

Coupling Between Light and Matter

Researchers at the University of Waterloo's Institute for Quantum Computing (IQC) recorded an interaction between light and matter 10 times larger than previously seen. The strength of the interaction between photons and a qubit was so large that it opens the door to a realm of physics and applications unattainable until now. [19]

A method created at Rice University closes the gap between light and matter and may help advance technologies like quantum computers and communications. [18]

Constructing quantum computers and other quantum devices requires the ability to leverage quantum properties such as superposition and entanglement – but these effects are fragile and therefore hard to maintain. Recently, scientists at Ecole Normale Supérieure in Paris demonstrated a novel method for controlling the quantum properties of light by probing a superconducting circuit in a cavity with microwave photons to control the energy levels that photon quanta can occupy. [17]

When two atoms are placed in a small chamber enclosed by mirrors, they can simultaneously absorb a single photon. [16]

Optical quantum technologies are based on the interactions of atoms and photons at the single-particle level, and so require sources of single photons that are highly indistinguishable – that is, as identical as possible. Current single-photon sources using semiconductor quantum dots inserted into photonic structures produce photons that are ultrabright but have limited indistinguishability due to charge noise, which results in a fluctuating electric field. [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.

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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.

Experiment achieves the strongest coupling between light and matter

Researchers at the University of Waterloo's Institute for Quantum Computing (IQC) recorded an interaction between light and matter 10 times larger than previously seen. The strength of the interaction between photons and a qubit was so large that it opens the door to a realm of physics and applications unattainable until now.

The results appear in the paper, "Ultrastrong coupling of a single artificial atom to an electromagnetic continuum in the nonperturbative regime," published in Nature Physics.

"We are enabling the investigation of light-matter interactions in a new domain in quantum optics," said Pol Forn-Diaz, a postdoctoral fellow at IQC and lead author of the paper. "The possibilities are exciting because our circuit could potentially act as a quantum simulator to study other interesting quantum systems in nature."

The ultrastrong coupling between photons and qubits may lead to the exploration of new physics related to biological processes, exotic materials such as high-temperature superconductors, and even relativistic physics.

To conduct their experiment, the researchers fabricated aluminum circuits in the University of Waterloo's Quantum NanoFab, and then cooled them in dilution refrigerators to a temperature as low as one per cent of a degree above absolute zero. The circuits become superconducting at these cold temperatures, meaning that they can carry a current without resistance or losing energy. These aluminum circuits, known as superconducting qubits, obey the laws of quantum mechanics and can behave as artificial atoms.

To control the quantum state of a superconducting circuit, the researchers sent photons using microwave pulses into the superconducting circuit and applied a small magnetic field through a coil inside the dilution refrigerator. By measuring the photon transmission, the researchers could define the resonance of the qubit, indicated by the reflection of the photons off the qubit. Usually, the qubit resonance is centered around a very narrow range of frequencies.

"We measured a range of frequencies broader than the qubit frequency itself," said Forn-Diaz. "This means there is a very strong interaction between the qubit and the photons. It is so strong that the qubit is seeing most of the photons that propagate in the circuit, which is a distinctive signature of ultrastrong coupling in an open system." [19]

Light and matter merge in quantum coupling

Where light and matter intersect, the world illuminates. Where light and matter interact so strongly that they become one, they illuminate a world of new physics, according to Rice University scientists.

Rice physicists are closing in on a way to create a new condensed matter state in which all the electrons in a material act as one by manipulating them with light and a magnetic field. The effect made possible by a custom-built, finely tuned cavity for terahertz radiation shows one of the strongest light-matter coupling phenomena ever observed.

The work by Rice physicist Junichiro Kono and his colleagues is described in Nature Physics. It could help advance technologies like quantum computers and communications by revealing new phenomena to those who study cavity quantum electrodynamics and condensed matter physics, Kono said.

Condensed matter in the general sense is anything solid or liquid, but condensed matter physicists study forms that are much more esoteric, like Bose-Einstein condensates. A Rice team was one of the first to make a Bose-Einstein condensate in 1995 when it prompted atoms to form a gas at ultracold temperatures in which all the atoms lose their individual identities and behave as a single unit.

The Kono team is working toward something similar, but with electrons that are strongly coupled, or "dressed," with light. Qi Zhang, a former graduate student in Kono's group and lead author of the paper, designed and constructed an extremely high-quality cavity to contain an ultrathin layer of gallium arsenide, a material they've used to study superfluorescence. By tuning the material with a

magnetic field to resonate with a certain state of light in the cavity, they prompted the formation of polaritons that act in a collective manner.

