High-Dimensional Quantum Encryption

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For the first time, physicists have demonstrated that hyperentangled photons can be transmitted in free space, which they showed by sending many thousands of these photons between the rooftops of two buildings in Vienna. [15]

Now in a new study, physicists have cloned quantum states and demonstrated that, because the clones are entangled, it's possible to precisely and simultaneously measure the complementary properties of the clones. [14]

Light particles (photons) occur as tiny, indivisible portions. Many thousands of these light portions can be merged to form a single super-photon if they are sufficiently concentrated and cooled. [13]

The concept of temperature is critical in describing many physical phenomena, such as the transition from one phase of matter to another. Turn the temperature knob and interesting things can happen. But other knobs might be just as important for some studying some phenomena. One such knob is chemical potential, a thermodynamic parameter first introduced in the nineteenth century scientists for keeping track of potential energy absorbed or emitted by a system during chemical reactions. [12]

For the first time, physicists have performed an experiment confirming that thermodynamic processes are irreversible in a quantum system—meaning that, even on the quantum level, you can't put a broken egg back into its shell. The results have implications for understanding thermodynamics in quantum systems and, in turn, designing quantum computers and other quantum information technologies. [11]

Disorder, or entropy, in a microscopic quantum system has been measured by an international group of physicists. The team hopes that the feat will shed light on the "arrow of time": the observation that time always marches *towards the future. The experiment involved continually flipping the spin of carbon atoms with an oscillating magnetic field and links the emergence of the arrow of time to quantum fluctuations between one atomic spin state and another. [10]*

Mark M. Wilde, Assistant Professor at Louisiana State University, has improved this theorem in a way that allows for understanding how quantum measurements can be approximately reversed under certain circumstances. The new results allow for understanding how quantum information that has been lost during a measurement can be nearly recovered, which has potential implications for a variety of quantum technologies. [9]

Today, we are capable of measuring the position of an object with unprecedented accuracy, but quantum physics and the Heisenberg uncertainty principle place fundamental limits on our ability to measure. Noise that arises as a result of the quantum nature of the fields used to make those measurements imposes what is called the "standard quantum limit." This same limit influences both the ultrasensitive measurements in nanoscale devices and the kilometer-scale gravitational wave detector at LIGO. Because of this troublesome background noise, we can never know an object's exact location, but a recent study provides a solution for rerouting some of that noise away from the measurement. [8]

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.

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Preface

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. In a new proposed experiment in this area, two toaster-sized "nanosatellites" carrying entangled condensates orbit around the Earth, until one of them moves to a different orbit with different gravitational field strength. As a result of the change in gravity, the entanglement between the condensates is predicted to degrade by up to 20%. Experimentally testing the proposal may be possible in the near future. [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.

High-dimensional quantum encryption performed in real-world city conditions for first time

For the first time, researchers have sent a quantum-secured message containing more than one bit of information per photon through the air above a city. The demonstration showed that it could one day be practical to use high-capacity, free-space quantum communication to create a highly secure link between ground-based networks and satellites, a requirement for creating a global quantum encryption network.

Quantum encryption uses photons to encode information in the form of quantum bits. In its simplest form, known as 2D encryption, each photon encodes one bit: either a one or a zero. Scientists have shown that a single photon can encode even more information—a concept known as high-dimensional quantum encryption—but until now this has never been demonstrated with free-space optical communication in real-world conditions. With eight bits necessary to encode just one letter, for example, packing more information into each photon would significantly speed up data transmission.

"Our work is the first to send messages in a secure manner using high-dimensional quantum encryption in realistic city conditions, including turbulence," said research team lead, Ebrahim Karimi, University of Ottawa, Canada. "The secure, free-space communication scheme we demonstrated could potentially link Earth with satellites, securely connect places where it is too expensive to install fiber, or be used for encrypted communication with a moving object, such as an airplane."

As detailed in Optica, The Optical Society's journal for high impact research, the researchers demonstrated 4D quantum encryption over a free-space optical network spanning two buildings 0.3 kilometers apart at the University of Ottawa. This high-dimensional encryption scheme is referred to as 4D because each photon encodes two bits of information, which provides the four possibilities of 01, 10, 00 or 11.

In addition to sending more information per photon, high-dimensional quantum encryption can also tolerate more signal-obscuring noise before the transmission becomes unsecure. Noise can arise from turbulent air, failed electronics, detectors that don't work properly and from attempts to intercept the data. "This higher noise threshold means that when 2D quantum encryption fails, you can try to implement 4D because it, in principle, is more secure and more noise resistant," said Karimi.

Using light for encryption

Today, mathematical algorithms are used to encrypt text messages, banking transactions and health information. Intercepting these encrypted messages requires figuring out the exact algorithm used to encrypt a given piece of data, a feat that is difficult now but that is expected to become easier in the next decade or so as computers become more powerful.

Given the expectation that current algorithms may not work as well in the future, more attention is being given to stronger encryption techniques such as quantum key distribution, which uses properties of light particles known as quantum states to encode and send the key needed to decrypt encoded data.

Although wired and free-space quantum encryption has been deployed on some small, local networks, implementing it globally will require sending encrypted messages between ground-based stations and the satellite-based quantum communication networks that would link cities and countries. Horizontal tests through the air can be used to simulate sending signals to satellites, with about three horizontal kilometers being roughly equal to sending the signal through the Earth's atmosphere to a satellite.

Before trying a three-kilometer test, the researchers wanted to see if it was even possible to perform 4D quantum encryption outside. This was thought to be so challenging that some other scientists in the field said that the experiment would not work. One of the primary problems faced during any free-space experiment is dealing with air turbulence, which distorts the optical signal.

Real-world testing

For the tests, the researchers brought their laboratory optical setups to two different rooftops and covered them with wooden boxes to provide some protection from the elements. After much trial and error, they successfully sent messages secured with 4D quantum encryption over their intracity link. The messages exhibited an error rate of 11 percent, below the 19 percent threshold needed to maintain a secure connection. They also compared 4D encryption with 2D, finding that, after error correction, they could transmit 1.6 times more information per photon with 4D quantum encryption, even with turbulence.

"After bringing equipment that would normally be used in a clean, isolated lab environment to a rooftop that is exposed to the elements and has no vibration isolation, it was very rewarding to see results showing that we could transmit secure data," said Alicia Sit, an undergraduate student in Karimi's lab.

As a next step, the researchers are planning to implement their scheme into a network that includes three links that are about 5.6 kilometers apart and that uses a technology known as adaptive optics to compensate for the turbulence. Eventually, they want to link this network to one that exists now in the city. "Our long-term goal is to implement a quantum communication network with multiple links but using more than four dimensions while trying to get around the turbulence," said Sit. [18]

How quantum mechanics can change computing

In early July, Google announced that it will expand its commercially available cloud computing services to include quantum computing. A similar service has been available from IBM since May. These aren't services most regular people will have a lot of reason to use yet. But making quantum computers more accessible will help government, academic and corporate research groups around the world continue their study of the capabilities of quantum computing.

