Optomechanical Systems

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An international team of physicists has monitored the scattering behavior of electrons in a non-conducting material in real-time. Their insights could be beneficial for radiotherapy. [23]

Researchers from the University of Illinois at Urbana-Champaign have demonstrated a new level of optical isolation necessary to advance on-chip optical signal processing. The technique involving light-sound interaction can be implemented in nearly any photonic foundry process and can significantly impact optical computing and communication systems. [22]

City College of New York researchers have now demonstrated a new class of artificial media called photonic hypercrystals that can control light-matter interaction in unprecedented ways. [21]

Experiments at the Institute of Physical Chemistry of the Polish Academy of Sciences in Warsaw prove that chemistry is also a suitable basis for storing information. The chemical bit, or 'chit,' is a simple arrangement of three droplets in contact with each other, in which oscillatory reactions occur. [20]

Researchers at Sandia National Laboratories have developed new mathematical techniques to advance the study of molecules at the quantum level. [19]

Correlation functions are often employed to quantify the relationships among interdependent variables or sets of data. A few years ago, two researchers proposed a property-testing problem involving Forrelation for studying the query complexity of quantum devices. [18]

A team of researchers from Australia and the UK have developed a new theoretical framework to identify computations that occupy the 'quantum *frontier'—the boundary at which problems become impossible for today's computers and can only be solved by a quantum computer. [17]*

Scientists at the University of Sussex have invented a ground-breaking new method that puts the construction of large-scale quantum computers within reach of current technology. [16]

Physicists at the University of Bath have developed a technique to more reliably produce single photons that can be imprinted with quantum information. [15]

Now a researcher and his team at Tyndall National Institute in Cork have made a 'quantum leap' by developing a technical step that could enable the use of quantum computers sooner than expected. [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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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.

Quantum thermometer or optical refrigerator?

In an arranged marriage of optics and mechanics, physicists have created microscopic structural beams that have a variety of powerful uses when light strikes them. Able to operate in ordinary, room-temperature environments, yet exploiting some of the deepest principles of quantum physics, these optomechanical systems can act as inherently accurate thermometers, or conversely, as a type of optical shield that diverts heat. The research was performed by a team led by the Joint Quantum Institute (JQI), a research collaboration of the National Institute of Standards and Technology (NIST) and the University of Maryland.

Described in a pair of new papers in Science and Physical Review Letters, the potential applications include chip-based temperature sensors for electronics and biology that would never need to be adjusted since they rely on fundamental constants of nature; tiny refrigerators that can cool state-of-the-art microscope components for higher-quality images; and improved "metamaterials" that could allow researchers to manipulate light and sound in new ways.

Made of silicon nitride, a widely used material in the electronics and photonics industries, the beams are about 20 microns (20 millionths of a meter) in length. They are transparent, with a row of holes drilled through them to enhance their optical and mechanical properties.

"You can send light down this beam because it's a transparent material. You can also send sound waves down the beam," explained Tom Purdy, a NIST physicist who is an author on both papers. The researchers believe the beams could lead to better thermometers, which are now ubiquitous in our devices, including cell phones.

"Essentially we're carrying a bunch of thermometers around with us all the time," said JQI Fellow Jake Taylor, senior author of the new papers. "Some provide temperature readings, and others let you know if your chip is too hot or your battery is too cold. Thermometers also play a crucial role in transportation systems—airplanes, cars—and tell you if your engine oil is overheating."

But the problem is that these thermometers are not accurate off the shelf. They need to be calibrated, or adjusted, to some standard. The design of the silicon nitride beam avoids this situation by relying on fundamental physics. To use the beam as a thermometer, researchers must be able to measure the tiniest possible vibrations in the beam. The amount that the beam vibrates is proportional to the temperature of its surroundings.

The vibrations can come from two kinds of sources. The first are ordinary "thermal" sources such as gas molecules buffeting the beam or sound waves passing through it. The second source of vibration comes purely from the world of quantum mechanics, the theory that governs behavior of matter at the atomic scale. The quantum behavior occurs when the researchers send particles of light, or photons, down the beam. Struck by light, the mechanical beam reflects the photons, and recoils in the process, creating small vibrations in the beam. Sometimes these quantum-based effects are described using the Heisenberg uncertainty relationship—the photon bounce leads to information about the beam's position, but because it imparts vibrations to the beam, it adds uncertainty to the beam's velocity.

"The quantum mechanical fluctuations give us a reference point because essentially, you can't make the system move less than that," Taylor said. By plugging in values of Boltzmann's constant and Planck's constant, the researchers can calculate the temperature. And given that reference point, when the researchers measure more motion in the beam, such as from thermal sources, they can accurately extrapolate the temperature of the environment.

However, the quantum fluctuations are a million times fainter than the thermal vibrations; detecting them is like hearing a pin drop in the middle of a shower.

In their experiments, the researchers used a state-of-the-art silicon nitride beam built by Karen Grutter and Kartik Srinivasan at NIST's Center for Nanoscale Science and Technology. By shining high-quality photons at the beam and analyzing photons emitted from the beam shortly thereafter, "we see a little bit of the quantum vibrational motion picked up in the output of light," Purdy explained. Their measurement approach is sensitive enough to see these quantum effects all the way up to room temperature for the first time, and is published in this week's issue of Science.