"This is a nonlinear optical study of a two-dimensional electronic material," said Zhang, who based his Ph.D. thesis on the work. "When you use light to probe a material's electronic structure, you're usually looking for light absorption or reflection or scattering to see what's happening in the material. That light is just a weak probe and the process is called linear optics.

"Nonlinear optics means light does something to the material," he said. "Light is not a small perturbation anymore; it couples strongly with the material. As you change the coupling strength, things change in the material. What we're doing is the extreme case of nonlinear optics, where the light and matter are coupled so strongly that we don't have light and matter anymore. We have something in between, called a polariton."

The researchers employed a parameter known as vacuum Rabi splitting to measure the strength of the light-matter coupling. "In more than 99 percent of previous studies of light-matter coupling in cavities, this value is a negligibly small fraction of the photon energy of the light used," said Xinwei Li, a co-author and graduate student in Kono's group. "In our study, vacuum Rabi splitting is as large as 10 percent of the photon energy. That puts us in the so-called ultrastrong coupling regime.

"This is an important regime because, eventually, if the vacuum Rabi splitting becomes larger than the photon energy, the matter goes into a new ground state. That means we can induce a phase transition, which is an important element in condensed matter physics," he said.

Phase transitions are transitions between states of matter, like ice to water to vapor. The specific transition Kono's team is looking for is the superradiant phase transition in which the polaritons go into an ordered state with macroscopic coherence.

Kono said the amount of terahertz light put into the cavity is very weak. "What we depend on is the vacuum fluctuation. Vacuum, in a classical sense, is an empty space. There's nothing. But in a quantum sense, a vacuum is full of fluctuating photons, having so-called zero-point energy. These vacuum photons are actually what we are using to resonantly excite electrons in our cavity.

"This general subject is what's known as cavity quantum electrodynamics (QED)," Kono said. "In cavity QED, the cavity enhances the light so that matter in the cavity resonantly interacts with the vacuum field. What is unique about solid-state cavity QED is that the light typically interacts with this huge number of electrons, which behave like a single gigantic atom."

He said solid-state cavity QED is also key for applications that involve quantum information processing, like quantum computers. "The light-matter interface is important because that's where so-called light-matter entanglement occurs. That way, the quantum information of matter can be transferred to light and light can be sent somewhere.

"For improving the utility of cavity QED in quantum information, the stronger the light-matter coupling, the better, and it has to use a scalable, solid-state system instead of atomic or molecular systems," he said. "That's what we've achieved here."

The high-quality gallium arsenide materials used in the study were synthesized via molecular beam epitaxy by John Reno of Sandia National Laboratories and John Watson and Michael Manfra of Purdue University, all co-authors of the paper. Weil Pan of Sandia National Laboratories and Rice graduate student Minhan Lou, who participated in sample preparation and transport and terahertz measurements, are also co-authors.

Zhang is now the Alexei Abrikosov Postdoctoral Fellow at Argonne National Laboratory. Kono is a Rice professor of electrical and computer engineering, of physics and astronomy and of materials science and nanoengineering. Li received a "Best First-Year Research Award" from Rice's Department of Electrical and Computer Engineering for his work on the project. [18]

Training Schrodinger's cat: Controlling the quantum properties of light

Constructing quantum computers and other quantum devices requires the ability to leverage quantum properties such as superposition and entanglement – but these effects are fragile and therefore hard to maintain. Recently, scientists at Ecole Normale Supérieure in Paris demonstrated a novel method for controlling the quantum properties of light by probing a superconducting circuit in a cavity with microwave photons to control the energy levels that photon quanta can occupy. Specifically, the scientists prevented access to a single energy level corresponding to a number of photons N , and thereby confined the dynamics of the field to levels 0 to $N-1$. In so doing, the intracavity field changed from a classical wave to a Schrödinger cat of light – a superposition between two waves of opposite phases instead of a single one. As a result, this new technique could apply to the development of quantum computers by protecting qubits from decoherence as well as enhancing quantum error correction and quantum systems measurement.

Prof. Benjamin Huard discussed the paper that he and his colleagues published in Science. "The primary difficulty in developing our method for manipulating electromagnetic modes by effectively controlling their phase space was to find a proper way of preventing any access to one or few energy levels," Huard tells Phys.org. "We did that using another quantum system – a superconducting qubit – which allowed us to change the energy of any level we chose by simply turning a microwave signal on or off. In this context, the main challenge was designing a cavity and a qubit with the right properties to realize and observe this new method of control."