Understanding how these systems work requires exploring a different area of physics than most people are familiar with. From everyday experience we are familiar with what physicists call "classical mechanics," which governs most of the world we can see with our own eyes, such as what happens when a car hits a building, what path a ball takes when it's thrown and why it's hard to drag a cooler across a sandy beach.

Quantum mechanics, however, describes the subatomic realm – the behavior of protons, electrons and photons. The laws of quantum mechanics are very different from those of classical mechanics and can lead to some unexpected and counterintuitive results, such as the idea that an object can have negative mass.

Physicists around the world – in government, academic and corporate research groups – continue to explore real-world deployments of technologies based on quantum mechanics. And computer scientists, including me, are looking to understand how these technologies can be used to advance computing and cryptography.

An explanation of quantum mechanics, in terms of how well you remember someone's name when you see him.

A brief introduction to quantum physics

In our regular lives, we are used to things existing in a well-defined state: A light bulb is either on or off, for example. But in the quantum world, objects can exist in a what is called a superposition of states: A hypothetical atomic-level light bulb could simultaneously be both on and off. This strange feature has important ramifications for computing.

The smallest unit of information in classical mechanics – and, therefore, classical computers – is the bit, which can hold a value of either 0 or 1, but never both at the same time. As a result, each bit can hold just one piece of information. Such bits, which can be represented as electrical impulses, changes in magnetic fields, or even a physical on-off switch, form the basis for all calculation, storage and communication in today's computers and information networks.

Qubits – quantum bits – are the quantum equivalent of classical bits. One fundamental difference is that, due to superposition, qubits can simultaneously hold values of both 0 and 1. Physical realizations of qubits must inherently be at an atomic scale: for example, in the spin of an electron or the polarization of a photon.

Computing with qubits

Another difference is that classical bits can be operated on independently of each other: Flipping a bit in one location has no effect on bits in other locations. Qubits, however, can be set up using a quantum-mechanical property called entanglement so that they are dependent on each other – even when they are far apart. This means that operations performed on one qubit by a quantum computer can affect multiple other qubits simultaneously. This property – akin to, but not the same as, parallel processing – can make quantum computation much faster than in classical systems.

Large-scale quantum computers – that is, quantum computers with hundreds of qubits – do not yet exist, and are challenging to build because they require operations and measurements to be done on a atomic scale. IBM's quantum computer, for example, currently has 16 qubits, and Google is promising a 49-qubit quantum computer – which would be an astounding advance – by the end of the year. (In contrast, laptops currently have multiple gigabytes of RAM, with a gigabyte being eight billion classical bits.)

A powerful tool

Notwithstanding the difficulty of building working quantum computers, theorists continue to explore their potential. In 1994, Peter Shor showed that quantum computers could quickly solve the complicated math problems that underlie all commonly used public-key cryptography systems, like the ones that provide secure connections for web browsers. A large-scale quantum computer would completely compromise the security of the internet as we know it. Cryptographers are actively exploring new public-key approaches that would be "quantum-resistant," at least as far as they currently know.

Interestingly, the laws of quantum mechanics can also be used to design cryptosystems that are, in some senses, more secure than their classical analogs. For example, quantum key distribution allows two parties to share a secret no eavesdropper can recover using either classical or quantum computers. Those systems – and others based on quantum computers – may become useful in the future, either widely or in more niche applications. But a key challenge is getting them working in the real world, and over large distances. [17]

Hype and cash are muddying public understanding of quantum computing

It's no surprise that quantum computing has become a media obsession. A functional and useful quantum computer would represent one of the century's most profound technical achievements.

For researchers like me, the excitement is welcome, but some claims appearing in popular outlets can be baffling.

A recent infusion of cash and attention from the tech giants has woken the interest of analysts, who are now eager to proclaim a breakthrough moment in the development of this extraordinary technology.

Quantum computing is described as "just around the corner", simply awaiting the engineering prowess and entrepreneurial spirit of the tech sector to realise its full potential.

What's the truth? Are we really just a few years away from having quantum computers that can break all online security systems? Now that the technology giants are engaged, do we sit back and wait for them to deliver? Is it now all "just engineering"?

Why do we care so much about quantum computing?

Quantum computers are machines that use the rules of quantum physics – in other words, the physics of very small things – to encode and process information in new ways.

They exploit the unusual physics we find on these tiny scales, physics that defies our daily experience, in order to solve problems that are exceptionally challenging for "classical" computers. Don't just think of quantum computers as faster versions of today's computers – think of them as computers that function in a totally new way. The two are as different as an abacus and a PC.

They can (in principle) solve hard, high-impact questions in fields such as codebreaking, search, chemistry and physics.

Chief among these is "factoring": finding the two prime numbers, divisible only by one and themselves, which when multiplied together reach a target number. For instance, the prime factors of 15 are 3 and 5.

As simple as it looks, when the number to be factored becomes large, say 1,000 digits long, the problem is effectively impossible for a classical computer. The fact that this problem is so hard for any conventional computer is how we secure most internet communications, such as through public-key encryption.

Some quantum computers are known to perform factoring exponentially faster than any classical supercomputer. But competing with a supercomputer will still require a pretty sizeable quantum computer.

Money changes everything

Quantum computing began as a unique discipline in the late 1990s when the US government, aware of the newly discovered potential of these machines for codebreaking, began investing in university research

The field drew together teams from all over the world, including Australia, where we now have two Centres of Excellence in quantum technology (the author is part of of the Centre of Excellence for Engineered Quantum Systems).

But the academic focus is now shifting, in part, to industry.

IBM has long had a basic research program in the field. It was recently joined by Google, who invested in a University of California team, and Microsoft, which has partnered with academics globally, including the University of Sydney.

Seemingly smelling blood in the water, Silicon Valley venture capitalists also recently began investing in new startups working to build quantum computers.

The media has mistakenly seen the entry of commercial players as the genesis of recent technological acceleration, rather than a response to these advances.

So now we find a variety of competing claims about the state of the art in the field, where the field is going, and who will get to the end goal – a large-scale quantum computer – first.

The state of the art in the strangest of technologies

Conventional computer microprocessors can have more than one billion fundamental logic elements, known as transistors. In quantum systems, the fundamental quantum logic units are known as qubits, and for now, they mostly number in the range of a dozen.

Such devices are exceptionally exciting to researchers and represent huge progress, but they are little more than toys from a practical perspective. They are not near what's required for factoring or any other application – they're too small and suffer too many errors, despite what the frantic headlines may promise.

For instance, it's not even easy to answer the question of which system has the best qubits right now.

Consider the two dominant technologies. Teams using trapped ions have qubits that are resistant to errors, but relatively slow. Teams using superconducting qubits (including IBM and Google) have relatively error-prone qubits that are much faster, and may be easier to replicate in the near term.

Which is better? There's no straightforward answer. A quantum computer with many qubits that suffer from lots of errors is not necessarily more useful than a very small machine with very stable qubits.

Because quantum computers can also take different forms (general purpose versus tailored to one application), we can't even reach agreement on which system currently has the greatest set of capabilities.

Similarly, there's now seemingly endless competition over simplified metrics such as the number of qubits. Five, 16, soon 49! The question of whether a quantum computer is useful is defined by much more than this.

