grows by changing the temperature dependent diffraction patterns of the electromagnetic oscillators.

Another important issue of the quark model is when one quark changes its flavor such that a linear oscillation transforms into plane oscillation or vice versa, changing the charge value with 1 or -1. This kind of change in the oscillation mode requires not only parity change, but also charge and time changes (CPT symmetry) resulting a right handed anti-neutrino or a left handed neutrino.

The right handed anti-neutrino and the left handed neutrino exist only because changing back the quark flavor could happen only in reverse, because they are different geometrical constructions, the u is 2 dimensional and positively charged and the d is 1 dimensional and negatively charged. It needs also a time reversal, because anti particle (anti neutrino) is involved.

The neutrino is a 1/2spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with ½ spin. The weak interaction changes the entropy since more or less particles will give more or less freedom of movement. The entropy change is a result of temperature change and breaks the equality of oscillator diffraction intensity of the Maxwell–Boltzmann statistics. This way it changes the time coordinate measure and makes possible a different time dilation as of the special relativity.

The limit of the velocity of particles as the speed of light appropriate only for electrical charged particles, since the accelerated charges are self maintaining locally the accelerating electric force. The neutrinos are CP symmetry breaking particles compensated by time in the CPT symmetry, that is the time coordinate not works as in the electromagnetic interactions, consequently the speed of neutrinos is not limited by the speed of light.

The weak interaction T-asymmetry is in conjunction with the T-asymmetry of the second law of thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes the weak interaction, for example the Hydrogen fusion.

Probably because it is a spin creating movement changing linear oscillation to 2 dimensional oscillation by changing d to u quark and creating anti neutrino going back in time relative to the proton and electron created from the neutron, it seems that the anti neutrino fastest then the velocity of the photons created also in this weak interaction?

A quark flavor changing shows that it is a reflection changes movement and the CP- and T- symmetry breaking!!! This flavor changing oscillation could prove that it could be also on higher level such as atoms, molecules, probably big biological significant molecules and responsible on the aging of the life.

Important to mention that the weak interaction is always contains particles and antiparticles, where the neutrinos (antineutrinos) present the opposite side. It means by Feynman's interpretation that these particles present the backward time and probably because this they seem to move faster than the speed of light in the reference frame of the other side.

Finally since the weak interaction is an electric dipole change with ½ spin creating; it is limited by the velocity of the electromagnetic wave, so the neutrino's velocity cannot exceed the velocity of light.

### The General Weak Interaction

The Weak Interactions T-asymmetry is in conjunction with the T-asymmetry of the Second Law of Thermodynamics, meaning that locally lowering entropy (on extremely high temperature) causes for example the Hydrogen fusion. The arrow of time by the Second Law of Thermodynamics shows the increasing entropy and decreasing information by the Weak Interaction, changing the temperature dependent diffraction patterns. A good example of this is the neutron decay, creating more particles with less known information about them.

The neutrino oscillation of the Weak Interaction shows that it is a general electric dipole change and it is possible to any other temperature dependent entropy and information changing diffraction pattern of atoms, molecules and even complicated biological living structures.

We can generalize the weak interaction on all of the decaying matter constructions, even on the biological too. This gives the limited lifetime for the biological constructions also by the arrow of time. There should be a new research space of the Quantum Information Science the 'general neutrino oscillation' for the greater then subatomic matter structures as an electric dipole change.

There is also connection between statistical physics and evolutionary biology, since the arrow of time is working in the biological evolution also.

The Fluctuation Theorem says that there is a probability that entropy will flow in a direction opposite to that dictated by the Second Law of Thermodynamics. In this case the Information is growing that is the matter formulas are emerging from the chaos. So the Weak Interaction has two directions, samples for one direction is the Neutron decay, and Hydrogen fusion is the opposite direction.

## Fermions and Bosons

The fermions are the diffraction patterns of the bosons such a way that they are both sides of the same thing.