The scientists also had an issue in finding that level occupation oscillated in time when using the same light mode and qubit for several operations. "The basic experiment consists in driving the light mode while the qubit controls its phase space," Huard explains. "However, in order to measure the level occupation in time, we had to use the same qubit as a photcounter, and the same light mode to measure the qubit state." (Photocounters tally photon distributions by counting photoelectric electrons, or photoelectrons – that is, electrons emitted by various metals when illuminated by photons.)

A third obstacle was using circuit quantum electrodynamics, or circuit-QED, architecture – the implementation of quantum electrodynamics (a quantum field theory of electromagnetic force) for circuits – to apply quantum Zeno dynamics (QZD) to light. QZD is based on the quantum Zeno effect (QZE) – named after the Zeno arrow paradox – in which if observed continuously an unstable particle

will never decay, meaning that an unstable quantum system measured with sufficient frequency will not evolve. However, in certain circumstances, quantum Zeno dynamics – in which the quantum system changes over time – can occur.

"With its large number of energy levels and ease of control," Huard points out, "a single electromagnetic mode offers a wider and more controllable phase space than atoms and two-level systems. Nevertheless, in order to make it work, we had to identify the several constraints on the parameters we had access to. Using superconducting circuits helped since it is fairly easy to tune their parameters and establish coupling to microwave light. Using the same systems twice for various operations required many careful calibrations, and we had to find the optimal temporal sequences to realize the experiment."

Huard addresses the implications of the finding stated in the paper that under a resonant drive, or cavity, the level occupation was found to oscillate in time, similarly to an N-level system. "By preventing any access to one energy level of the light mode, it indeed acts exactly as an N-level system – but here, since N can be chosen and modified in time, it's as if we had engineered an atom with a spin $(N-1)/2$ that can change at will in time by simply turning on or off microwave signals. It would be interesting to observe the dynamics of such a spin whose number is changing in time."

Huard next discusses how fine control of the field in its phase space may enable applications in quantum information and metrology. "Our method is a new technique that can produce exotic quantum states of light similar to Schrödinger cat states or vacuum squeezed states that are well-suited for quantum information or metrology purposes by increasing the precision of field or position measurements." (A vacuum squeezed state is a nonclassical state of light in which quantum noise is no longer independent of the phase of the light wave, and is below the standard quantum limit.) "Our method can also be used to generate and protect entanglement, which is a fundamental resource of quantum information, as well as to perform quantum error correction on qubits encoded using Schrödinger cat-like states."

In fact, the paper states that the new method allows the possibility of manipulating Schrödinger cat states in a unique way. "Our method is the essential brick that enables the creation of phase space light tweezers, as proposed by Jean-Michel Raimond and coworkers¹," Huard says. "These tweezers can displace parts of the Wigner function in its phase space one at a time." (The Wigner function is a so-called quasiprobability distribution that links the Schrödinger wavefunction to a probability distribution in phase space, and counterintuitively can have regions of negative probability density.) "It therefore becomes possible to enlarge or rotate a Schrödinger cat state directly in its phase space."

This leads to the ability to effect quantum error correction of cat-qubits (quantum information encoded in logical bases composed of Schrödinger cat states) as a quantum computing paradigm. "In fact," Huard points out, "a way to encode quantum information with superpositions of cat-like states was recently proposed in the context of circuit-QED by Mazyar Mirrahimi and coworkers²," adding that finding ways to perform quantum error correction on these states is essential for their potential use in a quantum computing architecture. "We believe that our technique could be used to perform this quantum error correction in a unique way. Indeed, decoherence leads to an exponential relaxation of the cat size, which needs to be overcome – and by displacing the cat 'legs' one by one using QZD, this relaxation can be canceled without losing any quantum information."

Looking ahead, Huard tells Phys.org that the researchers are "pursuing the investigation of the fascinating effect of measurement on quantum systems. For instance," he illustrates, "we now have an experiment where we intercept the signal that leaks towards the environment of a qubit and usually leads to decoherence.

However, using this signal we can now infer what the environment knows about the qubit state and preserve the purity of the quantum state – and we've recently managed to use that signal for preserving any state by feedback." In addition, he adds, they are interested in applying their technique to systems with longer coherence times and to Schrödinger cat preservations.