Where to from here?

There's been a media focus lately on achieving "quantum supremacy". This is the point where a quantum computer outperforms its best classical counterpart, and reaching this would absolutely mark an important conceptual advance in quantum computing.

But don't confuse "quantum supremacy" with "utility".

Some quantum computer researchers are seeking to devise slightly arcane problems that might allow quantum supremacy to be reached with, say, 50-100 qubits – numbers reachable within the next several years.

Achieving quantum supremacy does not mean either that those machines will be useful, or that the path to large-scale machines will become clear.

Moreover, we still need to figure out how to deal with errors. Classical computers rarely suffer hardware faults – the "blue screen of death" generally comes from software bugs, rather than hardware failures. The likelihood of hardware failure is usually less than something like one in a billion-quadrillion, or 10-24 in scientific notation.

The best quantum computer hardware, on the other hand, typically achieves only about one in 10,000, or 10-4. That's 20 orders of magnitude worse.

Is it all just engineering?

We're seeing a slow creep up in the number of qubits in the most advanced systems, and clever scientists are thinking about problems that might be usefully addressed with small quantum computers containing just a few hundred qubits.

But we still face many fundamental questions about how to build, operate or even validate the performance of the large-scale systems we sometimes hear are just around the corner.

As an example, if we built a fully "error-corrected" quantum computer at the scale of the millions of qubits required for useful factoring, as far as we can tell, it would represent a totally new state of matter. That's pretty fundamental.

At this stage, there's no clear path to the millions of error-corrected qubits we believe are required to build a useful factoring machine. Current global efforts (in which this author is a participant) are seeking to build just one error-corrected qubit to be delivered about five years from now.

At the end of the day, none of the teams mentioned above are likely to build a useful quantum computer in 2017 … or 2018. But that shouldn't cause concern when there are so many exciting questions to answer along the way. [16]

Hyperentanglement across roof tops paves the way toward a global quantum Internet

For the first time, physicists have demonstrated that hyperentangled photons can be transmitted in free space, which they showed by sending many thousands of these photons between the rooftops of two buildings in Vienna. Hyperentanglement means that the photons are simultaneously entangled in at least two different properties—in this experiment, the researchers combined two two-dimensionally entangled properties to achieve four-dimensional hyperentanglement.

By showing that hyperentanglement transmission is feasible in the real world and not only in the lab, the physicists expect that the demonstration could one day be scaled up to establish a highly secure quantum Internet that uses satellites to quickly and securely transmit quantum information across the globe.

The physicists, led by Rupert Ursin at the Institute for Quantum Optics and Quantum Information (IQOQI) at the Austrian Academy of Sciences in Vienna, have published a paper on the distribution of hyperentanglement via atmospheric free-space links in a recent issue of Nature Communications.

Hyperentangled states have several advantages over states with only one entangled property, including higher data rates and improved levels of security in quantum communication. So far, however, experiments involving hyperentanglement have only been demonstrated in protected laboratory environments across short distances. The ability to transmit hyperentangled states via optical free-space links will allow for transmission over longer distances than is possible using optical fibers on the ground.

As the physicists explain, the simplest type of entanglement between photons is polarization entanglement. When measured, a photon will exhibit one of two polarization states (vertical or horizontal), producing two-dimensional entanglement in the polarization degree of freedom. In two-dimensional polarization encoding, each photon is restricted to encoding at most one qubit.

But there are other ways to entangle photons, and these methods can be combined with polarization entanglement to achieve hyperentangled photons, which have the potential to store multiple qubits.

In the new work, the physicists combined polarization entanglement with a second kind of entanglement called energy-time entanglement, which involves the emission time of the photon pair and can take on many possible values, resulting in many higher dimensions. In this experiment, for technical reasons, the physicists used only two particular emission times, "early" and "late," corresponding to two degrees of freedom. When combined, the two types of entanglement enabled the researchers to create four-dimensional hyperentangled states.

"We encoded qubits in two properties of the photon simultaneously," coauthor Fabian Steinlechner at the Austrian Academy of Sciences told Phys.org. "We encoded one qubit in the well-studied polarization degree of freedom, and another in the time-energy degree of freedom, which had not yet been shown to withstand transmission via a turbulent free-space link. This way we doubled the amount of entanglement per photon compared to previous experiments over real-world optical links. Increasing the dimensionality of entanglement and transmitting high-dimensional entanglement under real-world atmospheric link conditions is an important step towards more efficient and practical quantum communication systems."

The hyperentangled photon source, which generates pairs of hyperentangled photons, was located in a laboratory at the IQOQI in Vienna. To demonstrate hyperentanglement distribution, the researchers stored one photon from each hyperentangled pair at the lab and sent the other photon in each pair through an optical fiber to a transmitter telescope on the roof of the building. The telescope then transmitted that photon in free space to a receiver on the roof of another building located 1.2 km away, which collected the photons and verified their hyperentanglement.

Although atmospheric turbulence caused the transmission efficiency of the hyperentangled photons to vary, and approximately half of the distributed photons were lost due to absorption by the optical components, the researchers still successfully detected about 20,000 photon pairs per second. The results demonstrate, for the first time, the feasibility of using energy-time/polarization hyperentanglement in real-world conditions. The researchers are now looking forward to developing applications that harness the advantages of hyperentanglement.

"Hyperentanglement, simultaneous entanglement in multiple degrees of freedom, can be used to encode several entangled qubits per photon," said coauthor Sebastian Ecker at the Austrian Academy of Sciences. "We refer to this as high-dimensional entanglement. Increasing the dimensionality of entanglement promises higher data rates and improved levels of security in quantum cryptography, since attempts to copy high-dimensional quantum states result in larger errors compared to two-dimensional encoding, thus making it easier to detect an eavesdropper. Furthermore, certain transformations are easier to accomplish when quantum states are encoded in several degrees of freedom, which can make quantum information processing protocols, such as quantum teleportation and dense coding, easier to implement in practice."

In the future, the physicists hope to increase the dimensionality far beyond four dimensions, pushing the amount of quantum information that can be transmitted by a single photon to its ultimate limits. This could significantly boost the data rates in future satellite experiments.

"In our experiment, we used two dimensions of the time-energy space," Steinlechner said. "However, unlike polarization, time-energy entanglement is not fundamentally limited to two possible states and its potential dimensionality is orders of magnitudes larger."

If hyperentanglement can be transmitted higher up in space, it would also open up possibilities for new kinds of fundamental physics experiments. These could include investigating gravity-induced collapse of the wave function and quantum information processing under relativistic conditions. [15]

Physicists measure complementary properties using quantum clones

In quantum mechanics, it's impossible to precisely and simultaneously measure the complementary properties (such as the position and momentum) of a quantum state. Now in a new study, physicists have cloned quantum states and demonstrated that, because the clones are entangled, it's possible to precisely and simultaneously measure the complementary properties of the clones. These measurements, in turn, reveal the state of the input quantum system.

The ability to determine the complementary properties of quantum states in this way not only has implications for understanding fundamental quantum physics, but also has potential applications for quantum computing, quantum cryptography, and other technologies.