Although the experimental thermometers are in a proof-of-concept phase, the researchers envision they could be particularly valuable in electronic devices, as on-chip thermometers that never need calibration, and in biology.

"Biological processes, in general, are very sensitive to temperature, as anyone who has a sick child knows. The difference between 37 and 39 degrees Celsius is pretty large," Taylor said. He foresees applications in biotechnology, when you want to measure temperature changes in "as small an amount of product as possible," he said.

The researchers go in the opposite direction in a second proposed application for the beams, described in a theoretical paper published in Physical Review Letters.

Instead of letting heat hit the beam and allow it to serve as a temperature probe, the researchers propose using the beam to divert the heat from, for example, a sensitive part of an electromechanical device.

In their proposed setup, the researchers enclose the beam in a cavity, a pair of mirrors that bounce light back and forth. They use light to control the vibrations of the beam so that the beam cannot re-radiate incoming heat in its usual direction, towards a colder object.

For this application, Taylor likens the behavior of the beam to a tuning fork. When you hold a tuning fork and strike it, it radiates pure sound tones instead of allowing that motion to turn into heat, which travels down the fork and into your hand.

"A tuning fork rings for a long time, even in air," he said. The two prongs of the fork vibrate in opposite directions, he explained, and cancel out a way for energy to leave the bottom of the fork through your hand.

The researchers even imagine using an optically controlled silicon nitride beam as the tip of an atomic force microscope (AFM), which detects forces on surfaces to build up atom-scale images. An optically controlled AFM tip would stay cool—and perform better. "You're removing thermal motion, which makes it easier to see signals," Taylor explained.

This technique also could be put to use to make better metamaterials, complex composite objects that manipulate light or sound in new ways and could be used to make better lenses or even so-called "invisibility cloaks" that cause certain wavelengths of light to pass through an object rather than bouncing from it.

"Metamaterials are our answer to, 'How do we make materials that capture the best properties for light and sound, or for heat and motion?'" Taylor said. "It's a technique that has been widely used in engineering, but combining the light and sound together remains still a bit open on how far we can go with it, and this provides a new tool for exploring that space." [26]

A 100-year-old physics problem has been solved

At EPFL, researchers challenge a fundamental law and discover that more electromagnetic energy can be stored in wave-guiding systems than previously thought. The discovery has implications in telecommunications. Working around the fundamental law, they conceived resonant and wave-guiding systems capable of storing energy over a prolonged period while keeping a broad bandwidth. Their trick was to create asymmetric resonant or wave-guiding systems using magnetic fields.

The study, which has just been published in Science, was led by Kosmas Tsakmakidis, first at the University of Ottawa and then at EPFL's Bionanophotonic Systems Laboratory run by Hatice Altug, where the researcher is now doing post-doctoral research.

This breakthrough could have a major impact on many fields in engineering and physics. The number of potential applications is close to infinite, with telecommunications, optical detection systems and broadband energy harvesting representing just a few examples.

Casting aside reciprocity

Resonant and wave-guiding systems are present in the vast majority of optical and electronic systems. Their role is to temporarily store energy in the form of electromagnetic waves and then release them. For more than 100 hundred years, these systems were held back by a limitation that was considered to be fundamental: the length of time a wave could be stored was inversely proportional to its bandwidth. This relationship was interpreted to mean that it was impossible to store large amounts of data in resonant or wave-guiding systems over a long period of time because increasing the bandwidth meant decreasing the storage time and quality of storage.

This law was first formulated by K. S. Johnson in 1914, at Western Electric Company (the forerunner of Bell Telephone Laboratories). He introduced the concept of the Q factor, according to which a resonator can either store energy for a long time or have a broad bandwidth, but not both at the same time. Increasing the storage time meant decreasing the bandwidth, and vice versa. A small bandwidth means a limited range of frequencies (or 'colors') and therefore a limited amount of data.

Until now, this concept had never been challenged. Physicists and engineers had always built resonant systems—like those to produce lasers, make electronic circuits and conduct medical diagnoses—with this constraint in mind.

But that limitation is now a thing of the past. The researchers came up with a hybrid resonant / wave-guiding system made of a magneto-optic material that, when a magnetic field is applied, is able to stop the wave and store it for a prolonged period, thereby accumulating large amounts of energy. Then when the magnetic field is switched off, the trapped pulse is released.

With such asymmetric and non-reciprocal systems, it was possible to store a wave for a very long period of time while also maintaining a large bandwidth. The conventional time-bandwidth limit was even beaten by a factor of 1,000. The scientists further showed that, theoretically, there is no upper ceiling to this limit at all in these asymmetric (non-reciprocal) systems.

"It was a moment of revelation when we discovered that these new structures did not feature any time-bandwidth restriction at all. These systems are unlike what we have all been accustomed to for decades, and possibly hundreds of years", says Tsakmakidis, the study's lead author. "Their superior wave-storage capacity performance could really be an enabler for a range of exciting applications in diverse contemporary and more traditional fields of research." Hatice Altug adds.