Regarding other areas of research that might benefit from their study, Huard concludes that "it's hard to tell right now – but in the long run, if our technique helps build quantum simulators or computers, it could have an impact in many areas requiring intense computation, such as machine learning or chemistry." [17]

Two atoms in an optical cavity can absorb one photon

When two atoms are placed in a small chamber enclosed by mirrors, they can simultaneously absorb a single photon. So says an international team of researchers, which has found that the reverse process – two excited atoms emitting a single photon – is also possible. According to the team, this process could be used to transmit information in a quantum circuit or computer.

Physicists have long known that a single atom can absorb or emit two photons simultaneously. These two-photon, one-atom processes are widely used for spectroscopy and for the production of entangled photons used in quantum devices. However, Salvatore Savasta of the University of Messina in Italy, together with colleagues at the RIKEN Institute in Japan, wondered if two atoms could absorb one photon. Savasta asked his PhD student at the time, Luigi Garziano, to simulate the process. When Garziano's simulation showed that the phenomenon was possible, Savasta was so excited that he "punched the wall," he told physicsworld.com.

One for two?

Their simulation found that the phenomenon occurs when the resonant frequency of the optical cavity containing the atoms is twice the transition frequency of an individual atom. For example, in a cavity whose resonant frequency is three times that of the atomic transition, three atoms can simultaneously absorb or emit a single photon. The optical-cavity's dimensions are determined by this resonant frequency, which must be a standing wave. According to the researchers' calculations, the two atoms would oscillate back and forth between their ground and excited states. Indeed, the atoms would first jointly absorb the photon, ending up in their excited states, before jointly emitting a single photon to return to their ground states. The cycle would then repeat. In addition, they found that the joint absorption and emission can occur with more than just two atoms.

Quantum switch

A two-atom, one-photon system could be used as a switch to transmit information in a quantum circuit, Savasta says. One atom would act as a qubit, encoding information as a superposition of the ground and excited states. To transmit the information outside of the cavity, the qubit would need to transfer the information to a photon in the cavity. The second atom would be used to control whether the qubit transmits the information. If the second atom's transition frequency is tuned to

half the resonance frequency of the cavity, the two atoms could jointly absorb and emit a single photon, which would contain the encoded information to be transmitted.

To ensure that the atoms do not re-adsorb the photon, the atom's resonant frequency can be changed by applying an external magnetic field.

Savasta's group has begun to look for experimental collaborators to produce its theoretical prediction in the lab. While the experiment could be performed using actual atoms, Savasta plans to use artificial atoms: superconducting particles that have quantized energy levels and behave analogously as atoms, but whose transition energies can be more easily tuned by the experimentalist. In addition, controlling real atoms involves expensive technology, while artificial atoms can be created cheaply on solid-state chips. "Real atoms are only good for proof-of-principle experiments," he says.

Savasta anticipates that their collaborators will be able to successfully perform the experiment in about a year. "We think that, especially if using superconducting qubits, that this experiment is well within the reach of present technology," he says.

According to Tatjana Wilk at the Max Planck Institute for Quantum Optics in Garching, who was not involved in the current research, speaking to the American Physical Society's Physics Focus, she cautions that the excited states of the atoms may not last long enough to be useful in an actual quantum device.

The research is published in Physical Review Letters. [16]

Quantum processor for single photons

"Nothing is impossible!" In line with this motto, physicists from the Quantum Dynamics Division of Professor Gerhard Rempe (director at the Max Planck Institute of Quantum Optics) managed to realise a quantum logic gate in which two light quanta are the main actors. The difficulty of such an endeavour is that photons usually do not interact at all but pass each other undisturbed. This makes them ideal for the transmission of quantum information, but less suited for its processing. The scientists overcame this steep hurdle by bringing an ancillary third particle into play: a single atom trapped inside an optical resonator that takes on the role of a mediator. "The distinct feature of our gate implementation is that the interaction between the photons is deterministic", explains Dr. Stephan Ritter. "This is essential for future, more complex applications like scalable quantum computers or global quantum networks."

In all modern computers, data processing is based on information being binary-coded and then processed using logical operations. This is done using so-called logic gates which assign predefined output values to each input via deterministic protocols. Likewise, for the information processing in quantum computers, quantum logic gates are the key elements. To realise a universal quantum computer, it is necessary that every input quantum bit can cause a maximal change of the other quantum bits. The practical difficulty lies in the special nature of quantum information: in contrast to classical bits, it cannot be copied. Therefore, classical methods for error correction cannot be applied, and the gate must function for every single photon that carries information.