The physicists, Guillame S. Thekkadath and coauthors at the University of Ottawa, Ontario, have published a paper on determining complementary properties of quantum clones in a recent issue of Physical Review Letters.

As the physicists explain, in the classical world it's possible to simultaneously measure a system's complementary states with exact precision, and doing so reveals the system's state. But as Heisenberg theoretically proposed in 1927 when he was beginning to develop his famous uncertainty principle, any measurement made on a quantum system induces a disturbance on that system.

This disturbance is largest when measuring complementary properties. For instance, measuring the position of a particle will disturb its momentum, changing its quantum state. These joint measurements have intrigued physicists ever since the time of Heisenberg.

As a way around the difficulty of performing joint measurements, physicists have recently investigated the possibility of making a copy of a quantum system, and then independently measuring one property on each copy of the system. Since the measurements are performed separately, they would not be expected to disturb each other, yet they would still reveal information about the original quantum system because the copies share the same properties as the original.

This strategy immediately encounters another quantum restriction: due to the no-cloning theorem, it's impossible to make a perfect copy of a quantum state. So instead, the physicists in the new study investigated the closest quantum analog to copying, which is optimal cloning. The parts of the clones' states that share the exact same properties as those of the input state are called "twins."

Whereas theoretical perfect copies of a quantum state are uncorrelated, the twins are entangled. The physicists showed that, as a consequence of this entanglement, independently measuring the complementary properties on each twin is equivalent to simultaneously measuring the complementary properties of the input state. This leads to the main result of the new study: that simultaneously measuring the complementary properties of twins gives the state (technically, the wave function) of the original quantum system.

"In quantum mechanics, measurements disturb the state of the system being measured," Thekkadath told Phys.org. "This is a hurdle physicists face when trying to characterize quantum systems such as single photons. In the past, physicists successfully used very gentle measurements (known as weak measurements) to circumvent this disturbance.

"As such, our work is not the first to determine complementary properties of a quantum system. However, we've shown that a different strategy can be used. It is based on a rather naïve idea. Suppose we want to measure the position and momentum of a particle. Knowing that these measurements will disturb the particle's state, can we first copy the particle, and measure position on one copy and momentum on the other? This was our initial motivation. But it turns out that copying alone is not enough. The measured copies must also be entangled for this strategy to work.

"This is what we showed experimentally. Instead of determining the position and momentum of a particle, we determined complementary polarization properties of single photons. You would intuitively expect this strategy to fail due to the no-cloning theorem. However, we showed that is not the case, and this is the greatest significance of our result: measuring complementary properties of the twins directly reveals the quantum state of the copied system."

As the physicists explain, one of the most important aspects of the demonstration is working around the limitations of the no-cloning theorem.

"In our daily lives, information is often copied, such as when we photocopy a document, or when DNA is replicated in our bodies," Thekkadath explained. "However, at a quantum level, information cannot be copied without introducing some noise or imperfections. We know this because of a mathematical result known as the no-cloning theorem. This has not stopped physicists from trying. They developed strategies, known as optimal cloning, that minimize the amount of noise introduced by the copying process. In our work, we go one step further. We showed that it is possible to eliminate this noise from our measurements on the copies using a clever trick that was theoretically proposed by Holger Hofmann in 2012. Our results do not violate the no-cloning theorem since we never physically produce perfect copies: we only replicate the measurement results one would get with perfect copies."

In their experiments, the physicists demonstrated the new method using photonic twins, but they expect that the ability to make precise, simultaneous measurements of complementary properties on twins can also be implemented with quantum computers. This could lead to many practical applications, such as providing an efficient method to directly measure high-dimensional quantum states, which are used in quantum computing and quantum cryptography.

"Determining the state of a system is an important task in physics," Thekkadath said. "Once a state is determined, everything about that system is known. This knowledge can then be used to, for example, predict measurement outcomes and verify that an experiment is working as intended. This verification is especially important when complicated states are produced, such as the ones needed in quantum computers or quantum cryptography.

"Typically, quantum states are determined tomographically, much like how the brain is imaged in a CAT scan. This approach has the limitation that the state is always globally reconstructed. In contrast, our method determines the value of quantum states at any desired point, providing a more efficient and direct method than conventional methods for state determination.

"We experimentally demonstrated our method using single photons. But, our strategy is also applicable in a variety of other systems. For instance, it can be implemented in a quantum computer by using only a single quantum logic gate. We anticipate that our method could be used to efficiently characterize complicated quantum states inside a quantum computer." [14]

Exotic quantum states made from light

Light particles (photons) occur as tiny, indivisible portions. Many thousands of these light portions can be merged to form a single super-photon if they are sufficiently concentrated and cooled. The individual particles merge with each other, making them indistinguishable. Researchers call this a photonic Bose-Einstein condensate. It has long been known that normal atoms form such condensates. Prof. Martin Weitz from the Institute of Applied Physics at the University of Bonn attracted attention among experts in 2010 when he produced a Bose-Einstein condensate from photons for the first time.

In his latest study, Prof. Weitz' team experimented with this kind of super-photon. In the experimental setup, a laser beam was rapidly bounced back and forth between two mirrors. In between was a pigment that cooled the laser light to such an extent that a super-photon was created from the individual light portions. "The special thing is that we have built a kind of optical well in various forms, into which the Bose-Einstein condensate was able to flow," reports Weitz.

A polymer varies the light path

The team of researchers used a trick here: It mixed a polymer into the pigment between the mirrors, which changed its refractive index depending on the temperature. The route between the mirrors for the light thus changed so that longer light wavelengths passed between the mirrors when heated. The extent of the light path between the mirrors could be varied, in that the polymer could be warmed via a very thin heating layer.

"With the help of various temperature patterns, we were able to create different optical dents," explains Weitz. The geometry of the mirror only appeared to warp, while the refractive index of the polymer changed at certain points - however, this had the same effect as a hollow shape. Part of the super-photon flowed into this apparent well. In this way, the researchers were able to use their apparatus to create different, very low-loss patterns that captured the photonic Bose-Einstein condensate.

Precursor of quantum circuits

The team of researchers investigated in detail the formation of two neighboring wells, controlled via the temperature pattern of the polymer. When the light in both optical hollows remained at a similar energy level, the super-photon flowed from one well into the neighboring one. "This was a precursor of optical quantum circuits," highlighted the physicist at the University of Bonn. "Perhaps even complex arrangements, for which quantum entanglement occurs in interaction with a possible photon interaction in suitable materials, can be produced with this experimental setup."