Medicine, the environment and telecommunications

One possible application is in the design of extremely quick and efficient all-optical buffers in telecommunication networks. The role of the buffers is to temporarily store data arriving in the form of light through optical fibers. By slowing the mass of data, it is easier to process. Up to now, the storage quality had been limited.+

With this new technique, it should be possible to improve the process and store large bandwidths of data for prolonged times. Other potential applications include on-chip spectroscopy, broadband light harvesting and energy storage, and broadband optical camouflaging ("invisibility cloaking"). "The reported breakthrough is completely fundamental—we're giving researchers a new tool. And the number of applications is limited only by one's imagination," sums up Tsakmakidis. [25]

A stream of superfluid light

Scientists have known for centuries that light is composed of waves. The fact that light can also behave as a liquid, rippling and spiraling around obstacles like the current of a river, is a much more recent finding that is still a subject of active research. The "liquid" properties of light emerge under special circumstances, when the photons that form the light wave are able to interact with each other.

Researchers from CNR NANOTEC of Lecce in Italy, in collaboration with Polytechnique Montreal in Canada have shown that for light "dressed" with electrons, an even more dramatic effect occurs. Light become superfluid, showing frictionless flow when flowing across an obstacle and reconnecting behind it without any ripples.

Daniele Sanvitto, leading the experimental research group that observed this phenomenon, states that "Superfluidity is an impressive effect, normally observed only at temperatures close to absolute zero (-273 degrees Celsius), such as in liquid Helium and ultracold atomic gasses. The extraordinary observation in our work is that we have demonstrated that superfluidity can also occur at room-temperature, under ambient conditions, using light-matter particles called polaritons."

"Superfluidity, which allows a fluid in the absence of viscosity to literally leak out of its container", adds Sanvitto, "is linked to the ability of all the particles to condense in a state called a Bose-Einstein condensate, also known as the fifth state of matter, in which particles behave like a single macroscopic wave, oscillating all at the same frequency.

Something similar happens, for example, in superconductors: electrons, in pairs, condense, giving rise to superfluids or super-currents able to conduct electricity without losses."

These experiments have shown that it is possible to obtain superfluidity at room-temperature, whereas until now this property was achievable only at temperatures close to absolute zero. This could allow for its use in future photonic devices.

Stéphane Kéna-Cohen, the coordinator of the Montreal team, states: "To achieve superfluidity at room temperature, we sandwiched an ultrathin film of organic molecules between two highly reflective mirrors. Light interacts very strongly with the molecules as it bounces back and forth between the mirrors and this allowed us to form the hybrid light-matter fluid. In this way, we can combine the properties of photons such as their light effective mass and fast velocity, with strong interactions due to the electrons within the molecules. Under normal conditions, a fluid ripples and whirls around anything that interferes with its flow. In a superfluid, this turbulence is suppressed around obstacles, causing the flow to continue on its way unaltered".

"The fact that such an effect is observed under ambient conditions", says the research team, "can spark an enormous amount of future work, not only to study fundamental phenomena related to Bose-Einstein condensates with table-top experiments, but also to conceive and design future photonic superfluid-based devices where losses are completely suppressed and new unexpected phenomena can be exploited". [24]

Turmoil in sluggish electrons' existence

An international team of physicists has monitored the scattering behavior of electrons in a non-conducting material in real-time. Their insights could be beneficial for radiotherapy.

We can refer to electrons in non-conducting materials as 'sluggish'. Typically, they remain fixed in a location, deep inside an atomic composite. It is hence relatively still in a dielectric crystal lattice. This idyll has now been heavily shaken up by a team of physicists led by Matthias Kling, the leader of the Ultrafast Nanophotonics group in the Department of Physics at Ludwig-Maximilians-Universitaet (LMU) in Munich, and various research institutions, including the Max Planck Institute of Quantum Optics (MPQ), the Institute of Photonics and Nanotechnologies (IFN-CNR) in Milan, the Institute of Physics at the University of Rostock, the Max Born Institute (MBI), the Center for Free-Electron Laser Science (CFEL) and the University of Hamburg. For the first time, these researchers managed to directly observe the interaction of light and electrons in a dielectric, a non-conducting material, on timescales of attoseconds (billionths of a billionth of a second). The study was published in the latest issue of the journal Nature Physics.

The scientists beamed light flashes lasting only a few hundred attoseconds onto 50 nanometer thick glass particles, which released electrons inside the material. Simultaneously, they irradiated the glass particles with an intense light field, which interacted with the electrons for a few femtoseconds (millionths of a billionth of a second), causing them to oscillate. This resulted, generally, in two different reactions by the electrons. First, they started to move, then collided with atoms within the particle, either elastically or inelastically. Because of the dense crystal lattice, the electrons could move freely between each of the interactions for only a few ångstrom (10-10 meter). "Analogous to billiard, the energy of electrons is conserved in an elastic collision, while their direction can change. For inelastic collisions, atoms are excited and part of the kinetic energy is lost. In our experiments, this energy loss leads to a depletion of the electron signal that we can measure," explains Professor Francesca Calegari (CNR-IFN Milan and CFEL/University of Hamburg).