Because of the special importance of photons as information carriers – for example, for communicating quantum information in extended quantum networks – the realisation of a deterministic photon-photon gate has been a long-standing goal. One of several possibilities to encode photonic quantum bits is the use of polarisation states of single photons. Then the states "0" and "1" of a classical bit correspond to two orthogonal polarisation states. In the two-photon gate, the polarisation of each photon can influence the polarisation of the other photon. As in the classical logic gate it is specified beforehand which input polarisation leads to which output polarisation. For example, a linear polarisation of the second photon is rotated by 90° if the first one is in the logic state "1", and remains unchanged if the first one is in "0". In contrast to classical logic gates, which would be fully specified by such a description, a quantum gate can take on an infinite number of possible input states. The quantum logic gate has to create the correct combination of output states for each one of these.

In the experiment presented here two independently polarised photons impinge, in quick succession, onto a resonator which is made of two high-reflectivity mirrors.

Inside a single rubidium atom is trapped forming a strongly coupled system with the resonator. The resonator amplifies the light field of the impinging photon at the position of the atom enabling a direct atom-photon interaction. As a result, the atomic state gets manipulated by the photon just as it is being reflected from the mirror. This change is sensed by the second photon when it arrives at the mirror shortly thereafter.

After their reflection, both photons are stored in a 1.2-kilometre-long optical fibre for some microseconds. Meanwhile, the atomic state is measured. A rotation of the first photon's polarisation conditioned on the outcome of the measurement enables the back action of the second photon on the first one. "The two photons are never at the same place at the same time and thus they do not see each other directly. Nevertheless, we achieve a maximal interaction between them", explains Bastian Hacker, PhD student at the experiment.

The scientists could prove experimentally that – depending on the choice of the photons' polarisations – either the first photon affects the second or vice versa. To this end, they measured the polarisation states of the two outgoing photons for different input states. From these, they generated "truth tables" which correspond to the expected gate operations and thus demonstrate the diverse operational modes of the photon-photon gate.

The case when the input polarisation of the two photons is chosen such that they influence each other is of particular interest: Here the two outgoing photons form an entangled pair. "The possibility to generate entanglement fundamentally distinguishes a quantum gate from its classical counterpart. One of the applications of entangled photons is in the teleportation of quantum states", explains Stephan Welte, PhD student at the experiment.

The scientists envision that the new photon-photon gate could pave the way towards all-optical quantum information processing. "The distribution of photons via an optical quantum network would allow linking any number of network nodes and thus enable the setup of a scalable optical quantum computer in which the photon-photon gate plays the role of a central processing unit (CPU)", explains Professor Gerhard Rempe. [15]

The path to perfection: Quantum dots in electrically-controlled cavities yield bright, nearly identical photons

Optical quantum technologies are based on the interactions of atoms and photons at the single-particle level, and so require sources of single photons that are highly indistinguishable – that is, as identical as possible. Current single-photon sources using semiconductor quantum dots inserted into photonic structures produce photons that are ultrabright but have limited indistinguishability due to charge noise, which results in a fluctuating electric field. Conversely, parametric down conversion sources yield photons that while being highly indistinguishable have very low brightness. Recently, however, scientists at CNRS - Université Paris-Saclay, Marcoussis, France; Université Paris Diderot, Paris, France; University of Queensland, Brisbane, Australia; and Université Grenoble Alpes, CNRS, Institut Néel, Grenoble, France; have developed devices made of quantum dots in electrically-controlled cavities that provide large numbers of highly indistinguishable photons with strongly reduced charge noise that are 20 times brighter than any source of equal quality. The researchers state that by demonstrating efficient generation of a pure single photon with near-unity indistinguishability, their novel approach promises significant advances in optical quantum technology complexity and scalability.

Dr. Pascale Senellart and Phys.org discussed the paper, Near-optimal single-photon sources in the solid state, that she and her colleagues published in Nature Photonics, which reports the design and fabrication of the first optoelectronic devices made of quantum dots in electrically controlled cavities that provide bright source generating near-unity indistinguishability and pure single photons. "The ideal single photon source is a device that produces light pulses, each of them containing exactly one, and no more than one, photon. Moreover, all the photons should be identical in spatial shape, wavelength, polarization, and a spectrum that is the Fourier transform of its temporal profile," Senellart tells Phys.org. "As a result, to obtain near optimal single photon sources in an optoelectronic device, we had to solve many scientific and technological challenges, leading to an achievement that is the result of more than seven years of research."