This would, in turn, be the prerequisite for a new technique for quantum communication and quantum computers. "But that's still a long way off," says Weitz. The findings by the research team could also conceivably be used to further develop lasers - for instance for highly precise welding work. [13]

Controlling the thermodynamics of light

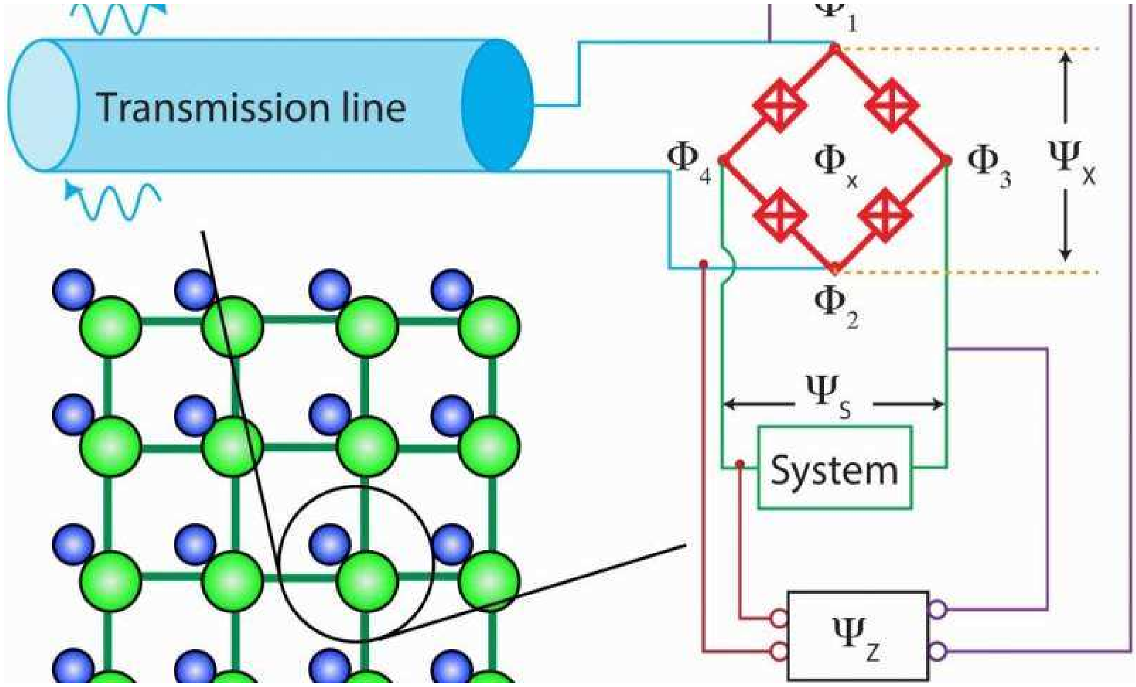
In these reactions different atomic species rearranged themselves into new configuration while conserving the overall inventory of atoms. That is, atoms could change their partners but the total number of identity of the atoms remained invariant.

Chemical potential is just one of many examples of how flows can be described. An imbalance in temperature results in a flow of energy. An imbalance in electrical potential results in a flow of charged particles. An imbalance in chemical potential results in a flow of particles; and specifically an imbalance in chemical potential for light would results in a flow of photons.

Can the concept of chemical light apply to light? At first the answer would seem to be no since particles of light, photons, are regularly absorbed when then they interact with regular matter. The number of photons present is not preserved. But recent experiments have shown that under special conditions photon number can be conserved, clearing the way for the use of chemical potential for light.

Now three JQI scientists offer a more generalized theoretical description of chemical potential (usually denoted by the Greek letter mu) for light and show how mu can be controlled and applied in a number of physics research areas.

A prominent experimental demonstration of chemical potential for light took place at the University of Bonn in 2010. It consisted of quanta of light (photons) bouncing back and forth inside a reflective cavity filled with dye molecules. The dye molecules, acting as a tunable energy bath (a parametric bath), would regularly absorb photons (seemingly ruling out the idea of photon number being conserved) but would re-emit the light. Gradually the light warmed the molecules and the molecules cooled the light until they were all at thermal equilibrium. This was the first time photons had been successfully "thermalized" in this way. Furthermore, at still colder temperatures the photons collapsed into a single quantum state; this was the first photonic Bose-Einstein condensate (BEC).



Apparatus for demonstrating chemical potential for light. The reaction of photons (represented by the green balls in the picture) with circuits (represented by blue balls) leads to a controllable thermal equilibrium of the light with the circuits. The Greek letters psi and phi refer to various modes of light.

In a paper published in the journal Physical Review B the JQI theorists describe a generic approach to chemical potential for light. They illustrate their ideas by showing how a chemical-potential protocol can be implemented a microcircuit array. Instead of crisscrossing a single cavity, the photons are set loose in an array of microwave transmission lines. And instead of interacting with a bath of dye molecules, the photons here interact with a network of tuned circuits

"One likely benefit in using chemical potential as a controllable parameter will be carrying out quantum simulations of actual condensed-matter systems," said Jacob Taylor, one of the JQI theorists taking part in the new study. In what some call a prototype for future full-scale quantum computing, quantum simulations use tuned interactions in a small microcircuit setup to arrive at a numerical solution to calculations that (in their complexity) would defeat a normal digital computer.

In the scheme described above, for instance, the photons, carefully put in a superposition of spin states, could serve as qubits. The qubits can be programmed to perform special simulations. The circuits, including the transmission lines, act as the coupling mechanism whereby photons can be respectively up- or down-converted to lower or higher energy by obtaining energy from or giving energy to excitations of the circuits. [12]

Physicists confirm thermodynamic irreversibility in a quantum system

The physicists, Tiago Batalhão at the Federal University of ABC, Brazil, and coauthors, have published their paper on the experimental demonstration of quantum thermodynamic irreversibility in a recent issue of Physical Review Letters.

Irreversibility at the quantum level may seem obvious to most people because it matches our observations of the everyday, macroscopic world. However, it is not as straightforward to physicists because the microscopic laws of physics, such as the Schrödinger equation, are "time-symmetric," or reversible. In theory, forward and backward microscopic processes are indistinguishable.

In reality, however, we only observe forward processes, not reversible ones like broken egg shells being put back together. It's clear that, at the macroscopic level, the laws run counter to what we observe. Now the new study shows that the laws don't match what happens at the quantum level, either.

Observing thermodynamic processes in a quantum system is very difficult and has not been done until now. In their experiment, the scientists measured the entropy change that occurs when applying an oscillating magnetic field to carbon-13 atoms in liquid chloroform. They first applied a magnetic field pulse that causes the atoms' nuclear spins to flip, and then applied the pulse in reverse to make the spins undergo the reversed dynamics.

If the procedure were reversible, the spins would have returned to their starting points—but they didn't. Basically, the forward and reverse magnetic pulses were applied so rapidly that the spins' flipping couldn't always keep up, so the spins were driven out of equilibrium. The measurements of the spins indicated that entropy was increasing in the isolated system, showing that the quantum thermodynamic process was irreversible.

By demonstrating that thermodynamic irreversibility occurs even at the quantum level, the results reveal that thermodynamic irreversibility emerges at a genuine microscopic scale. This finding makes the question of why the microscopic laws of physics don't match our observations even more pressing. If the laws really are reversible, then what are the physical origins of the time-asymmetric entropy production that we observe?

The physicists explain that the answer to this question lies in the choice of the initial conditions. The microscopic laws allow reversible processes only because they begin with "a genuine equilibrium process for which the entropy production vanishes at all times," the scientists write in their paper. Preparing such an ideal initial state in a physical system is extremely complex, and the initial states of all observed processes aren't at "genuine equilibrium," which is why they lead to irreversible processes.