Since chance decides whether a collision occurs elastically or inelastically, with time inelastic collisions will eventually take place, reducing the number of electrons that scattered only elastically. Employing precise measurements of the electrons' oscillations within the intense light field, the researchers managed to find out that it takes about 150 attoseconds on average until elastically colliding electrons leave the nanoparticle. "Based on our newly developed theoretical model we could extract an inelastic collision time of 370 attoseconds from the measured time delay. This enabled us to clock this process for the first time," describes Professor Thomas Fennel from the University of Rostock and Berlin's Max Born Institute in his analysis of the data.

The researchers' findings could benefit medical applications. With these worldwide first ultrafast measurements of electron motions inside non-conducting materials, they have obtained important insight into the interaction of radiation with matter, which shares similarities with human tissue. The energy of released electrons is controlled with the incident light, such that the process can be investigated for a broad range of energies and for various dielectrics. "Every interaction of high-energy radiation with tissue results in the generation of electrons. These in turn transfer their energy via inelastic collisions onto atoms and molecules of the tissue, which can destroy it. Detailed insight about electron scattering is therefore relevant for the treatment of tumors. It can be used in computer simulations to optimize the destruction of tumors in radiotherapy while sparing healthy tissue," highlights Professor Matthias Kling of the impact of the work. As a next step, the scientists plan to replace the glass nanoparticles with water droplets to study the interaction of electrons with the very substance which makes up the largest part of living tissue. [23]

Achieving near-perfect optical isolation using opto-mechanical transparency

Researchers from the University of Illinois at Urbana-Champaign have demonstrated a new level of optical isolation necessary to advance on-chip optical signal processing. The technique involving light-sound interaction can be implemented in nearly any photonic foundry process and can significantly impact optical computing and communication systems.

"Low-loss optical isolators are critical components for signal routing and protection, but their chip-scale integration into photonic circuits is not yet practical. Isolators act as optical diodes by allowing light to pass through one way while blocking it in the opposite direction," explained Gaurav Bahl, an assistant professor of mechanical science and engineering at Illinois. "In this study, we demonstrated that complete optical isolation can be obtained within any dielectric waveguide using a very simple approach, and without the use of magnets or magnetic materials."

The key characteristics of ideal optical isolators are that they should permit light with zero loss one way, while absorbing light perfectly in the opposite direction, i.e. the condition of 'complete' isolation. Ideal isolators should also have a wide bandwidth and must be linear, i.e. the optical signal wavelength does not change through the device and the properties are independent of signal strength. The best method, to date, for achieving isolation with these characteristics has been through the magneto-optic Faraday rotation effect occurring in special gyrotropic materials, e.g. garnet crystals. Unfortunately, this technique has proven challenging to implement in chip-scale photonics due to fabrication complexity, difculty in locally confining magnetic fields, and significant material losses. In light of this challenge, several non-magnetic alternatives for breaking reciprocity have been explored both theoretically and experimentally.

In a previous study, Bahl's research team experimentally demonstrated, for the first time, the phenomenon of Brillouin Scattering Induced Transparency (BSIT), in which light-sound coupling can be used to slow down, speed up, and block light in an optical waveguide.

"The most significant aspect of that discovery is the observation that BSIT is a non-reciprocal phenomenon—the transparency is only generated one way. In the other direction, the system still absorbs light," Bahl said. "This non-reciprocal behavior can be exploited to build isolators and circulators that are indispensable tools in an optical designer's toolkit."

"In this work, we experimentally demonstrate complete linear optical isolation in a waveguide-resonator system composed entirely of silica glass, by pushing the BSIT interaction into the strong coupling regime, and probing optical transmission through the waveguide in the forward and backward directions simultaneously," stated JunHwan Kim, a graduate student and first author of the paper, "Complete linear optical isolation at the microscale with ultralow loss," appearing in Scientific Reports.

"Experimentally, we have demonstrated a linear isolator capable of generating a record-breaking 78.6 dB of contrast for only 1 dB of forward insertion loss within the isolation band," J. Kim added. "This means that light propagating backwards is nearly 100-million times more strongly suppressed than light in the forward direction. We also demonstrate the dynamic optical recon?gurability of the isolation direction."

"Currently the effect has been demonstrated in a narrow bandwidth. In the future, wider bandwidth isolation may also be approached if the waveguide and resonator are integrated on-chip, since remaining mechanical issues can be eliminated and the interacting modes can be designed precisely, " Bahl said. "Achieving complete linear optical isolation through opto-mechanical interactions like BSIT that occur in all media, irrespective of crystallinity or amorphicity, material band structure, magnetic bias, or presence of gain, ensures that the technique could be implemented with nearly any optical material in nearly any commercial photonics foundry."

Since it avoids magnetic fields or radiofrequency driving fields, this approach is particularly attractive for chip-scale cold atom microsystems technologies, for both isolation and shuttering of optical signals, and on-chip laser protection without loss. [22]

Physicists demonstrate photonic hypercrystals for control of light-matter interaction

Control of light-matter interaction is central to fundamental phenomena and technologies such as photosynthesis, lasers, LEDs and solar cells. City College of New York researchers have now demonstrated a new class of artificial media called photonic hypercrystals that can control light-matter interaction in unprecedented ways.

This could lead to such benefits as ultrafast LEDs for Li-Fi (a wireless technology that transmits high-speed data using visible light communication), enhanced absorption in solar cells and the development of single photon emitters for quantum information processing, said Vinod M. Menon, professor of physics in City College's Division of Science who led the research.