While quantum dots can be considered artificial atoms that therefore emit photons one by one, she explains, due to the high refractive index of any semiconductor device, most single photons emitted by the quantum dot do not exit the semiconductor and therefore cannot be used. "We solved this problem by coupling the quantum dot to a microcavity in order to engineer the electromagnetic field around the emitter and force it to emit in a well-defined mode of the optical field," Senellart points out. "To do so, we need to position the quantum dot with nanometer-scale accuracy in the microcavity."

Senellart notes that this is the first challenge that the researchers had to address since targeting the issue of quantum dots growing with random spatial positions.

"Our team solved this issue in 2008 by proposing a new technology, in-situ lithography, which allows measuring the quantum dot position optically and drawing a pillar cavity around it. With this technique, we can position a single quantum dot with 50 nm accuracy at the center of a micron-sized pillar." In these cavities, two distributed Bragg reflectors confine the optical field in the vertical direction, and the contrast of the index of refraction between the air and the semiconductor provides the lateral confinement of the light. "Prior to this technology, the fabrication yield of quantum dot cavity devices was in the 10⁻⁴ – but today it is larger than 50%." The scientists used this

technique to demonstrate the fabrication of bright single photon sources in 2013², showing that the device can generate light pulses containing a single photon with a probability of 80% – but while all photons had the same spatial shape and wavelength, they were not perfectly identical.

"Indeed, for the photons to be fully indistinguishable, the emitter should be highly isolated from any source of decoherence induced by the solid-state environment.

However, our study showed that collisions of the carriers with phonons and fluctuation of charges around the quantum dot were the main limitations." To solve this problem, the scientists added an electrical control to the device, such that the application of an electric field stabilized the charges around the quantum dot by sweeping out any free charge. This in turn removed the noise. Moreover, she adds, this electrical control allows tuning the quantum dot wavelength – a process that was previously done by increasing temperature at the expense of increasing vibration.

"I'd like to underline here that the technology described above is unique worldwide," Senellart stresses. "Our group is the only one with such full control of all of the quantum dot properties. That is, we control emission wavelength, emission lifetime and coupling to the environment, all in a fully deterministic and scalable way."

Specifically, implementing control of the charge environment for quantum dots in connected pillar cavities, and applying an electric field on a cavity structure optimally coupled to a quantum dot, required significant attention. "We had strong indications back in 2013 that the indistinguishability of our photons was limited by some charge fluctuations around the quantum dot: Even in the highest-quality semiconductors, charges bound to defects fluctuate and create a fluctuating electric field³. In the meantime, several colleagues were observing very low charge noise in structures where an electric field was applied to the quantum dot – but this was not combined with a cavity structure." The challenge, Senellart explains, was to define a metallic contact on a microcavity (which is typically a cylinder with a diameter of 2-3 microns) without covering the pillar's top surface.

"We solved this problem by proposing a new kind of cavity – that is, we showed that we can actually connect the cylinder to a bigger frame using some one-dimensional bridges without modifying too much the confinement of the optical field." This geometry, which the researchers call connected pillars, allows having the same optical confinement as an isolated pillar while defining the metallic contact far from the pillar itself. Senellart says that the connected pillars geometry was the key to both controlling the quantum wavelength of dot and efficiently collecting its emission⁴.

In demonstrating the efficient generation of a pure single photon with near-unity indistinguishability, Senellart continues, the researchers had one last step – combining high photon extraction efficiency and perfect indistinguishability – which they did by implementing a resonant excitation scheme of the quantum dot. "In 2013, Prof. Chao-Yang Lu's team in Hefei, China showed that one could obtain photons with 96% indistinguishability by exciting the quantum dot state in a strictly resonant way⁵. Their result was beautiful, but again, not combined with an efficient extraction of the photons. The experimental challenge here is to suppress the scattered light from the laser and collect only the single photons radiated by the quantum dot."

Senellart adds that while removing scattered photons when transmitting light in processed microstructures is typically complicated, in their case this step was straightforward. "Because the

quantum dot is inserted in a cavity, the probability of the incident laser light to interact with the quantum dot is actually very high. It turns out that we send only a few photons – that is, less than 10 – on the device to have the quantum dot emitting one photon. This beautiful efficiency, also demonstrated in the excitation process, which we report in another paper⁶, made this step quite easy."

The devices reported in the paper have a number of implications for future technologies, one being the ability to achieve strongly-reduced charge noise by applying an electrical bias. "Charge noise has been extensively investigated in quantum dot structures," Senellart says, "especially by Richard Warburton's group."