"Our experiment shows the irreversible nature of quantum dynamics, but does not pinpoint, experimentally, what causes it at the microscopic level, what determines the onset of the arrow of time," coauthor Mauro Paternostro at Queen's University in Belfast, UK, told Phys.org. "Addressing it would clarify the ultimate reason for its emergence."

The researchers hope to apply the new understanding of thermodynamics at the quantum level to high-performance quantum technologies in the future.

"Any progress towards the management of finite-time thermodynamic processes at the quantum level is a step forward towards the realization of a fully fledged thermo-machine that can exploit the laws of quantum mechanics to overcome the performance limitations of classical devices," Paternostro said. "This work shows the implications for reversibility (or lack thereof) of non-equilibrium quantum dynamics. Once we characterize it, we can harness it at the technological level." [11]

Physicists put the arrow of time under a quantum microscope

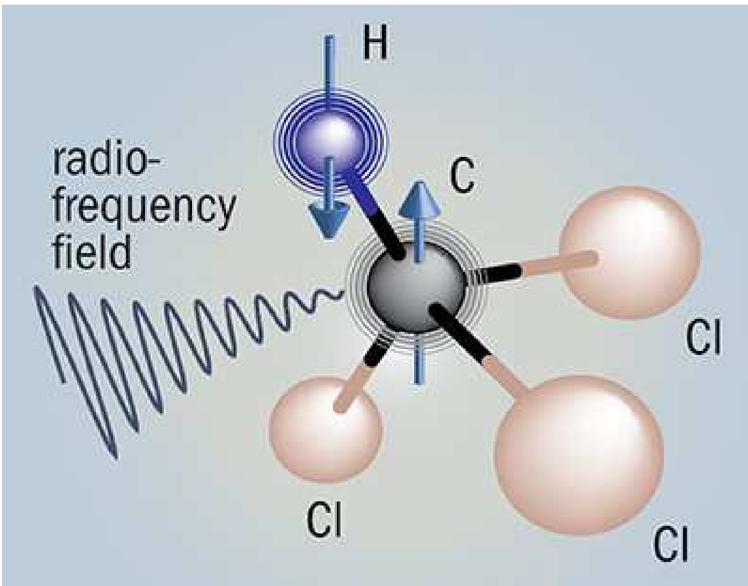


Diagram showing the spin of a carbon atom in a chloroform molecule

Disorder, or entropy, in a microscopic quantum system has been measured by an international group of physicists. The team hopes that the feat will shed light on the "arrow of time": the observation that time always marches towards the future. The experiment involved continually flipping the spin of carbon atoms with an oscillating magnetic field and links the emergence of the arrow of time to quantum fluctuations between one atomic spin state and another.

"That is why we remember yesterday and not tomorrow," explains group member Roberto Serra, a physicist specializing in quantum information at the Federal University of ABC in Santo André, Brazil. At the fundamental level, he says, quantum fluctuations are involved in the asymmetry of time.

Egging on

The arrow of time is often taken for granted in the everyday world. We see an egg breaking, for example, yet we never see the yolk, white and shell fragments come back together again to recreate the egg. It seems obvious that the laws of nature should not be reversible, yet there is nothing in the underlying physics to say so.

The dynamical equations of an egg breaking run just as well forwards as they do backwards.

Entropy, however, provides a window onto the arrow of time. Most eggs look alike, but a broken egg can take on any number of forms: it could be neatly cracked open, scrambled, splattered all over a pavement, and so on. A broken egg is a disordered state – that is, a state of greater entropy – and because there are many more disordered than ordered states, it is more likely for a system to progress towards disorder than order.

This probabilistic reasoning is encapsulated in the second law of thermodynamics, which states that the entropy of a closed system always increases over time.

According to the second law, time cannot suddenly go backwards because this would require entropy to decrease. It is a convincing argument for a complex system made up of a great many interacting particles, like an egg, but what about a system composed of just one particle?

Murky territory

Serra and colleagues have delved into this murky territory with measurements of entropy in an ensemble of carbon-13 atoms contained in a sample of liquid chloroform. Although the sample contained roughly a trillion chloroform molecules, the non-interacting quantum nature of the molecules meant that the experiment was equivalent to performing the same measurement on a single carbon atom, one trillion times.

Serra and colleagues applied an oscillating external magnetic field to the sample, which continually flipped the spin state of a carbon atom between up and down.

They ramped up the intensity of the field oscillations to increase the frequency of the spin-flipping, and then brought the intensity back down again.

Had the system been reversible, the overall distribution of carbon spin states would have been the same at the end as at the start of the process. Using nuclear magnetic resonance and quantum-state tomography, however, Serra and colleagues measured an increase in disorder among the final spins. Because of the quantum nature of the system, this was equivalent to an increase in entropy in a single carbon atom.

According to the researchers, entropy rises for a single atom because of the speed with which it is forced to flip its spin. Unable to keep up with the field-oscillation intensity, the atom begins to fluctuate randomly, like an inexperienced dancer failing to keep pace with up-tempo music. "It's easier to dance to a slow rhythm than a fast one," says Serra.

Many questions remain

The group has managed to observe the existence of the arrow of time in a quantum system, says experimentalist Mark Raizen of the University of Texas at Austin in the US, who has also studied irreversibility in quantum systems. But Raizen stresses that the group has not observed the "onset" of the arrow of time. "This [study] does not close the book on our understanding of the arrow of time, and many questions remain," he adds.

One of those questions is whether the arrow of time is linked to quantum entanglement – the phenomenon whereby two particles exhibit instantaneous correlations with each other, even when separated by vast distances. This idea is nearly 30 years old and has enjoyed a recent resurgence in popularity. However, this link is less to do with growing entropy and more to do with an unstoppable dispersion of quantum information.

Indeed, Serra believes that by harnessing quantum entanglement, it may even be possible to reverse the arrow of time in a microscopic system. "We're working on it," he says. "In the next generation of our experiments on quantum thermodynamics we will explore such aspects." [10]

Small entropy changes allow quantum measurements to be nearly reversed

In 1975, Swedish physicist Göran Lindblad developed a theorem that describes the change in entropy that occurs during a quantum measurement. Today, this theorem is a foundational component of quantum information theory, underlying such important concepts as the uncertainty principle, the second law of thermodynamics, and data transmission in quantum communication systems.

Now, 40 years later, physicist Mark M. Wilde, Assistant Professor at Louisiana State University, has improved this theorem in a way that allows for understanding how quantum measurements can be approximately reversed under certain circumstances. The new results allow for understanding how quantum information that has been lost during a measurement can be nearly recovered, which has potential implications for a variety of quantum technologies.

Quantum relative entropy never increases

Most people are familiar with entropy as a measure of disorder and the law that "entropy never decreases"—it either increases or stays the same during a thermodynamic process, according to the second law of thermodynamics. However, here the focus is on "quantum relative entropy," which in some sense is the negative of entropy, so the reverse is true: quantum relative entropy never increases, but instead only decreases or stays the same.