Photonic crystals and metamaterials are two of the most well-known artificial materials used to manipulate light. However, they suffer from drawbacks such as bandwidth limitation and poor light emission. In their research, Menon and his team overcame these drawbacks by developing hypercrystals that take on the best of both photonic crystals and metamaterials and do even better. They demonstrated significant increase in both light emission rate and intensity from nanomaterials embedded inside the hypercrystals.

The emergent properties of the hypercrystals arise from the unique combination of length scales of the features in the hypercrystal as well as the inherent properties of the nanoscale structures.

The CCNY research appears in the latest issue of the Proceedings of the National Academy of Sciences.

The team included graduate students Tal Galfsky and Jie Gu from Menon's research group in CCNY's Physics Department and Evgenii Narimanov (Purdue University), who first theoretically predicted the hypercrystals. The research was supported by the Army Research Office, the National Science

Foundation - Division of Materials Research MRSEC program, and the Gordon and Betty Moore Foundation. [21]

The first one-bit chemical memory unit—the 'chit'

In classical computer science, information is stored in bits; in quantum computer science, information is stored in quantum bits, or qubits. Experiments at the Institute of Physical Chemistry of the Polish Academy of Sciences in Warsaw prove that chemistry is also a suitable basis for storing information. The chemical bit, or 'chit,' is a simple arrangement of three droplets in contact with each other, in which oscillatory reactions occur.

In typical electronic memory, zeros and ones are recorded, stored and read by physical phenomena such as the flow of electricity or the change in electrical or magnetic properties. Dr. Konrad Gizynski and Prof. Jerzy Gorecki from the Institute of Physical Chemistry of the Polish Academy of Sciences (IPC PAS) in Warsaw have demonstrated a working memory based on chemical phenomena. A single bit is stored here in three adjoining droplets, between which chemical reaction fronts propagate steadily, cyclically, and in a strictly defined manner.

The chemical foundation of this form of memory is the Belousov-Zhabotinsky (BZ) reaction. The course of the reaction is oscillatory. When one cycle ends, the reagents necessary to start the next cycle are reconstituted in the solution. Before the reaction stops, there are usually several tens to hundreds of oscillations. They are accompanied by a regular change in the colour of the solution, caused by ferroin—the reaction catalyst. The second catalyst used by the Warsaw researchers was ruthenium. The introduction of ruthenium causes the BZ reaction to become photosensitive—when the solution is illuminated by blue light, it ceases to oscillate. This feature makes it possible to control the course of the reaction.

"Our idea for the chemical storage of information was simple. From our previous experiments, we knew that when Belousov-Zhabotinsky droplets are in contact, chemical fronts can propagate from droplet to droplet. So we decided to look for the smallest droplet systems in which excitations could take place in several ways, with at least two being stable. We could then assign one sequence of excitations a logic value of 0, the other 1, and in order to switch between them and force a particular change of memory state, we could use light," explains Prof. Gorecki.

Experiments were carried out in a container filled with a thin layer of lipid solution in oil (decane). Small amounts of oscillating solution added to the system with a pipette formed droplets. These were positioned above the ends of optical fibres brought to the base of the container. To prevent the droplets from sliding off the optical fibres, each was immobilized by several rods protruding from the base of the container.

The search began with a study of pairs of coupled droplets in which four types (modes) of oscillation can take place: droplet one excites droplet two; droplet two excites droplet one; both droplets excite each other simultaneously; both excite each other alternately (i.e., when one is excited, the other one is in the refractory phase).

"In paired droplet systems, most often, one droplet excited the other. Unfortunately, only one mode of this type was always stable, and we needed two," says Dr. Gizynski. "Both droplets are made up of the same solution, but they never have exactly the same dimensions. As a result, in each droplet, the chemical oscillations occur at a slightly different pace. In such cases, the droplet oscillating more slowly begins to adjust its rhythm to its faster 'friend.' Even if it were possible with light to force the slower oscillating droplet to excite the faster oscillating droplet, the system would return to the mode in which the faster droplet stimulated the slower one."

In this situation, the IPC PAS researchers looked into triplets of adjoining droplets arranged in a triangle (so each droplet touched its two neighbours). Chemical fronts can propagate here in many ways: Droplets may oscillate simultaneously in anti-phase, two droplets can oscillate simultaneously and force oscillations in the third, etc. The researchers were most interested in rotational modes, in which the chemical fronts passed from droplet to droplet in a 1-2-3 sequence or in the opposite direction (3-2-1).

A droplet in which the Belousov-Zhabotinsky reaction proceeds excites rapidly, but it takes much longer for it to return to its initial state and only then can become excited again. So if in the 1-2-3 mode the excitation were to reach droplet three too quickly, it would not get through to droplet one to initiate a new cycle, because droplet one would not have enough time to 'rest.' As a result, the rotational mode would disappear. IPC PAS researchers were only interested in rotational modes capable of multiple repetitions of the cycle of excitations. They had an added advantage: The chemical fronts circulating between the droplets resemble a spiral wave, and waves of this type are characterized by increased stability.