Warburton and his team demonstrated that in the best quantum dot samples, the charge noise could take place on a time scale of few microseconds – which is actually very good, since the quantum dot emission lifetime is around 1 nanosecond⁷. However, this was no longer the case in etched structures, where a strong charge noise is always measured on very short time scale – less than 1 ns – that prevents the photon from being indistinguishable. "I think the idea we had – that this problem would be solved by applying an electric field – was an important one," Senellart notes. "The time scale of this charge noise does not only determine the degree of indistinguishability of the photons, it also determines how many indistinguishable photon one can generate with the same device. Therefore, this number will determine the complexity of any quantum computation or simulation scheme one can implement." Senellart adds that in a follow-up study⁷ the scientists generated long streams of photons that can contain more than 200 being indistinguishable by more than 88%.

In addressing how these de novo devices may lead to new levels of complexity and scalability in optical quantum technologies, Senellart first discusses the historical sources used develop optical quantum technologies. She makes the point that all previous implementations of optical quantum simulation or computing have been implemented using Spontaneous Parametric Down Conversion (SPDC) sources, in which pairs of photons are generated by the nonlinear interaction of a laser on a nonlinear crystal, wherein one photon of the pair is detected to announce the presence of the other photon. This so-called heralded source can present strongly indistinguishable photons, but only at the cost of extremely low brightness. "Indeed, the difficulty here is that the one pulse does not contain a single pair only, but some of the time several pairs," Senellart explains. "To reduce the probability of having several pairs generated that would degrade the fidelity of a quantum simulation, calculation or the security of a quantum communication, the sources are strongly attenuated, to the point where the probability of having one pair in a pulse is below 1%. Nevertheless, with these sources, the quantum optics community has demonstrated many beautiful proofs of concept of optical quantum technologies, including long-distance teleportation, quantum computing of simple chemical or physical systems, and quantum simulations like BosonSampling." (A BosonSampling device is a quantum machine expected to perform tasks intractable for a classical computer, yet requiring minimal non-classical resources compared to full-scale quantum computers.) "Yet, the low efficiency of these sources limits the manipulation to low photon numbers: It takes typically hundreds of hours to manipulate three photons, and the measurement time increases exponentially with the number of photons. Obviously, with the possibility to generate more many indistinguishable photons with an efficiency more than one order of magnitude greater

than SPDC sources, our devices have the potential to bring optical quantum technologies to a whole new level."

Other potential applications of the newly-demonstrated devices will focus on meeting near-future challenges in optical quantum technologies, including scalability of photonic quantum computers and intermediate quantum computing tasks. "The sources presented here can be used immediately to implement quantum computing and intermediate quantum computing tasks. Actually, very recently – in the first demonstration of the superiority of our new single photon sources – our colleagues in Brisbane made use of such bright indistinguishable quantum dot-based single photon sources to demonstrate a three photon BosonSampling experiment⁸, where the solid-state multi-photon source was one to two orders-of-magnitude more efficient than downconversion sources, allowing to complete the experiment faster than those performed with SPDC sources. Moreover, this is a first step; we'll progressively increase the number of manipulated photons, in both quantum simulation and quantum computing tasks."

Another target area is quantum communications transfer rate. "Such bright single photon sources could also drastically change the rate of quantum communication protocols that are currently using attenuated laser sources or SPDC sources. Yet, right now, our sources operate at 930 nm when 1.3 μm or 1.55 μm sources are needed for long distance communications. Our technique can be transferred to the 1.3 μm range, a range at which single photon emission has been successfully demonstrated – in particular by the Toshiba research group – slightly changing the quantum dot material. Reaching the 1.55 μm range will be more challenging using quantum dots, as it appears that the single photon emission is difficult to obtain at this wavelength. Nevertheless, there's a very promising alternative possibility: the use of a 900 nm bright source, like the one we report here, to perform quantum frequency conversion of the single photons. Such efficient frequency conversion of single photons has recently been demonstrated, for example, in the lab of Prof. Yoshie Yamamoto at Stanford⁹."

Regarding future research, Senellart says "There are many things to do from this point. On the technology side, we will try to improve our devices by further increasing the source brightness. For that, a new excitation scheme will be implemented to excite the device from the side, as was done by Prof. Valia Voliotis and her colleagues on the Nanostructures and Quantum Systems team at Pierre and Marie Curie University in Paris and Prof. Glenn Solomon's group at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. Applying this technique to our cavities should allow gaining another factor of four on source brightness. In addition, operating at another wavelength would be another important feature for our devices, since as discussed above, this would allow using the source for quantum telecommunication. For example, a shorter wavelength, in the visible/near infrared range, would open new possibilities to interconnect various quantum systems, including ions or atoms through their interaction with photons, as well as applications in quantum imaging and related fields."