In fact, this was the entropy inequality theorem that Lindblad proved in 1975: that the quantum relative entropy cannot increase after a measurement. In this context, quantum relative entropy is interpreted as a measure of how well one can distinguish between two quantum states, so it's this distinguishability that can never increase. (Wilde describes a proof of Lindblad's result in greater detail in his textbook Quantum Information Theory, published by Cambridge University Press.)

One thing that Lindblad's proof doesn't address, however, is whether it makes any difference if the quantum relative entropy decreases by a little or by a lot after a measurement.

In the new paper, Wilde has shown that, if the quantum relative entropy decreases by only a little, then the quantum measurement (or any other type of so-called "quantum physical evolution") can be approximately reversed.

"When looking at Lindblad's entropy inequality, a natural question is to wonder what we could say if the quantum relative entropy goes down only by a little when the quantum physical evolution is applied," Wilde told Phys.org. "It is quite reasonable to suspect that we might be able to approximately reverse the evolution. This was arguably open since the work of Lindblad in 1975, addressed in an important way by Denes Petz in the late 1980s (for the case in which the quantum relative entropy stays the same under the action of the evolution), and finally formulated as a conjecture around 2008 by Andreas Winter. What my work did was to prove this result as a theorem: if the quantum relative entropy goes down only by a little under a quantum physical evolution, then we can approximately reverse its action."

Wide implications

Wilde's improvements to Lindblad's theorem have a variety of implications, but the main one that Wilde discusses in his paper is how the new results allow for recovering quantum information.

"If the decrease in quantum relative entropy between two quantum states after a quantum physical evolution is relatively small," he said, "then it is possible to perform a recovery operation, such that one can perfectly recover one state while approximately recovering the other. This can be interpreted as quantifying how well one can reverse a quantum physical evolution." So the smaller the relative entropy decrease, the better the reversal process.

The ability to recover quantum information could prove useful for quantum error correction, which aims to protect quantum information from damaging external effects. Wilde plans to address this application more in the future with his colleagues.

As Wilde explained, Lindblad's original theorem can also be used to prove the uncertainty principle of quantum mechanics in terms of entropies, as well as the second law of thermodynamics for quantum systems, so the new results have implications in these areas, as well.

"Lindblad's entropy inequality underlies many limiting statements, in some cases said to be physical laws or principles," Wilde said. "Examples are the uncertainty principle and the second law of thermodynamics. Another example is that this entropy inequality is the core step in determining limitations on how much data we can communicate over quantum communication channels. We could go as far as to say that the above entropy inequality constitutes a fundamental law of quantum information theory, which is a direct mathematical consequence of the postulates of quantum mechanics."

Regarding the uncertainty principle, Wilde and two coauthors, Mario Berta and Stephanie Wehner, discuss this angle in a forthcoming paper. They explain that the uncertainty principle involves quantum measurements, which are a type of quantum physical evolution and therefore subject to Lindblad's theorem. In one formulation of the uncertainty principle, two experiments are performed on different copies of the same quantum state, with both experimental outcomes having some uncertainty.

"The uncertainty principle is the statement that you cannot generally make the uncertainties of both experiments arbitrarily small, i.e., there is generally a limitation," Wilde said. "It is now known that a statement of the uncertainty principle in terms of entropies can be proved by using the 'decrease of quantum relative entropy inequality.' So what the new theorem allows for doing is relating the uncertainties of the measurement outcomes to how well we could try to reverse the action of one of the measurements. That is, there is now a single mathematical inequality which captures all of these notions."

In terms of the second law of thermodynamics, Wilde explains how the new results have implications for reversing thermodynamic processes in both classical and quantum systems.

"The new theorem allows for quantifying how well we can approximately reverse a thermodynamic transition from one state to another without using any energy at all," he said.

He explained that this is possible due to the connection between entropy, energy, and work. According to the second law of thermodynamics, a thermodynamic transition from one quantum state to another is allowed only if the free energy decreases from the original state to the final state. During this process, one can gain work and store energy. This law can be rewritten as a statement involving relative entropies and can be proved as a consequence of the decrease of quantum relative entropy.

"What my new work with Stephanie Wehner and Mischa Woods allows for is a refinement of this statement," Wilde said. "We can say that if the free energy does not go down by very much under a thermodynamic transition (i.e., if there is not too much work gained in the process), then it is possible to go back approximately to the original state from the final state, without investing any work at all. The key word here is that you can go back only approximately, so we are not in violation of the second law, only providing a refinement of it."

In addition to these implications, the new theorem can also be applied to other research topics in quantum information theory, including the Holevo bound, quantum discord, and multipartite information measures.

Wilde's work was funded in part by The DARPA Quiness program (ending now), which focused on quantum key distribution, or using quantum mechanics to ensure secret communication between two parties. He describes more about this application, in particular how Alice and Bob might use a quantum state to share secrets that can be kept private from an eavesdropper Eve (and help them survive being attacked by a bear), in a recent blog post. [9]

Tricking the uncertainty principle

"If you want to know where something is, you have to scatter something off of it," explains Professor of Applied Physics Keith Schwab, who led the study. "For example, if you shine light at an object, the photons that scatter off provide information about the object. But the photons don't all hit and scatter at the same time, and the random pattern of scattering creates quantum fluctuations"—that is, noise. "If you shine more light, you have increased sensitivity, but you also have more noise. Here we were looking for a way to beat the uncertainty principle—to increase sensitivity but not noise."

Schwab and his colleagues began by developing a way to actually detect the noise produced during the scattering of microwaves—electromagnetic radiation that has a wavelength longer than that of visible light. To do this, they delivered microwaves of a specific frequency to a superconducting electronic circuit, or resonator, that vibrates at 5 gigahertz—or 5 billion times per second. The electronic circuit was then coupled to a mechanical device formed of two metal plates that vibrate at around 4 megahertz—or 4 million times per second. The researchers observed that the quantum noise of the microwave field, due to the impact of individual photons, made the mechanical device shake randomly with an amplitude of 10-15 meters, about the diameter of a proton.

"Our mechanical device is a tiny square of aluminum—only 40 microns long, or about the diameter of a hair. We think of quantum mechanics as a good description for the behaviors of atoms and electrons and protons and all of that, but normally you don't think of these sorts of quantum effects manifesting themselves on somewhat macroscopic objects," Schwab says. "This is a physical manifestation of the uncertainty principle, seen in single photons impacting a somewhat macroscopic thing."

Once the researchers had a reliable mechanism for detecting the forces generated by the quantum fluctuations of microwaves on a macroscopic object, they could modify their electronic resonator, mechanical device, and mathematical approach to exclude the noise of the position and motion of the vibrating metal plates from their measurement.

The experiment shows that a) the noise is present and can be picked up by a detector, and b) it can be pushed to someplace that won't affect the measurement. "It's a way of tricking the uncertainty principle so that you can dial up the sensitivity of a detector without increasing the noise," Schwab says.

Although this experiment is mostly a fundamental exploration of the quantum nature of microwaves in mechanical devices, Schwab says that this line of research could one day lead to the observation of quantum mechanical effects in much larger mechanical structures. And that, he notes, could allow the demonstration of strange quantum mechanical properties like superposition and entanglement in large objects—for example, allowing a macroscopic object to exist in two places at once.