Experiments showed that both of the studied rotational modes are stable, and if a system enters one of them, it remains until the Belousov-Zhabotinsky reaction ceases. It was also proved that by correctly selecting the time and length of illumination of appropriate droplets, the direction of rotation of the excitations can be changed. The triplet droplet system, with multiple chemical fronts, was thus capable of permanently storing one of two logic states.

"In fact, our chemical bit has a slightly greater potential than the classical bit. The rotational modes we used to record states zero and one had the shortest oscillation periods of 18.7 and 19.5 seconds, respectively. So if the system oscillated any slower, we could talk about an additional third logic state," commented Dr. Gizynski, and notes that this third state could be used, for example, to verify the correctness of the record.

The research on memory made up of oscillating droplets was basic in nature and served only to demonstrate that stable storage of information using chemical reactions is possible. The newly formed memory reactions were only responsible for storing information, while its recording and reading required physical methods. It will likely be many years before a fully functioning chemical memory can be built as part of a future chemical computer. [20]

Team develops math techniques to improve computational efficiency in quantum chemistry

Researchers at Sandia National Laboratories have developed new mathematical techniques to advance the study of molecules at the quantum level.

Mathematical and algorithmic developments along these lines are necessary for enabling the detailed study of complex hydrocarbon molecules that are relevant in engine combustion.

Existing methods to approximate potential energy functions at the quantum scale need too much computer power and are thus limited to small molecules. Sandia researchers say their technique will speed up quantum mechanical computations and improve predictions made by theoretical chemistry models. Given the computational speedup, these methods can potentially be applied to bigger molecules.

Sandia postdoctoral researcher Prashant Rai worked with researchers Khachik Sargsyan and Habib Najm at Sandia's Combustion Research Facility and collaborated with quantum chemists So Hirata and Matthew Hermes at the University of Illinois at Urbana-Champaign. Computing energy at fewer geometric arrangements than normally required, the team developed computationally efficient methods to approximate potential energy surfaces.

A precise understanding of potential energy surfaces, key elements in virtually all calculations of quantum dynamics, is required to accurately estimate the energy and frequency of vibrational modes of molecules.

"If we can find the energy of the molecule for all possible configurations, we can determine important information, such as stable states of molecular transition structure or intermediate states of molecules in chemical reactions," Rai said.

Initial results of this research were published in Molecular Physics in an article titled "Low-rank canonical-tensor decomposition of potential energy surfaces: application to grid-based diagrammatic vibrational Green's function theory."

"Approximating potential energy surfaces of bigger molecules is an extremely challenging task due to the exponential increase in information required to describe them with each additional atom in the system," Rai said. "In mathematics, it is termed the Curse of Dimensionality."

Beating the curse

The key to beating the curse of dimensionality is to exploit the characteristics of the specific structure of the potential energy surfaces. Rai said this structure information can then be used to approximate the requisite high dimensional functions.

"We make use of the fact that although potential energy surfaces can be high dimensional, they can be well approximated as a small sum of products of one-dimensional functions. This is known as the low-rank structure, where the rank of the potential energy surface is the number of terms in the sum," Rai said. "Such an assumption on structure is quite general and has also been used in similar problems in other fields. Mathematically, the intuition of low-rank approximation techniques comes from multilinear algebra where the function is interpreted as a tensor and is decomposed using standard tensor decomposition techniques."

The energy and frequency corrections are formulated as integrals of these high-dimensional energy functions. Approximation in such a low-rank format renders these functions easily integrable as it breaks the integration problem to the sum of products of one- or two-dimensional integrals, so standard integration methods apply.

The team tried out their computational methods on small molecules such as water and formaldehyde. Compared to the classical Monte Carlo method, the randomness-based standard workhorse for high dimensional integration problems, their approach predicted energy and frequency of water molecule that were more accurate, and it was at least 1,000 times more computationally efficient.

Rai said the next step is to further enhance the technique by challenging it with bigger molecules, such as benzene.

"Interdisciplinary studies, such as quantum chemistry and combustion engineering, provide opportunities for cross pollination of ideas, thereby providing a new perspective on problems and their possible solutions," Rai said. "It is also a step towards using recent advances in data science as a pillar of scientific discovery in future." [19]

Towards the separation of quantum and classical query complexities

Correlation functions are often employed to quantify the relationships among interdependent variables or sets of data. A few years ago, two researchers proposed a property-testing problem involving Forrelation for studying the query complexity of quantum devices. Now, scientists have realized an experimental study of Forrelation in a 3-qubit nuclear magnetic resonance quantum information processor.

The new study was published in Science Bulletin. Four scholars from Tsinghua University, Li Hang, Gao Xun, Xin Tao and Long Guilu, collaborated with a scholar from Southern University of Science and Technology, Yung Man-Hong. In the study, they solved two-fold and three-fold Forrelation problems in nuclear spins and controlled the spin fluctuation to within a threshold value using a set of optimized GRAPE pulse sequences.

It is widely believed that quantum computers have an advantage over classical computers in many computational problems. In the black-box model, many quantum algorithms exhibit quantum speedups. This raises a question: Within the black-box model, just how large a quantum speedup is possible? Specifically, in query complexity, can we find the largest separation between classical and quantum query complexities?