## Van Der Waals force

Named after the Dutch scientist Johannes Diderik van der Waals – who first proposed it in 1873 to explain the behaviour of gases – it is a very weak force that only becomes relevant when atoms and molecules are very close together. Fluctuations in the electronic cloud of an atom mean that it will have an instantaneous dipole moment. This can induce a dipole moment in a nearby atom, the result being an attractive dipole–dipole interaction.

# Electromagnetic inertia and mass

## Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

## Relativistic change of mass

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

## The frequency dependence of mass

Since $E = h\nu$ and $E = mc^2$, $m = h\nu / c^2$ that is the $m$ depends only on the $\nu$ frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the $m_o$ inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

## Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [2]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

# Gravity from the point of view of quantum physics

## The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Bing Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass rate Mp=1840 Me. In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.
There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## The Higgs boson

By March 2013, the particle had been proven to behave, interact and decay in many of the expected ways predicted by the Standard Model, and was also tentatively confirmed to have + parity and zero spin, two fundamental criteria of a Higgs boson, making it also the first known scalar particle to be discovered in nature, although a number of other properties were not fully proven and some partial results do not yet precisely match those expected; in some cases data is also still awaited or being analyzed.

Since the Higgs boson is necessary to the W and Z bosons, the dipole change of the Weak interaction and the change in the magnetic effect caused gravitation must be conducted. The Wien law is also important to explain the Weak interaction, since it describes the $T_{max}$ change and the diffraction patterns change. [2]

## Higgs mechanism and Quantum Gravity

The magnetic induction creates a negative electric field, causing an electromagnetic inertia. Probably it is the mysterious Higgs field giving mass to the charged particles? We can think about the photon as an electron-positron pair, they have mass. The neutral particles are built from negative and positive charges, for example the neutron, decaying to proton and electron. The wave – particle duality makes sure that the particles are oscillating and creating magnetic induction as an inertial mass, explaining also the relativistic mass change. Higher frequency creates stronger magnetic induction, smaller frequency results lesser magnetic induction. It seems to me that the magnetic induction is the secret of the Higgs field.

In particle physics, the Higgs mechanism is a kind of mass generation mechanism, a process that gives mass to elementary particles. According to this theory, particles gain mass by interacting with the Higgs field that permeates all space. More precisely, the Higgs mechanism endows gauge bosons in a gauge theory with mass through absorption of Nambu–Goldstone bosons arising in spontaneous symmetry breaking.

The simplest implementation of the mechanism adds an extra Higgs field to the gauge theory. The spontaneous symmetry breaking of the underlying local symmetry triggers conversion of components of this Higgs field to Goldstone bosons which interact with (at least some of) the other fields in the theory, so as to produce mass terms for (at least some of) the gauge bosons. This mechanism may also leave behind elementary scalar (spin-0) particles, known as Higgs bosons.

In the Standard Model, the phrase "Higgs mechanism" refers specifically to the generation of masses for the $W^{\pm}$, and Z weak gauge bosons through electroweak symmetry breaking. The Large Hadron Collider at CERN announced results consistent with the Higgs particle on July 4, 2012 but stressed that further testing is needed to confirm the Standard Model.

### What is the Spin?

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarizations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarizations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particles like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

### The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [3]

## Conclusions

The method developed by the researchers involves transferring a photonic qubit to an atomic qubit trapped inside an optical cavity. The photon-atom quantum information transfer is initiated via a quantum “logic-gate” operation, performed by reflecting the photon from the atom-cavity system, which creates an entangled atom-photon state. [9]

In August 2013, the achievement of "fully deterministic" quantum teleportation, using a hybrid technique, was reported. On 29 May 2014, scientists announced a reliable way of transferring data by quantum teleportation. Quantum teleportation of data had been done before but with highly unreliable methods. [8]

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also. [1]

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing.

The Secret of Quantum Entanglement that the particles are diffraction patterns of the electromagnetic waves and this way their quantum states every time is the result of the quantum state of the intermediate electromagnetic waves. [2]

The key breakthrough to arrive at this new idea to build qubits was to exploit the ability to control the nuclear spin of each atom. With that insight, the team has now conceived a unique way to use the nuclei as facilitators for the quantum logic operation between the electrons. [5]

Basing the gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions also.

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