"Subatomic particles act in quantum ways—they have a wave-like nature—and so can atoms, and so can whole molecules since they're collections of atoms,"

Schwab says. "So the question then is: Can you make bigger and bigger objects behave in these weird wave-like ways? Why not? Right now we're just trying to figure out where the boundary of quantum physics is, but you never know." [8]

Particle Measurement Sidesteps the Uncertainty Principle

Quantum mechanics imposes a limit on what we can know about subatomic particles. If physicists measure a particle’s position, they cannot also measure its momentum, so the theory goes. But a new experiment has managed to circumvent this rule—the so-called uncertainty principle—by ascertaining just a little bit about a particle’s position, thus retaining the ability to measure its momentum, too.

The uncertainty principle, formulated by Werner Heisenberg in 1927, is a consequence of the fuzziness of the universe at microscopic scales. Quantum mechanics revealed that particles are not just tiny marbles that act like ordinary objects we can see and touch. Instead of being in a particular place at a particular time, particles actually exist in a haze of probability. Their chances of being in any given state are described by an equation called the quantum wavefunction. Any measurement of a particle "collapses" its wavefunction, in effect forcing it to choose a value for the measured characteristic and eliminating the possibility of knowing anything about its related properties.

Recently, physicists decided to see if they could overcome this limitation by using a new engineering technique called compressive sensing. This tool for making efficient measurements has already been applied successfully in digital photographs, MRI scans and many other technologies. Normally, measuring devices would take a detailed reading and afterward compress it for ease of use. For example, cameras take large raw files and then convert them to compressed jpegs. In compressive sensing, however, engineers aim to compress a signal while measuring it, allowing them to take many fewer measurements—the equivalent of capturing images as jpegs rather than raw files.

This same technique of acquiring the minimum amount of information needed for a measurement seemed to offer a way around the uncertainty principle. To test compressive sensing in the quantum world, physicist John C. Howell and his team at the University of Rochester set out to measure the position and momentum of a photon—a particle of light. They shone a laser through a box equipped with an array of mirrors that could either point toward or away from a detector at its end. These mirrors formed a filter, allowing photons through in some places and blocking them in others. If a photon made it to the detector, the physicists knew it had been in one of the locations where the mirrors offered a throughway. The filter provided a way of measuring a particle's position without knowing exactly where it was—without collapsing its wavefunction. "All we know is either the photon can get through that pattern, or it can't," says Gregory A. Howland, first author of a paper reporting the research published June 26 in Physical Review Letters. "It turns out that because of that we're still able to figure out the momentum—where it's going. The penalty that we pay is that our measurement of where it's going gets a little bit of noise on it." A less precise momentum measurement, however, is better than no momentum measurement at all.

The physicists stress that they have not broken any laws of physics. "We do not violate the uncertainty principle," Howland says. "We just use it in a clever way." The technique could prove powerful for developing technologies such as quantum cryptography and quantum computers, which aim to harness the fuzzy quantum properties of particles for technological applications. The more information quantum measurements can acquire, the better such technologies could work. Howland's experiment offers a more efficient quantum measurement than has traditionally been possible, says Aephraim M. Steinberg, a physicist at the University of Toronto who was not involved in the research. "This is one of a number of novel techniques which seem poised to prove indispensible for economically characterizing large systems." In other words, the physicists seem to have found a way to get more data with less measurement—or more bangs for their buck. [7]

A new experiment shows that measuring a quantum system does not necessarily introduce uncertainty

Contrary to what many students are taught, quantum uncertainty may not always be in the eye of the beholder. A new experiment shows that measuring a quantum system does not necessarily introduce uncertainty. The study overthrows a common classroom explanation of why the quantum world appears so fuzzy, but the fundamental limit to what is knowable at the smallest scales remains unchanged.

At the foundation of quantum mechanics is the Heisenberg uncertainty principle. Simply put, the principle states that there is a fundamental limit to what one can know about a quantum system. For example, the more precisely one knows a particle's position, the less one can know about its momentum, and vice versa. The limit is expressed as a simple equation that is straightforward to prove mathematically.

Heisenberg sometimes explained the uncertainty principle as a problem of making measurements. His most well-known thought experiment involved photographing an electron. To take the picture, a scientist might bounce a light particle off the electron's surface. That would reveal its position, but it would also impart energy to the electron, causing it to move. Learning about the electron's position would create uncertainty in its velocity; and the act of measurement would produce the uncertainty needed to satisfy the principle.

Physics students are still taught this measurement-disturbance version of the uncertainty principle in introductory classes, but it turns out that it's not always true. Aephraim Steinberg of the University of Toronto in Canada and his team have performed measurements on photons (particles of light) and showed that the act of measuring can introduce less uncertainty than is required by Heisenberg’s principle. The total uncertainty of what can be known about the photon's properties, however, remains above Heisenberg's limit.

Delicate measurement

Steinberg's group does not measure position and momentum, but rather two different inter-related properties of a photon: its polarization states. In this case, the polarization along one plane is intrinsically tied to the polarization along the other, and by Heisenberg’s principle, there is a limit to the certainty with which both states can be known.

The researchers made a ‘weak’ measurement of the photon’s polarization in one plane — not enough to disturb it, but enough to produce a rough sense of its orientation. Next, they measured the polarization in the second plane. Then they made an exact, or 'strong', measurement of the first polarization to see whether it had been disturbed by the second measurement.

When the researchers did the experiment multiple times, they found that measurement of one polarization did not always disturb the other state as much as the uncertainty principle predicted. In the strongest case, the induced fuzziness was as little as half of what would be predicted by the uncertainty principle.

Don't get too excited: the uncertainty principle still stands, says Steinberg: “In the end, there's no way you can know [both quantum states] accurately at the same time.” But the experiment shows that the act of measurement isn't always what causes the uncertainty. “If there's already a lot of uncertainty in the system, then there doesn't need to be any noise from the measurement at all,” he says.

The latest experiment is the second to make a measurement below the uncertainty noise limit. Earlier this year, Yuji Hasegawa, a physicist at the Vienna University of Technology in Austria, measured groups of neutron spins and derived results well below what would be predicted if measurements were inserting all the uncertainty into the system.

But the latest results are the clearest example yet of why Heisenberg’s explanation was incorrect. "This is the most direct experimental test of the Heisenberg measurement-disturbance uncertainty principle," says Howard Wiseman, a theoretical physicist at Griffith University in Brisbane, Australia "Hopefully it will be useful for educating textbook writers so they know that the naive measurement-disturbance relation is wrong."

Shaking the old measurement-uncertainty explanation may be difficult, however. Even after doing the experiment, Steinberg still included a question about how measurements create uncertainty on a recent homework assignment for his students. "Only as I was grading it did I realize that my homework assignment was wrong," he says. "Now I have to be more careful." [6]

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 $E = hv$ and $E = mc^2$, $m = hv /c^2$ that is the m depends only on the v 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 accelerated charges self-maintaining potential shows the locality of the relativity, working on the quantum level also. [1]

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]

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 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. 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.

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