Two years ago, Aaronson and Ambainis introduced a new property-testing problem called Forrelation, which determines whether one Boolean function is highly correlated with the Fourier transform of another Boolean function. And they showed that it gave the largest quantum black-box speedup yet known.

Professor Long Guilu and his collaborators designed a quantum circuit for implementing multi-fold Forrelations. They realized the two-fold and three-fold case of Forrelations on a nuclear magnetic resonance spectrometer by measuring the value of Forrelation to determine if it was larger than 3/5 or the absolute value was less than 1/100. This is the first experimental realization of the Forrelation problem reported in literature. Their results are shown in figure 1.

Professor Long Guilu, who directed the experiment, says, "One of the difficulties is achieving a high fidelity of the final states, since the value of Forrelation is highly sensitive to the measurement. To control the error within a threshold value, we utilized an optimized gradient ascent pulse engineering technique instead of a composite pulse sequence of hard pulses and J-coupling evolutions."

Professor Yung Man-Hong points out the future development of their work: "All the quantum algorithms are implemented on a three-qubit quantum information processor, which may not present the power of quantum computation over classical computation due to the present experimental techniques. However, this prototype experiment indicates that we may gain quantum supremacy in relatively simple quantum devices in the near future." [18]

Beyond classical computing without fault-tolerance: Looking for the quantum frontier

A team of researchers from Australia and the UK have developed a new theoretical framework to identify computations that occupy the 'quantum frontier'—the boundary at which problems become impossible for today's computers and can only be solved by a quantum computer. Importantly, they demonstrate that these computations can be performed with near-term, intermediate, quantum computers.

"Until recently it has been difficult to say definitively when quantum computers can outperform classical computers," said Professor Michael Bremner, Chief Investigator at the Centre for Quantum Computation and Communication Technology and founding member of the UTS Centre for Quantum Software and Information (UTS:QSI).

"The big challenge for quantum complexity theorists over the last decade has been to find stronger evidence for the existence of the quantum frontier, and then to identify where it lives. We're now getting a sense of this, and beginning to understand the resources required to cross the frontier to solve problems that today's computers can't."

The team has identified quantum computations that require the least known physical resources required to go beyond the capabilities of classical computers, significant because of the technological challenges associated with scaling up quantum computers.

Prof Bremner said that the result also indicates that full fault-tolerance may not be required to outperform classical computers. "To date, it has been widely accepted that error correction would be a necessary component of future quantum computers, but no one has yet been able to achieve this at a meaningful scale," said Bremner.

"Our work shows that while some level of error mitigation is needed to cross the quantum frontier, we may be able to outperform classical computers without the added design complexity of full fault tolerance," he said.

Dr Ashley Montanaro of the University of Bristol collaborated with Bremner to develop the framework.

"We started out with the goal of defining the minimum resources required to build a post-classical quantum computer, but then found that our model could be classically simulated with a small amount of noise, or physical imperfection," said Montanaro.

"The hope among scientists had always been that if the amount of noise in a quantum system was small enough then it would still be superior to a classical computer, however we have now shown that this probably isn't the case, at least for this particular class of computations," he said.

"We then realised that it is possible to use a classical encoding on a quantum circuit to overcome 'noise' in a much simpler way to mitigate these errors. The effectiveness of this approach was surprising. What it suggests is that we could use such structures to develop new quantum algorithms in a way that can directly avoid certain types of errors."

"This is a result that could lead to useful 'intermediate' quantum computers in the medium term, while we continue to pursue the goal of a full-scale universal quantum computer." [17]

Construction of practical quantum computers radically simplified

Scientists at the University of Sussex have invented a ground-breaking new method that puts the construction of large-scale quantum computers within reach of current technology.

Quantum computers could solve certain problems - that would take the fastest supercomputer millions of years to calculate - in just a few milliseconds.

They have the potential to create new materials and medicines, as well as solve long-standing scientific and financial problems.

Universal quantum computers can be built in principle - but the technology challenges are tremendous. The engineering required to build one is considered more difficult than manned space travel to Mars – until now.

Quantum computing on a small scale using trapped ions (charged atoms) is carried out by aligning individual laser beams onto individual ions with each ion forming a quantum bit.

However, a large-scale quantum computer would need billions of quantum bits, therefore requiring billions of precisely aligned lasers, one for each ion.

Instead, scientists at Sussex have invented a simple method where voltages are applied to a quantum computer microchip (without having to align laser beams) – to the same effect.

Professor Winfried Hensinger and his team also succeeded in demonstrating the core building block of this new method with an impressively low error rate at their quantum computing facility at Sussex.

Professor Hensinger said: "This development is a game changer for quantum computing making it accessible for industrial and government use. We will construct a large-scale quantum computer at Sussex making full use of this exciting new technology."

Quantum computers may revolutionise society in a similar way as the emergence of classical computers. Dr Seb Weidt, part of the Ion Quantum Technology Group said: "Developing this step-changing new technology has been a great adventure and it is absolutely amazing observing it actually work in the laboratory." [16]

More reliable way to produce single photons

Physicists at the University of Bath have developed a technique to more reliably produce single photons that can be imprinted with quantum information.

The invention will benefit a variety of processes which rely on photons to carry quantum information, such as quantum computing, secure quantum communication and precision measurements at low light levels.