The researchers also want to profit from the full potential of these sources and head to high photon number manipulation in, for instance, quantum simulation schemes. "We're aiming at performing BosonSampling measurements with 20-30 photons, with the objective of testing the extended Church Turing thesis and proving the superiority of a quantum computer over a classical one." The original Church Turing thesis, based on investigations of Alonzo Church and Alan Turing into

computable functions, states that, ignoring resource limitations, a function on the natural numbers is computable by a human being following an algorithm, if and only if it is computable by a Turing machine.

Another promising impact on future optical quantum technologies is the generation of entangled photon pairs. "A quantum dot can also generate entangled photon pairs, and in 2010 we demonstrated that we could use the in situ lithography to obtain the brightest source of entangled photon pairs¹⁰. That being said, photon indistinguishability needs to be combined with high pair brightness – and this is the next challenge we plan to tackle. Such a device would play an important role in developing quantum relays for long distance communication and quantum computing tasks."

Senellart tells Phys.org that other areas of research might well benefit from their findings, in that devices similar to the one the scientists developed to fabricate single photon sources could also provide nonlinearities at the low photon count scale. This capability could in turn allow the implementation of deterministic quantum gates, a new optical quantum computing paradigm in which reversible quantum logic gates – for example, Toffoli or CNOT (controlled NOT) gates – can simulate irreversible classical logic gates, thereby allowing quantum computers to perform any computation which can be performed by a classical deterministic computer. "Single photons can also be used to probe the mechanical modes of mechanical resonator and develop quantum sensing with macroscopic objects. Other applications," she concludes, "could benefit from the possibility to have very efficient single photon sources, such as an imaging system with single photon sources that could allow dramatically increased imaging sensitivity. Such technique could have applications in biology where the lower the photon flux, the better for exploring in vivo samples." [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 challenging 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.

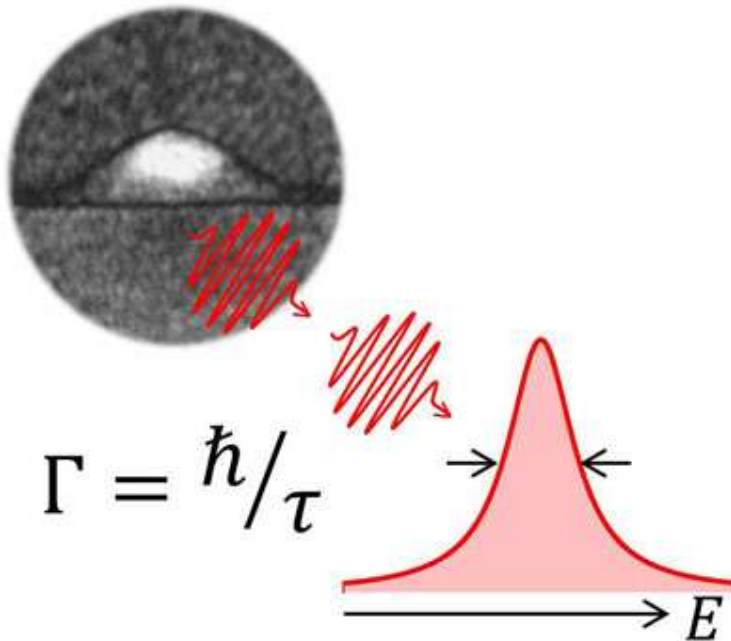
The micropillar is about 2.5 μm in diameter and about 10 μm tall, and it allowed the team to harness the "Purcell effect", whereby the rate of fluorescence is increased significantly when the emitter is placed in a resonant cavity.

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: $ds/dt = a$ (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 Δx position difference and with a Δp momentum difference such a way that their product is about the half Planck reduced constant. For the proton this Δx is much less in the nucleus, than in the orbit of the electron in the atom, the Δp is much higher because of the greater proton mass.

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

Wave – Particle Duality

The accelerating electrons explain the wave – particle duality of the electrons and photons, since the elementary charges are distributed on Δx position with Δp impulse and creating a wave packet of the electron. The photon gives the electromagnetic particle of the mediating force of the electron's 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 its 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 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 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 $1/2$ spin creator particle to make equal the spins of the weak interaction, for example neutron decay to 2 fermions, every particle is fermions with $1/2$ 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 $\frac{1}{2}$ 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 than 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 ν 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_0 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 Big 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 ratio $M_p=1840 M_e$. 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 their 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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