Photons, particles of light, can be imprinted with information to be used for things like carrying out calculations and transmitting messages. To do this you need to create individual photons, which is a complicated and difficult process.

However researchers from the Centre for Photonics and Photonic Materials have implemented a new way to improve the performance of single-photon sources using fibre-optics and fast optical switches.

They combined several individual sources of photons using optical switches, a technique called multiplexing, using fibre optics fabricated at the University. The resulting device not only makes generating single photons more reliable but also allows control of properties of the photons created, including their colour.

Dr Robert Francis-Jones, from the Centre for Photonics and Photonic Materials, said: "Developing improved sources of single photons is one of the most pressing issues in quantum information processing. Through this research we hope to accelerate the transition of quantum-enhanced technologies from the lab to applications such as drug discovery."

The study is published in the journal Optica. [15]

Quantum dot LEDs that can produce entangled photons

Quantum computing is heralded as the next revolution in terms of global computing. Google, Intel and IBM are just some of the big names investing millions currently in the field of quantum computing which will enable faster, more efficient computing required to power the requirements of our future computing needs.

Now a researcher and his team at Tyndall National Institute in Cork have made a 'quantum leap' by developing a technical step that could enable the use of quantum computers sooner than expected.

Conventional digital computing uses 'on-off' switches, but quantum computing looks to harness quantum state of matters—such as entangled photons of light or multiple states of atoms—to encode information. In theory, this can lead to much faster and more powerful computer processing, but the technology to underpin quantum computing is currently difficult to develop at scale.

Researchers at Tyndall have taken a step forward by making quantum dot light-emitting diodes (LEDs) that can produce entangled photons (whose actions are linked), theoretically enabling their use to encode information in quantum computing.

This is not the first time that LEDs have been made that can produce entangled photons, but the methods and materials described in the new paper have important implications for the future of quantum technologies, explains researcher Dr Emanuele Pelucchi, Head of Epitaxy and Physics of Nanostructures and a member of the Science Foundation Ireland-funded Irish Photonic Integration Centre (IPIC) at Tyndall National Institute in Cork.

"The new development here is that we have engineered a scalable array of electrically driven quantum dots using easily-sourced materials and conventional semiconductor fabrication technologies, and our method allows you to direct the position of these sources of entangled photons," he says.

"Being able to control the positions of the quantum dots and to build them at scale are key factors to underpin more widespread use of quantum computing technologies as they develop."

The Tyndall technology uses nanotechnology to electrify arrays of the pyramid-shaped quantum dots so they produce entangled photons. "We exploit intrinsic nanoscale properties of the whole "pyramidal" structure, in particular, an engineered self-assembled vertical quantum wire, which selectively injects current into the vicinity of a quantum dot," explains Dr Pelucchi.

"The reported results are an important step towards the realisation of integrated quantum photonic circuits designed for quantum information processing tasks, where thousands or more sources would function in unison."

"It is exciting to see how research at Tyndall continues to break new ground, particularly in relation to this development in quantum computing. The significant breakthrough by Dr Pelucchi advances our understanding of how to harness the opportunity and power of quantum computing and undoubtedly accelerates progress in this field internationally. Photonics innovations by the IPIC team at Tyndall are being commercialised across a number sectors and as a result, we are directly driving global innovation through our investment, talent and research in this area," said Dr Kieran Drain, CEO at Tyndall National Institute. [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.

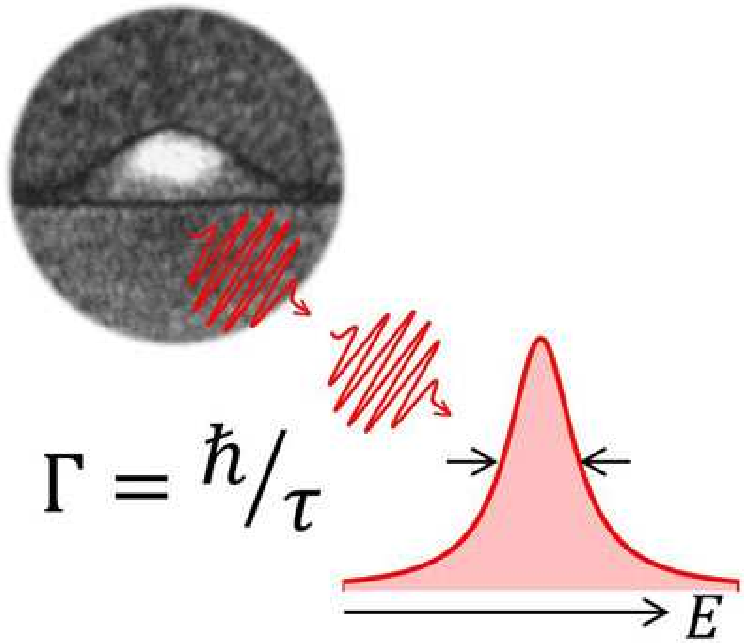
The micropillar is about 2.5 µm in diameter and about 10 µm tall, and it allowed the team to harness the "Purcell effect", whereby the rate of fluorescence is increased significantly when the emitter is placed in a resonant cavity.

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 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_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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